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U–Pb geochronology of the granite magmatism in the Embu Terrane: Implications for the evolution of the Central Ribeira Belt, SE Brazil

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ABSTRACT

The Embu Domain represents the central part of the Ribeira Fold Belt in São Paulo, Brazil. It hosts several granitic occurrences of varied composition ranging from small granitic bodies that outcrop in a domain bounded by the intersection of two major sutures (Taxaquara and Guararema Faults) and batholitic masses outcropping to the east. Understanding the evolution of such granites is of vital importance to better constrain evolutionary models for the Ribeira Belt. In the present study, a set of samples from eleven main granite occurrences from the east of São Paulo state was selected for geochronological investigation using laser ablation-multicollector-inductively coupled plasma spectrometry (LA-MC-ICP-MS) and thermal ionization mass spectrometry (TIMS) U–Pb dating of zircon and monazite crystals, respectively. The results indicate a remarkable cluster of ages around 590 Ma with older events of granite magmatism between 660 and 600 Ma registered for four plutons, indicating a long history of crustal reworking and magma generation.

The ages of reworked sources were evaluated from inherited zircon cores. Although highly discordant these point to the predominance of Paleoproterozoic (2.4–2.1 Ga) sources, with minor contributions from Mesoproterozoic (1.1–0.9 Ga) and Archean sources (~3.1 Ga). The new data bring important insights into the role played by the Embu Domain on the paleogeography and evolution of the Ribeira Belt.

1. Introduction

Granite magmatism is widespread in all sectors of the Neoproterozoic Mantiqueira Province in eastern Brazil. Studies on a regional scale have demonstrated that it consists of several distinct associations marking successive events of convergent (continental arc; collision) and extensional tectonism (Campos Neto and Figueiredo, 1995; Heilbron et al., 2008; Pedrosa-Soares et al., 2001). The Ribeira Belt corresponds to the central portion of the Mantiqueira Province (Heilbron et al., 2004) and is composed of several different domains/terranes, amalgamated during the convergence between the São Francisco and Southern Congo cratons; all these terranes were intruded by large volumes of Neoproterozoic granites spanning a wide age interval of at least 150 Ma (~650–500 Ma). Older manifestations with ages around 800 Ma have been reported in the Ribeira Belt (Cordani et al., 2002; Heilbron and Machado, 2003; Vlach, 2001) and appear to be related to an early convergent episode of arc magmatism and orogenesis, but these ages are scattered and were obtained on samples from poorly known occurrences of orthogneisses. A recent review by Heilbron et al. (2008) identifies in the central Ribeira Belt a major episode of granite generation related to the building of a continental margin magmatic arc at 635–620 Ma (Rio Negro Complex) followed by three main collision episodes, associated with metamorphism and granite generation. These collision events would be related to the west-vergent (towards the São Francisco craton) docking of the Embu and Paraíba do Sul terranes at 605–580 Ma, followed by docking of the Oriental terrane (at 580–550 Ma, corresponding to the Rio Doce orogeny of Campos Neto and Figueiredo, 1995) and finally by collision of the Cabo Frio terrane at 530–510 Ma.

In this model, the Embu Terrane corresponds to one of the first "exotic" masses accreted at 605–580 Ma to a continental mass just-formed (at ~630–610 Ma) by the amalgamation between the São Francisco and Paranapanema cratons (Campos Neto, 2000). Although voluminous, the granite magmatism of the Embu Terrane is still poorly known, and a systematic study of the main occurrences is necessary to fully understand the significance of this terrane and its connections with other portions of the Ribeira Belt. In a previous work (Janasi et al., 2003) that reported preliminary results of U–Pb TIMS monazite dating of peraluminous (mostly

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two-mica) leucogranites from the Embu Terrane, the results define a main age interval between 590 and 540 Ma. Even though peraluminous granites are notably abundant in the Embu Terrane, biotite granites, which often do not carry monazite, also constitute an important component of this magmatism. The present work focuses on U–Pb dating of representative granite plutons from the Embu Terrane making use mostly of "in situ" LA-MC-ICP-MS; some new TIMS dates of both zircon and monazite are also presented. These results complement previous dating and/or place constraints on the ages for some plutons previously investigated by TIMS (e.g., Janasi et al., 2003). The new geochronological results clearly document the age of main magmatic events of crustal melting and granite generation in the Embu Terrane. The application of high spatial resolution methodology also allows the investigation of provenance via the study of inherited zircon crystal cores within magmatic crystals.

2. Geological context

Fig. 1 is a sketch map of the main tectonic units of the crystalline basement of southeastern Brazil. The Mantiqueira Province runs NNE, roughly parallel to the coast, and is divided into three major segments, from north to south the Araçuaí, Ribeira and Dom Feliciano fold belts. It is therefore a tectonic feature developed after a previous event that amalgamated the São Francisco Craton with another cratonic mass now concealed below the Paraná Basin, and whose margins, strongly reworked by Neoproterozoic magmatism, are represented by the Apiaí-Guaxupé Terrane (Campos Neto, 2000).

The subdivision into the Araçuaí and Ribeira fold belts is in fact artificial, since they are contiguous, and the limit is arbitrarily set at the region in the north of the Rio de Janeiro State where the main direction of the tectonic structures change southwards from NNE to NE (Heilbron et al., 2008). However, correlations between these two belts are still controversial (e.g., Tupinambá et al., 2007). A major twofold division is recognized in the Ribeira belt:

(1) The western domain (Occidental Terrain of Heilbron et al., 2008), in tectonic contact with the cratonic area, exposes Neoproterozoic meta-supracrustal sequences and their Paleoproterozoic basement. Apparently, there is an important along-strike variation in depth of exposure, with progressively deeper levels appearing towards NE, where the medium-to high-grade Paraíba do Sul supracrustals occur as remnants among two older units (the Juiz de Fora granulites to the NW and the Quirino orthogneisses to the SE). Within the Embu Terrane, metasupracrustal rocks are largely predominant, and exposures of older rocks are scattered (Fig. 1); there is a clear predominance of lower-grade mica-schists towards SW, also consistent with exposure of shallower levels in this direction. Sm–Nd T(DM) ages of intrusive granites and metamorphic rocks are typically >1.8 Ga, reaching values up to 3.0 Ga. A metassedimentary sequence with ophiolitic remnants (Ribeirão da Folha Fm) and an association of calc-alkaline granitoids interpreted as representative of a magmatic arc formed by oceanic comnsumption (Galileia Batolith) separate the Juiz de Fora granulites from the São Francisco craton in the northernmost portion of this domain, already within the Araçuaí Fold Belt (Pedrosa-Soares et al., 2008).

(2) The eastern domain (Oriental Terrane of Heilbron et al., 2008) is dominated by high-grade metamorphic rocks intruded by huge volumes of foliated granitic rocks. No clear signs of basement are present, and the terrane is interpreted as a magmatic arc, initially developed in an oceanic setting and then at a continental margin, as evidenced by relatively high εNd(t) (+4 to −12, Heilbron et al., 2008) and lower Sm–Nd T(DM) (usually 1.4–1.6 Ga, but as low as 1.0 Ga).

The ~N60E trending Embu Terrane (Fig. 1 inset) is interpreted to have been laterally juxtaposed to the Apiaí-Guaxupé Domain by dextral escape tectonics concomitantly with a frontal collision further north between the Juiz de Fora Terrane and the São Francisco Craton (Campos Neto, 2000). Small basement inliers composed of migmatitic orthogneisses are exposed throughout the Embu Terrane (e.g., Fernandes, 1991), but metasupracrustal sequences affected by medium to high-grade metamorphism are predominant. The depositional age of these supracrustal sequences is poorly constrained, but is assumed by most authors to be Neoproterozoic; its upper limit is constrained by a widespread metamorphic event at ~800 Ma that was apparently coeval with early arc-related magmatism which produced calc-alkaline granites and tonalites now transformed into orthogneisses (Vlach, 2001; Cordani et al., 2002). There is no consensus in the literature about the internal divisions within the Embu Terrane, but there are suggestions that it may consist of a few blocks with more or less distinctive geological evolution. The Guararema Fault running N80E truncates the main structures of the Embu Terrane (Fig. 1) and metasupracrustal sequences on both sides of the fault were shown to have different metamorphic degree and apparently different P–T regimes (Alves, 1975). In a broad scale, a higher-grade sequence of peraluminous paragneisses is predominant north of the Guararema Fault, while mica-schists are the main rock type to the south, where low-grade mica schists are locally described (Vieira, 1990).

The southeast limit of the Embu Terrane is defined by the Cubatão Fault, which separates it from a domain that runs along the coastal areas in the State of São Paulo and is largely dominated by a wide variety of deformed granitic rocks. Locally known as the Costeiro or Serra do Mar Domain, this domain is the southwestern continuation of the Oriental Terrane defined by Heilbron et al. (2008), as revealed, among other features, by their lower (Mesoproterozoic) Sm–Nd T(DM) ages (e.g., Campos Neto, 2000).

The granite magmatism, initiated further north in the Rio de Janeiro State as a continental-margin magmatic arc at ~630–620 Ma (Tupinambá et al., 2000), continued here long after its cessation in the Embu Terrane, with the generation of large volumes of (collision-related?) granites and charnockites from 580 to ~560 Ma (Campos Neto and Figueiredo, 1995; Machado et al., 1996). The youngest event of granite generation in this domain is represented by a post-collisional K-rich granite–diorite association derived from enriched mantle and lower crustal sources dated at 510–500 Ma (Wiedemann et al., 2002). According to some authors, the renewed mantle heating revealed by this magmatism may be related to the collapse of a new orogenic belt formed at ~520 Ma by the accretion of the Cabo Frio terrane, exposed in the easternmost portion of the Rio de Janeiro State (Heilbron et al., 2008; Schmitt et al., 2004; Azevedo Sobrinho et al., 2011).

3. Neoproterozoic granitic magmatism in the Embu Terrane

About 30% of the exposed area of the Embu Terrane is made up of Neoproterozoic granites, but few studies have been specifically devoted to these rocks. An old association of orthogneisses occurring as elongated bodies intrusive into the metasupracrustal sequences was recognized in regional studies (Fernandes, 1991). More recently, some of them were dated, and shown to have ages around 800 Ma (811 ± 13 Ma; Shrimp U–Pb zircon dating of a tonalitic gneiss; (Cordani et al., 2002); ~790 Ma; U–Th–total Pb chemical dating of monazite from the Salto Granite; Vlach, 2001). The exact magnitude and significance of this magmatism is still

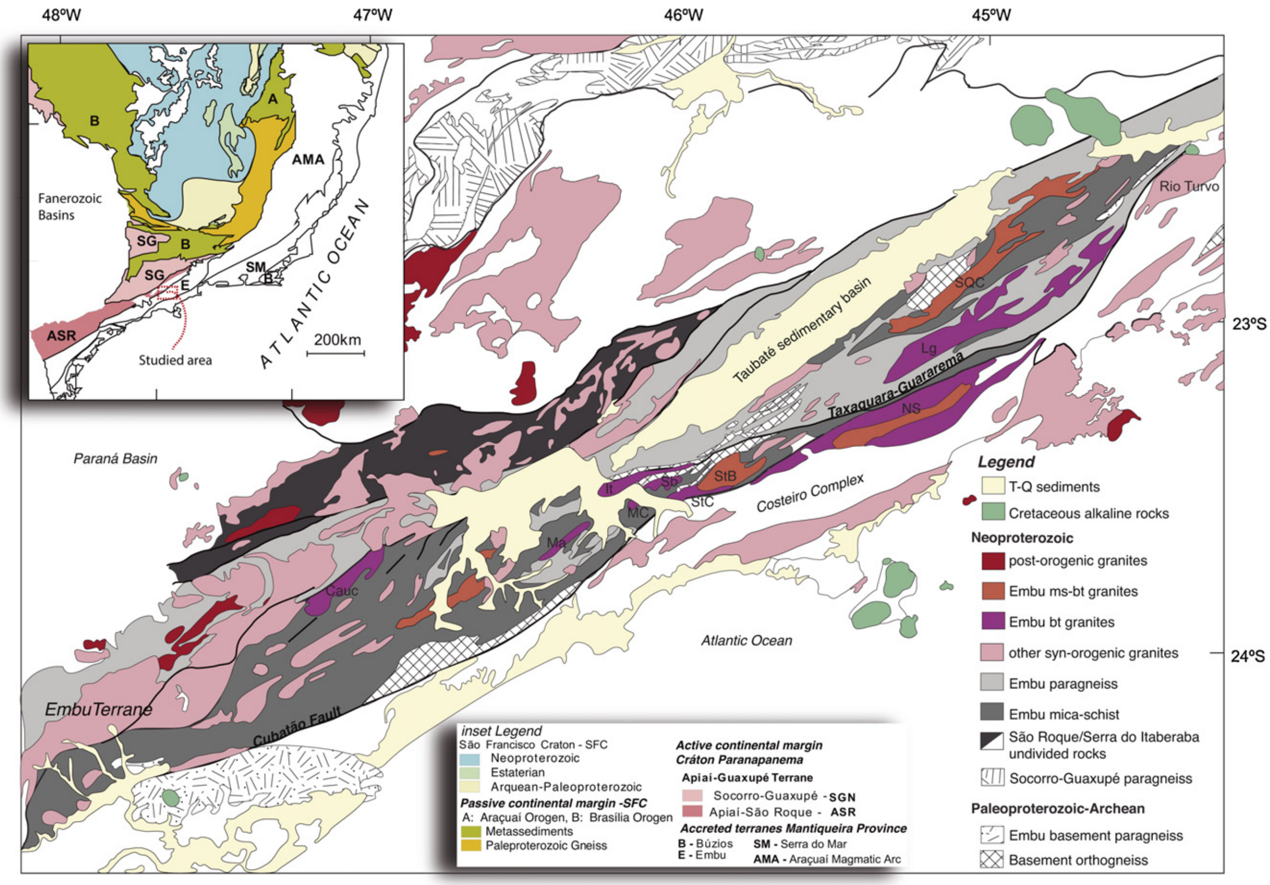

Fig. 1. Geological map of the Ribeira Folded Belt and location of the studied plutons in the vicinities of São Paulo city, Brazil. *SÃO FRANCISCO CRATON*: (infilled) Cretaceous cover; (SF) Late Ediacaran carbonate platform of São Francisco Supergroup; (E) Statherian volcanosedimentary sequence followed by a Stenian-Tonian rift-sag basin units of Espinhaço Supergroup; (A-P) Archaen-Paleoproterozoic basement. *PASSIVE CONTINENTAL MARGIN*: Metasedimentary pile of Araçuaí orogen (A), or Brasília orogen (B); (gn) reworked and nappe engaged Paleoproterozoic gneisses. *ACTIVE CONTINENTAL MARGIN*: (G) Goiás magmatic arc. Apiaí-Guaxupé Terrane: (SGN) Socorro-Guaxupé Terrane; (ASR) Apiaí-São Roque Domain. *MANTIQUEIRA ACCRETED TERRANES*: (BT) Late Ediacaran-Cambrian Buzios Terrane; (AMA) Ediacaran Araçuaí magmatic arc; (PT) Ediacaran Paranaguá Terrane; (SMT) Cryogenian-Ediacaran Serra do Mar Terrane, or Oriental Terrane (including Rio Negro magmatic arc); (ET) Cryognenian-Ediacaran Embú Terrane; (CT) Paleoproterozoic-Ediacaran Curitiba Terrane. *LUIS ALVES CRATON (LA)*: *Studied granites*: Sb: Sabaúna granite; StB: Santa Branca granite; StC: Santa Catarina granite; It: Itapeti granite; Ma: Mauá granite; MC: Mogi das Cruzes granite; Cauc: Caucaia granite; NS: Natividade da Serra granite; SQC: Serra do Quebra Cangalha granite; Lg: Lagoinnha granite.

unclear as no detailed studies were dedicated to these rocks. In this respect, it is remarkable that two muscovite leucogranites from the westernmost portion of the Embu Terrane (the Juquiá and Sete Barras granites) dated by monazite TIMS at ~600 Ma yield U–Pb zircon ages in the 740–760 Ma range (Passarelli et al., 2004). The zircon ages are interpreted as inheritance, but indicate that sources with this age are voluminous in the region. There is also evidence that the main metamorphic event recorded in several portions of the Embu Terrane is within this time range (Vlach, 2001); thus, in our view, this appears to correspond to an early episode of plate convergence that has yet to be better documented.

By far the largest volume of Neoproterozoic granites present in the Embu Terrane is formed by medium-sized plutons which have usually elongated shapes concordant with the regional ENE structural trend and are thought to be syn-tectonic with the latest events of convergence in the Ribeira Belt. In some cases, however, in spite of the elongated shapes, the plutons are characterized by magmatic foliation (e.g., defined by shape orientation of euhedral K feldspar crystals and lack of evidences of high temperature solid-state overprint). This is the case, for instance, of a group of plutons located to the east of the city of São Paulo (the Mauá, Mogi das Cruzes and Itapeti plutons) which appears to have a late-orogenic character. A typical feature of the magmatism in the Embu Terrane is the predominance of felsic granites with peraluminous character (biotite ± muscovite monzogranite); typical metaluminous granites with calcic hornblende are missing.

The internal structure of the Embu Terrane is still poorly known; it consists of an array of blocks with contrasted lithological content that could possibly have distinct geological evolution. However, a most obvious boundary is the Guararema Fault which, as previously described, separates sub-domains with contrasted metamorphic degree. It is remarkable that biotite–muscovite leucogranites seem to be more abundant south of the Guararema Fault, intruding lower-grade mica-schists (amphibolite facies, locally with St + Ky; Silva, 1992), whereas to the north of this fault biotite granites are predominant; this suggests some sort of vertical zoning in the type of granite magmatism, with the more evolved compositions reaching shallower crustal levels. A noteworthy exception to this zoning is the occurrence of the Serra do Quebra-Cangalha Batholith at the NE extreme of the Embu Terrane; however, its country rocks are dominantly mica-schists, a rock uncommon in that region. In the following, we present the main aspects of the geology and petrography of the granite plutons that were dated in this work.

3.1. Plutons located south of the Guararema Fault

Most granite plutons from the Embu Terrane outcropping to the west of the city of São Paulo are poorly known, and even simple field descriptions are sometimes unavailable. Exceptions are the Juquiá and Sete Barras muscovite–biotite granites which were studied by Passarelli et al. (2004). U–Pb TIMS zircon ages of 761 ± 2 Ma (Juquiá) and 739 ± 63 Ma (Sete Barras) were interpreted by these authors as inheritance, and younger monazite ages (respectively, 598 ± 9 Ma and 631 ± 23 Ma) would date the magmatic crystallization of these plutons.

The *Caucaia Granite* is a ~34 km × 5 km pluton elongated N60E parallel to the Caucaia Fault which locally corresponds to the limit between the Ribeira Belt (represented by the Embu Terrane) and the Apiaí Domain (Fig. 1, inset). The pluton is composed of slightly to moderately foliated biotite granites with textures varying from equigranular fine-grained to inequigranular medium-grained. A remarkable feature of this pluton is a strong aerogamaspectrometric signal related to high Th contents, reflecting the abundance of allanite.

The *Guacuri Granite* is a small (14 km^2) occurrence outcropping in the metropolitan area south of the São Paulo city. It is dominated by medium-grained equigranular muscovite–biotite monzogranite with CI ~ 4–6; tourmaline-bearing leucogranites occur at the pluton's core. Metapelite xenoliths and mafic *schlieren* are abundant.

The *Mauá Granite* is an elongated pluton running N45E along ~25 km with maximum width of 2–2.5 km and total area of 45 km^2 (Filipov and Janasi, 2001). Most of the pluton is made up of a grayish porphyritic biotite granite with color index (CI) ~ 8 showing 1–2-cm long tabular alkali-feldspar megacrysts set in a medium-grained matrix and aligned in a magmatic foliation. In the southwest portion of the pluton these rocks grade into a more felsic inequigranular biotite granite (CI ~ 6) that in turn pass into an equigranular tourmaline–muscovite leucogranite interpreted as a cupula unit (Filipov and Janasi, 2001). A remarkable feature of the pluton is the abundance of enclaves of both metamorphic and igneous origin, respectively biotite-rich tabular enclaves and ellipsoidal microgranular enclaves. The latter were studied in detail by Alves et al. (2009) who demonstrated that they correspond to products of self-mixing between new inputs of felsic magmas and the resident crystal mush. The age of the pluton was determined by Filipov and Janasi (2001) who obtained 588 ± 2 Ma by U–Pb TIMS in monazite from a typical porphyritic biotite granite.

The *Itapeti Granite* is a ~75 km^2 pluton with a strongly elongated shape due to the influence of the Guararema Fault Zone which delineates its northern limit. The main rock type is a porphyritic biotite granite, with CI = 8–10 and 2–3-cm long alkali-feldspar megacrysts that often show rounded shapes due to solid state deformation, also reflected in strong poligonization of quartz–feldspar lenses (Morais, 1995). Although slightly less differentiated, the typical porphyritic granites from Itapeti have several petrographic similarities with similar rocks from the Mauá Pluton, including the presence of micrograntic enclaves which are chemically (but not isotopically) just slightly more primitive than the host granites (Alves, 2009).

The *Mogi das Cruzes Granite* is a small sub-rounded pluton with ~8 km^2 that is mainly composed of inequigranular muscovite–biotite monzogranites with CI ~ 6 evolving to lighter equigranular granites in the centre of the pluton. These rocks are petrographicaly similar to more felsic varieties from the Mauá Granite; microgranitic enclaves slightly less differentiated than the host granite are common, much alike what is observed in Mauá and Itapeti, to which this pluton seems to be genetically related. Monazite chemical dating by EMPA indicates a crystallization age of 590 ± 12 Ma (Vlach, 2002).

The *Sabaúna Granite* is 16 km × 4 km pluton elongated in the N70E direction with ~40 km^2 of exposed area, located immediately to the NE of Mogi das Cruzes (Fig. 1). The main rock type is a medium-grained inequigranular muscovite–biotite granite with CI ~ 8 which appears to grade into a porphyritic variety with tabular to subrounded 1–2-cm alkali feldspar megacrysts. Magmatic microgranular enclaves are not described, but the study of this pluton is complicated by deep weathering of most outcrops.

The *Santa Catarina Granite* is a 13 km × 2.5 km pluton oriented N65E with ~32 km^2 dominated by a porphyritic biotite granite with CI ~ 10–12, distinguished in the field by the presence of abundant brownish titanite crystals; this rock grades northeastward into an inequigranular biotite monzogranite with lower CI (~7). A solid-state foliation is marked by the rounded contours of the alkali feldspar megacrysts and preferred orientation of deformed quartz and biotite.

The *Santa Branca Granite* forms a large pluton (up to 140 km^2 in area) with irregular shape and is in direct contact with the Santa Catarina in its SW portion; field relations are ambiguous, but seem to be consistent with an intrusive character for Santa Branca into the Santa Catarina pluton. The main rock type in Santa Branca is an inequigranular medium-grained muscovite–biotite monzogranite. The pluton seems to be compositionally zoned, with equigranular leucogranites being more common in its center, where aplitic and pegmatitic dykes are abundant. A solid state foliation is evident throughout the pluton, and is usually stronger at its borders. The contacts with the metasedimentary country-rocks, which in part seem to correspond to "roof-pendants", are very irregular (Alves, 1975); xenoliths of calc-silicate rock are locally abundant. Previous dating attempts of the Santa Branca Granite by U–Pb ID-TIMS in monazite resulted in strongly discordant results of doubtful significance (Janasi et al., 2003).

3.2. *Granite plutons located north of the Guararema Fault*

A series of small granite plutons appear intruding the meta-supracrustal sequence dominated by peraluminous gneisses that extends to the north of the Guararema Fault (Fig. 1). Orthogneisses seem to be relatively abundant in this region and may be difficult to separate from deformed varieties of the younger granites; the Salto Tonalite dated by Vlach (2001) is distinguished by a peculiar composition, both mafic-rich and peraluminous. Among other possible exposures of orthogneiss in this region is the Jambeiro Granite (Fig. 1), made up of strongly foliated biotite granite, so far undated.

The Aparecida Monzonite is remarkable because of its more primitive composition, dominated by mafic to intermediate rocks (diorite and monzonite) that show abundant structures of magma mingling with metaluminous granitic rocks. These unfoliated rocks may correspond to a young magmatic event as yet not recognized in the Embu Terrane, but also remain undated.

The two occurrences dated in this work are the huge Serra do Quebra Cangalha and Lagoinha batholiths (Fig. 1); both probably correspond to the amalgamation of several individual plutons which remain poorly studied so far and run parallel to each other along N60E for over 60 km with variable widths (5–15 km) and total areas over 300 km^2.

Serra do Quebra-Cangalha, mostly intrusive into schists, is dominated by white peraluminous biotite–muscovite leucogranite (CI < 5), usually coarse-grained and showing a well-developed solid-state foliation marked by stretched quartz and rounded big feldspar crystals. Most outcrops are strongly weathered, and it is hard to obtain fresh samples for laboratory analysis. Lagoinha, intrusive into peraluminous paragneisses, appears to be dominated by inequigranular to porphyritic biotite granites; scarce descriptions in literature and our visits to the area suggest significant variations in texture and mafic contents (e.g., CI = 10–3).

4. Methods

4.1. Mineral concentration

Mineral concentration procedures were conducted at the facilities of Centro de Pesquisas Geocronológicas (CPGeo), Universidade de São Paulo, Brazil. Samples were crushed in a jaw crusher and the resultant material was gradually grounded in a disc mill and progressively passed through 250, 149 and 60 μm sieves. The concentration of zircon and monazite was done using gravity separation methods (Wiffley table and heavy liquids); with the aid of a hand magnet, the heavy mineral concentrates were separated from magnetite and further concentrated by density separation using methylene iodide. A Frantz Isodynamic magnetic separator was used to split the concentrate into fractions with different magnetic susceptibilities. Details on separation procedures can be obtained from Passarelli et al. (2004).

4.2. TIMS analyses

The analytical procedures for thermal ionization mass spectrometer analyses (TIMS) were carried out at RIF (Radiogenic Isotope Facility; Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Canada) and CPGeo (Centro de Pesquisas Geocronológicas, Instituto de Geociências, Universidade de São Paulo Brazil).

Monazite crystals were chosen based on criteria such as transparency, color and magnetic fraction and these were picked up from monazite concentrates obtained from the Frantz Isodynamic magnetic separator at 0.5–0.7 A with the aid of a high-magnification binocular microscope. Before dissolution, the mineral fractions were immersed in 4 N HNO_3 and alternately subjected to cleansing with H_2O and acetone, then weighed. The selected grain was transferred to a 7 ml pre-cleaned Savillex® beaker and washed in Milli-Q water and in 7 N HNO_3 solution, 6 μl of H_2SO_4 and 5 μl of a $^{205}Pb/^{235}U$ spike was added to the becker and the mixture was taken to a hot plate at 150 °C for three days; the becker was then opened for complete drying. The extraction of U and Pb was done using ionic exchange columns filled with 3 drops of 1 × 8 Eichrom resin, alternately washed with 210 μl of MilliQ water and 6 N HCl solution.

The resin was conditioned using 120 ml of HCl 3 N and the sample was added to the column for extraction of U and Pb using 200 ml of Milli-Q water after the extraction of other constituents via addition of 90 ml of HCl 3 N and 120 ml of HCl 6 N. A drop of phosphoric acid was added to the solution containing U and Pb and the sample was partially dried in a hot plate and loaded onto a filament for analysis.

Zircon crystals were separated and analyzed at the Radiogenic Isotope Facility (University of Alberta). The crystals were selected from non-magnetic aliquots (from 0.6 to 1.0 Å) in order to obtain fractions containing from 8 to 30 colorless, idiomorphic zircons; these were transferred to Teflon bombs to which a HF–HNO_3 (10:1) mixture and a spike solution with $^{205}Pb/^{235}U$ were added. These bombs were left for 7 days in an oven at 220 °C. Mineral fractions were heated on a hotplate for 5–7 days at 150 °C. U and Pb were then purified using anion-exchange chromatography, according to the procedures summarized in Heaman et al. (2002) and Passarelli et al. (2009). The U and Pb aliquots were then loaded together onto single Re filaments with a mixture of silica-gel and H_3PO_4. At the RIF isotope ratios were measured by thermal ionization using a VG354 mass spectrometer in a single Faraday detector or Daly photomultiplier detector mode. The mass discrimination corrections of 0.088% amu^{-1} for Pb and 0.155% amu^{-1} for U were applied to all Faraday data; these values are based on repeat measurements of the NBS981 and U500 standards during the study. Average blank analyses were estimated at 2 pg for Pb and 0.5 pg for U. The isotopic composition of the common Pb in the analysis in excess of the analytical blank was estimated from the two-stage Pb evolution model of Stacey and Kramers (1975) calculated for the age of the sample. All age calculations were performed using Isoplot (Ludwig, 1992). Decay constants used were ^{238}U (1.55125×10^{-10} y^{-1}) and ^{235}U (9.8485×10^{-10} y^{-1}).

4.3. LA-MC-ICP-MS analyses

U–Pb data on zircon and titanite crystals were acquired using a Nu-Plasma MC-ICP-MS (Nu Instruments, UK) coupled to a frequency quintupled (λ = 213 nm) Nd:YAG laser ablation system (New Wave Research, USA) at the RIF, University of Alberta, Edmonton Canada. The collector configuration consists of 12 Faraday 'buckets' and three ion counters, allowing for the simultaneous acquisition of ion signals ranging from mass ^{203}Tl to ^{238}U, with the ^{207}Pb, ^{206}Pb and ^{204}Pb (^{+204}Hg) ion beams measured on the ion counting channels. Detailed information regarding the nature of the ion counters, calibration and data reduction can be found in Simonetti et al. (2005).

A 30 s blank analysis prior to ablation is performed for determination of ^{204}Hg contribution and is followed by ablation for another 30 s. The ablation is Tl-doped in order to correct instrumental mass bias using $^{205}Tl/^{203}Tl$. Internal standards [LH94-15 (Ashton et al., 1999) for zircons and large titanite crystals from Khan mine pegmatite (Simonetti et al., 2006)] were used for correction of instrumental drift and the standard was analyzed after every 12 unknown zircon grains. Common lead correction is readily possible from ^{204}Pb measurements and data reduction for error propagation was performed using an in-house spreadsheet.

The acquisition of accurate U–Pb ages using titanite grains depends upon the correct assessment of the common Pb component. Here we use the line projected through the uncorrected data on a Tera-Wasserburg diagram to determine the common Pb-component on the $^{207}Pb/^{206}Pb$ axis. The intercept is then used to calculate the proportion of common Pb for each individual analysis.

5. Results of U–Pb dating

5.1. Caucaia Granite (sample PD-2448)

Sample PD-2448 is a slightly foliated inequigranular biotite granite typical of the central portion of the Caucaia Granite. Zircon crystals are typically clean, with few inclusions and fractures, and typical aspect ratios of 2:1 to 3:1.

The LA-MC-ICP-MS results are mostly nearly concordant, and a Concordia age of 583.2 ± 3.6 Ma (n = 32 analyses; Fig. 2) with a very low MSWD (0.12) is interpreted as representing the time of crystallization. A single inherited core (grain #18) was detected, and although 14% discordant, it yields an Archean $^{207}Pb/^{206}Pb$ of 3112 ± 16 Ma.

5.2. Itapeti Granite (sample E-38)

Sample E-38 is a typical porphyritic biotite granite outcropping at the southwest end of the Itapeti pluton. Zircon crystals are usually prismatic with a 3:2 aspect ratio, irregular to concentric magmatic oscillatory zoning and highly fractured, as revealed by BSE images. Some crystals show rimward increase in brightness in BSE images that might be associated with higher U and Th contents. Some inherited cores were identified as unzoned rounded areas that appear darker in BSE images (Fig. 3).

Fifty zircon crystals were analyzed by LA-MC-ICP-MS and yielded discordant results (Appendix A in supplementary data). An intercept age could not be constrained since some of the analyzed

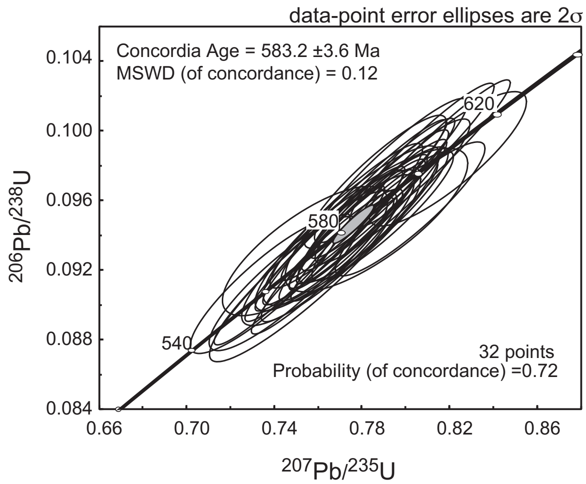

Fig. 2. Concordia plot with constrained crystallization age of Caucaia pluton.

zircons show an inheritance component or experienced Pb loss as shown in the Concordia diagram and the probability plot (Fig. 4a and b). A weighted average based on 19 analyses representing the peak on the probability plot resulted in 581.3 ± 5.6 which is interpreted as the best estimate of the magmatic age for this sample (Fig. 4b, inset).

Four inherited cores showing discontinuous zoning patterns in relation to magmatic rims were also analyzed. Three spots yielded upper intercept ages around 1.1 Ga (spots E38-7, E38-8 and E38-26, with discordances of 50, 38 and 35%, respectively); another spot resulted in an upper intercept age of 1.4 Ga but this shows extremely discordant behavior (spot 29, 63% discordance).

5.3. Sabaúna Granite (sample E-26)

Sample E-26 is a porphyritic biotite granite outcropping in the central part of the Embu Domain and yielded zircons with dimensions varying from 100 to 350 μm; BSE images reveal diffuse zoning patterns, in part parallel to crystal faces; crystals are often fractured and host erratically distributed inclusions.

Sixty grains were selected and analyzed by LA-MC-ICP-MS using beam diameters of 40 or 30 μm. The results are variably discordant (Appendix A), and a weighted average excluding points with signs of inheritance yields 581.9 Ma ± 6.3 (Fig. 4c). However, in a probability plot a bimodal distribution with a main peak around 580 Ma is identified (Fig. 4d) and the resultant weighted average of 580.6 ± 4.6 Ma yields a lower MSWD and is considered as the best crystallization estimate for Sabaúna pluton (Fig. 4d, inset).

It is possible to identify two other populations in the probability plot, one with concordant ages around 630 Ma and a second discordia line defined by points with concordant ages of ∼550 Ma. The older population is interpreted as carrying inherited component whereas the younger population would represent Pb loss.

5.4. Santa Catarina Granite (sample E-24)

Zircon crystals from sample E-24, a porphyritic biotite granite with well-developed solid state deformation, were analyzed by LA-MC-ICP-MS. The grains show short prismatic habits and extremely irregular zoning patterns, with BSE images showing cores that present bright colors resulting from possible enrichments in HREE, followed by darker rims, in a fashion contrary to the pattern observed in other studied plutons.

The analyses are variably discordant (Fig. 4e) and define four different populations in a probability plot for $^{206}Pb/^{238}U$ ages (Fig. 4e, inset).

A regression line disregarding inherited (spot #16) and Pb loss ages results in an age of 631.8 ± 5.4 Ma and this is considered the best estimate for the crystallization age of the pluton (Fig. 4f). One point suspected from BSE images to correspond to an inherited core shows much older $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ dates, (see supplementary data). Although discordant, it has a Paleoproterozoic age that might vary from 2.37 to 2.10 Ga (upper intercept ages anchored at the crystallization age and at zero age, respectively).

To further constrain the age of the Santa Catarina pluton, LA-ICP-MS analyses were performed in 25 titanite crystals from the same sample; results are presented in Appendix C and Fig. 4g. In the Tera-Wasserburg plot, the *y*-intercept of the linear regression represents the $^{207}Pb/^{206}Pb$ composition of the common Pb component (e.g., Simonetti et al., 2006), the idea being that the latter is devoid of any U or Th and therefore its $^{238}U/^{206}Pb$ value is zero. The crystallization age of the mineral is given by the intersection of the regression line and the Concordia curve, which represents the isotopic composition of a “radiogenic” component with a $^{238}U/^{206}Pb$ age of 659 ± 10 Ma. The weighted average of $^{206}Pb/^{238}U$ results in a much older age of 676.1 ± 9.9 Ma (Fig. 4h). Even if the uncertainties are taken into consideration, this age is older than the magmatic crystallization age estimated from zircon data, and its significance is unclear, but it confirms an older crystallization age for Santa Catarina pluton.

5.5. Santa Branca Granite (sample E-23)

Sample E-23 is an equigranular muscovite–biotite granite from the southern portion of Santa Branca pluton. Two single grains of clean monazite crystals were dated by TIMS at CPGeo. The crystals have similar U and Pb contents (1233–1343 ppm and 783–861 ppm, respectively) and resulted in slightly discordant ages. The crystal from the fraction magnetic at 0.5 A yielded a $^{206}Pb/^{207}Pb$ age of 609.6 ± 2.4 Ma, and the least magnetic fraction resulted in a $^{207}Pb/^{206}Pb$ age of 594.7 ± 1.2 Ma. Since the younger age has the lower discordance (only 1.2% discordance), it is considered the best estimate for the crystallization age of Santa Branca Granite.

5.6. Guacuri Granite (sample E-30)

Sample E-30 is a foliated muscovite–biotite equigranular granite outcropping in the central part of Guacuri pluton. Two multi-grain monazite fractions with three crystals each were analyzed by TIMS at RIF and show slight and variable discordance (−1.6 and 1.6%). The $^{206}Pb/^{238}U$ ages are similar (Appendix B) and result in a weighted average of 589.8 ± 7.7 Ma, which is considered the best estimate of the Guacuri Granite magmatic age.

5.7. Mauá Granite (sample MAU-29)

The magmatic age of the Mauá Granite is well established at 588 ± 2 Ma by U–Pb TIMS dating in monazite (Filipov and Janasi, 2001). The results obtained by LA-MC-ICP-MS in zircon crystals from sample MAU-29, a porphyritic biotite granite from the central part of the pluton, are very discordant for most of the analyzed crystals (over 25%, see Concordia plot Fig. 5a); however these are nonetheless consistent with the crystallization age determined previously determined (Fig. 5a, inset). The presence of inherited cores might help to constrain the age of the sources contributing to the Mauá Granite; a slightly reverse discordant point (#11, 3% discordance) yielded ages close to 1.0 Ga, whereas other four points

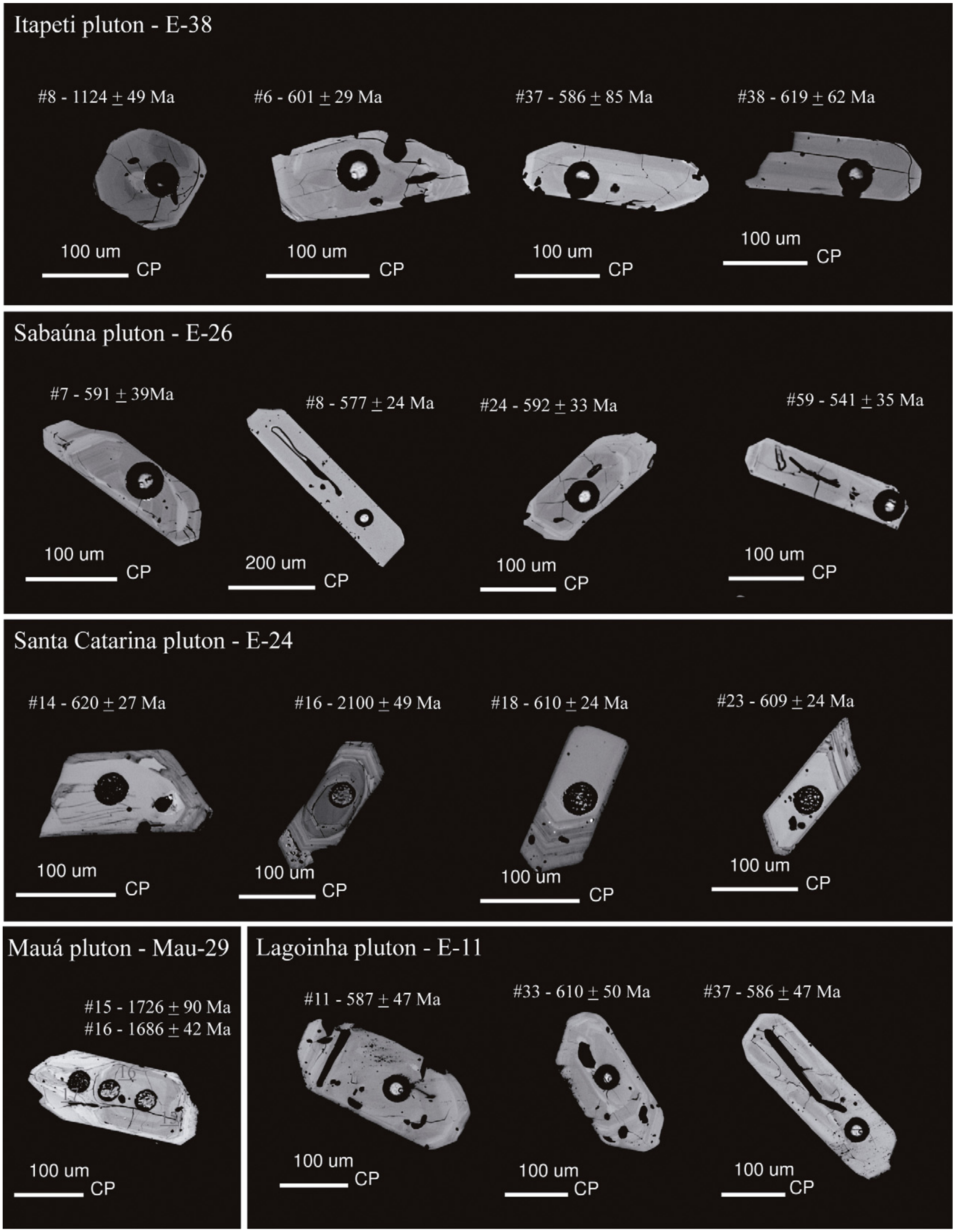

Fig. 3. Representative BSE images showing different zircon types from the studied granite plutons.

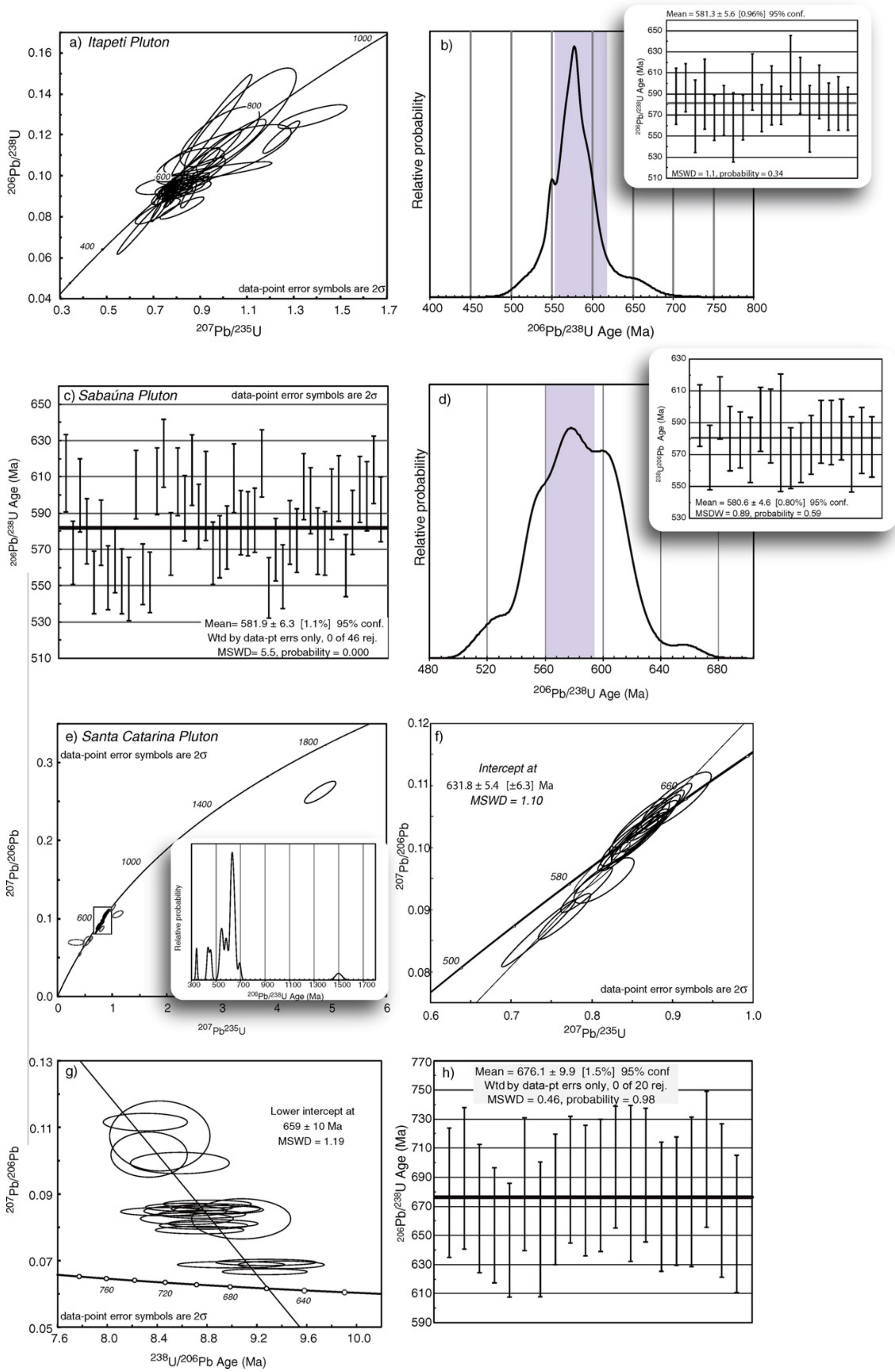

Fig. 4. Age constraints from zircon LA-ICP-MS U–Pb results. *Itapeti pluton*: (a) Concordia diagram with all data from Itapeti pluton; (b) probability plot and weighted average of $^{206}Pb/^{238}U$ ages, the inset uses only data that plot inside the main peak on the probability distribution (shown in grey); *Sabaúna pluton*: (c) probability plot of $^{206}Pb/^{238}U$ ages; (d) probability plot and weighted average of $^{206}Pb/^{238}U$ ages, the inset uses only data that plot inside the main peak on the probability distribution (shown in grey); *Santa Catarina pluton*: (e) Corcordia plot of all LA-IC-MS results and probability distribution of $^{206}Pb/^{238}U$ ages, the square marks points used in the regression assuming present-day Pb loss (f); (g) Tera-Wasserburg plot for titanite LA-ICP-MS; (h) weighted average plot of $^{206}Pb/^{238}U$ ages for titanate data.

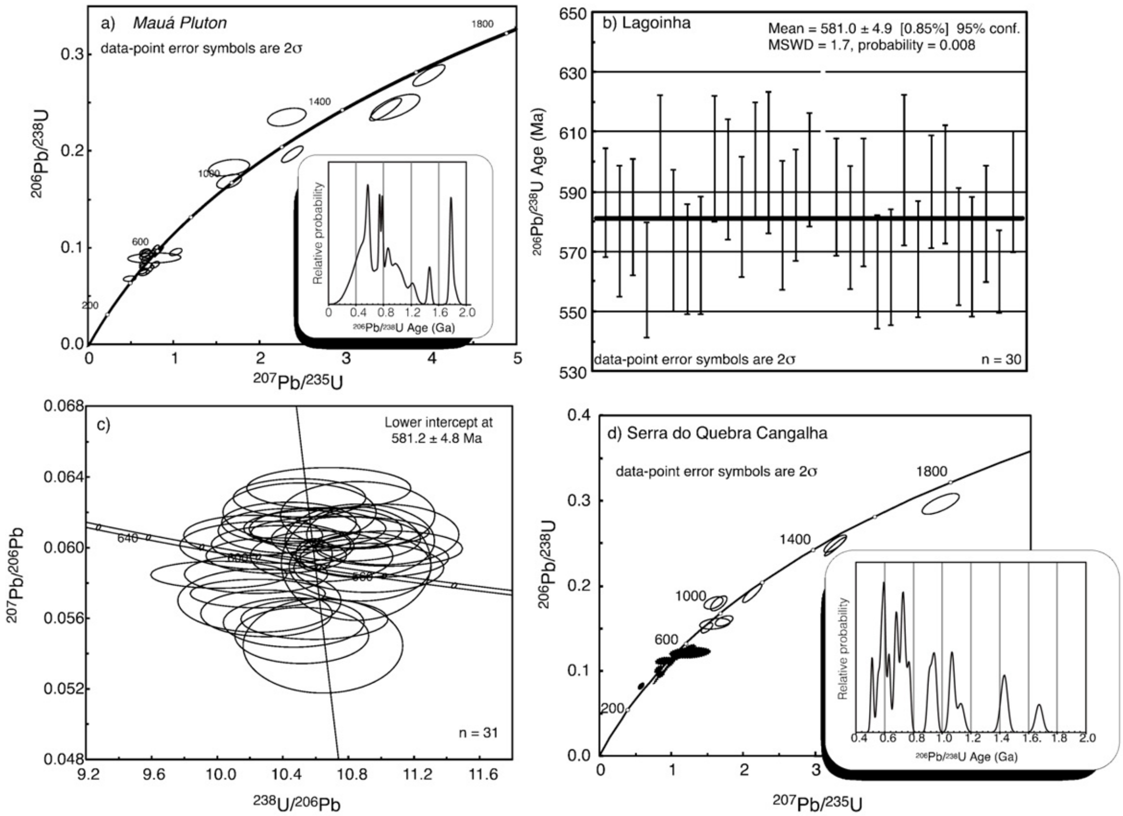

Fig. 5. Age constraints from zircon LA-ICP-MS U–Pb results. *Mauá pluton*: (a) Concordia diagram showing all analysed crystals and probability plot for $^{206}Pb/^{238}U$ ages (inset); *Lagoinha pluton*: (b) weighted average plot for $^{206}Pb/^{238}U$ ages with a rejected point showed in as a grey filled box; (c) anchored Tera-Wasserburg plot for zircons showed in (c); *Serra do Quebra Cangalha pluton:* (d) Concordia diagram showing all results and probability distribution plot of $^{206}Pb/^{238}U$ ages, filled ellipses correspond to ages close to the assumed crystallization age of the pluton whereas unfilled ellipses correspond to points taken in crystal cores.

with discordances between 7 and 19% yielded $^{207}Pb/^{206}Pb$ ages of ~1.4 Ga (#2) and ~1.7 Ga (#15, 16 and 28).

5.8. *Lagoinha Batholith (sample E-11)*

Sample E-11 is a porphyritic biotite granite collected in the central part of the Lagoinha Batholith. Forty zircon crystals with sizes variable from 100 to 300 μm were chosen for LA-MC-ICP-MS; BSE images reveal diffuse zoning patterns with no well-defined internal structures.

Most points lie close to concordia with $^{206}Pb/^{238}U$ ratios yielding similar weighted averages (581.0 ± 4.9 Ma, Fig. 5b). An undistinguishable result (581.2 ± 4.8 Ma) is obtained in a Tera-Wasserburg plot constructed with the y intercept anchored to the $^{207}Pb/^{206}Pb$ composition of 0.883 for Pb that is 580 Ma old using Stacey and Kramers (1975) two-stage Pb evolution diagram (Fig. 5c). Ages with apparent Pb loss or inherited component were not considered in the mixing line and these are identified in Appendix A.

5.9. *Serra do Quebra Cangalha Granite (E-07)*

Sample E-07 is a typical coarse-grained muscovite–biotite granite from the Serra do Quebra-Cangalha batholith, and yielded both zircon and monazite crystals.

Twenty U–Pb LA-MC-ICP-MS determinations were performed in zircon crystals inferred from BSE images to correspond to rounded inherited cores with zoning patterns truncated by magmatic overgrowths. Most results are discordant but constraint on inheritance is possible for some of the data (Fig. 5d). Fraction #12, only 3% discordant, resulted in a $^{207}Pb/^{206}Pb$ age of ~1.1 Ga, which is similar to $^{207}Pb/^{206}Pb$ ages observed to spots #1 to #3. An older inherited component of 1.5–1.9 Ga is indicated by the upper intercept ages (anchored to zero) of analyses #13 and #16, with moderate discordance (13%). A younger component is also observed on the concordia plot (Fig. 5d), but no crystallization age could be determined from this population. As an attempt to determine the crystallization age of the granite, points were taken at the overgrowths (identified in Appendix A), the results were, in most cases, meaningless or highly discordant. However, 206/238 ages of the spots #9, 15, 19 and 20 are within error with monazite data presented below.

U–Pb TIMS monazite dating was performed to estimate the magmatic crystallization age of the sample. Two monazite fractions were previously presented by Janasi et al. (2003). The results were discordant with different $^{207}Pb/^{206}Pb$ ages (679.3 ± 5.1 Ma and 655.6 ± 3.7 Ma), and no unambiguous interpretation could be offered for the exact magmatic age of the sample. Two new monazite fractions were analyzed at CPGeo; one is nearly concordant (0.96% discordant) with a $^{207}Pb/^{206}Pb$ age of 664.1 ± 1.3 Ma, and is preferred over a younger one (656.8 ± 3.3) in view of the significantly lower error associated to the $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ratios.

6. Discussion of the U–Pb results

The ages obtained in this work contribute to the chronostratigraphy of granite magmatism in the Embu Terrane for which scarce high-quality data were previously obtained. For some monazite-bearing peraluminous granites, TIMS U–Pb monazite ages were reported by Filipov and Janasi (2001) and Janasi et al. (2003), whereas EPMA chemical dates were presented by Vlach (2002) for the Mogi das Cruzes Granite.

Table 1
Summary of preferred crystallization ages for granite plutons from the central part of the Ribeira Fold Belt.

Pluton	Sample	Location	Mineral	Age (Ma)
Caucaia	PD-2448	−47.017, −23.698	Zircon	583.2 ± 3.6
Itapeti	E-38	−46.266, −23.519	Zircon	578.6 ± 5.1
Sabaúna	E-26	−46.094, −23.483	Zircon	577.3 ± 4.8
Santa Catarina	E-24	−46.040, −23.547	Zircon	631.8 ± 5.4
Santa Branca	E-23	−45.881, −23.492	Monazite (TIMS)	594.7 ± 1.2
Guacuri	E-30	−46.585, −23.688	Monazite (TIMS)	589.8 ± 7.7
Mauá	Mau-6[a]	−46.473, −23.713	Monazite (TIMS)	588.0 ± 2.0
Lagoinha	E-11	−45.044, −22.978	Zircon	581.0 ± 4.9
Serra Q. Cangalha	E-07	−45.112, −22.918	Monazite (TIMS)	664.1 ± 1.3

[a] Sample analyzed by Filipov and Janasi (2001).

Our new LA-MC-ICP-MS zircon dates allowed the determination of crystallization ages of plutons formed dominantly by biotite granites, which are the most abundant granite type in this region. As most of the granites from the Embu Terrane are products of low-temperature crustal melts, inheritance is expected to be significant, inhibiting the use of U–Pb TIMS as dating tool. The use of LA-MC-ICP-MS also allowed the study of inherited cores previously identified from BSE imaging, giving some clues on the crustal sources involved in this magmatism, which has some important implications for granite petrogenesis and also for the evolution of this part of the Ribeira Belt.

New ID-TIMS ages on monazite and zircon improved on some previously obtained results (e.g., for the Santa Branca and Serra do Quebra-Cangalha granites) or were used to further constrain the LA-MC-ICP-MS ages.

A summary of the preferred ages now available for the granites from the Embu Terrane is presented in Table 1. A remarkable cluster of ages around 590 Ma is evident, including most plutons located to the south of the Guararema Fault and also the Lagoinha batholith. Older events of granite magmatism are represented by the ∼660 Ma Serra do Quebra Cangalha batholith, the 630 Ma Santa Catarina Granite and the ∼600 Ma Santa Branca Granite. It is remarkable that no plutons younger than ∼580 Ma we identified, although we suspect that the Aparecida Monzonite would be a candidate for that, given its unfoliated character and peculiar composition that seems unrelated to the other plutons.

Considering the geologic relationships established in previous work, the results are very consistent, and yield a firm basis for inferences on petrogenetic relationships among the different plutons (Alves, 2009). The neighbouring but contrasted Itapeti, Mauá and Mogi das Cruzes plutons share important field and geochemical-isotopic features that point to a cogenetic relationship (Alves, 2009); their ages are identical within error and therefore consistent with such an inference. On the other hand, other two plutons from the same domain (Guacuri and Sabaúna) also show the same age and must therefore be products of the same magmatic event, even if resulting from the melting of different source areas, as clearly shown in the case of Guacuri, which shows a very different isotope signature (e.g., 87Sr/86Sr(i)= 0.71556, against 0.7101–0.7127 for other plutons, Alves, 2009).

The two older granite occurrences outcropping immediately south of the above plutons (Santa Branca and Santa Catarina) are clearly distinct based on their field relationships since both were pervasively affected by a high-temperature solid-state foliation. From structural relations, Santa Catarina is inferred to be older than Santa Branca, which is in agreement with their estimated ages (respectively, 632.4 ± 5.3 Ma and 599.4 ± 1.6 Ma).

The two major batholiths outcropping to the northeast of the Guararema Fault are still poorly studied, and the age estimates now available are an important, though still limited, contribution to the understanding of their significance. Geochemical and Sr–Nd–Pb isotope data for samples of these batholiths (Alves, 2009) suggest some key affinities between the Serra do Quebra Cangalha batholith and the Natividade da Serra batholith, also dominated by peraluminous granites, but located south of the Cubatão Fault and therefore located in the Oriental Terrane of Heilbron et al. (2008). Both batholiths seem to derive from a similar source, younger and less depleted as compared to those involved in the generation of the other granites from the Embu Terrane. However, the age of Serra do Quebra-Cangalha (∼660 Ma) shows that it must be the product of a completely independent event that was so far undocumented in the Embu Terrane. The Lagoinha batholith was dated at 584.0 ± 4.2 Ma, reinforcing the suggestion that the 590–580 Ma period witnessed the peak of granite magma generation over the whole region of study; it is interesting to note that the age of the Natividade da Serra batholith (587 ± 7 Ma; U–Pb monazite TIMS, Janasi et al., 2003) also overlaps with this peak.

As expected for low-temperature granites derived from dominantly crustal sources, inheritance was identified in most plutons for which LA-MC-ICP-MS U–Pb zircon results were obtained. In some cases, crystals with ages only slightly older than the magmatic ages seem to be present, a phenomenon that has been recognized in several recent U–Pb dating studies using "in situ" techniques (e.g., Silva et al., 2005b). These could correspond to reworking of previous magma pulses from the same magma system, but the uncertainties associated with individual age determinations impede further inferences on this matter. Older inheritance was more clearly evidenced in samples from the Caucaia, Mauá, Santa Catarina and Serra do Quebra-Cangalha granites. Inherited zircon cores with Paleoproterozoic (2.1–2.4 Ga) age are present in Santa Catarina and Mauá, whereas an Archaean (≥3.1 Ga) core was identified in Caucaia. A Paleo- to Mesoproterozoic (1.5–1.9 Ga) interval of zircon generation is clearly evidenced only in the Serra do Quebra-Cangalha sample. On the other hand, a younger zircon-forming event at ∼0.9–1.1 Ga was identified in both Serra do Quebra-Cangalha and in Mauá, and may place important constraints on the age of the sources of these granites.

6.1. *Implications for the magmatic evolution in the southern Ribeira Belt*

The results presented in this work indicate that, although spanning a long time range of up to 200 m.y. (Janasi et al., 2003), most of the granite magmatism in the Embu Terrane was concentrated in a narrow interval around 590–580 Ma. This finding is important, since, as it is becoming clear from recent U–Pb dating programs, it confirms that granite magmatism related to convergent tectonics is at least some 10–15 m.y. younger in the central Ribeira Belt as compared to the neighbor domains to the north (the Apiaí-Guaxupé Terrane, corresponding to the reworked border of the Paranapanema Craton; Campos Neto, 2000), where the "syn-orogenic" granites were mostly formed in the range 630–600 Ma (e.g., Leite et al., 2007). Moreover, the 590–580 Ma interval witnesses the installation of a linear post-orogenic granite province at the southern border of the Apiaí-Guaxupé Terrane (the Itu Granitic Province), extending for ∼350 km as a 60-km wide belt parallel to the Embu Terrane, suggesting that it can have been generated as an inboard response to slab break-off possibly provoked by arrival of the cratonic keel at the subduction domain and coeval with the lateral emplacement of the Embu Terrane (Janasi et al., 2009).

The granites from the Embu Terrane are, to a large extent, the products of crustal melting at relatively low temperatures (<800 °C; Alves, 2009), and their tectonic significance is far from understood. The 605–580 Ma time interval is associated with the first collisional episode recorded in the Ribeira Belt (Heilbron et al., 2008), responsible for the lateral (dextral) emplacement of the Embu Terrane against the assembled margin of Paranapanema-São Francisco protocontinent; this "docking" would represent an outboard lateral terrane scape coeval with the frontal collision following oceanic closure further north (the Araçuaí orogen), with collage of the Juiz de Fora granulitic terrane with the São Francisco Craton.

The question remains as to whether the predominantly peraluminous, low-temperature, crust-derived granites from the Embu Terrane are products of collisional magmatism. In the absence of reliable markers of the passage from magmatic arc to collisional tectonics, there is no clear answer to this question at the moment. The few available determinations of the age of the main metamorphic event recorded in the metasupracrustal rocks of the Embu Terrane point to ages around 800 Ma (Vlach, 2001), unrelated to the main episode of granite generation. As discussed earlier, the ~590 Ma granites of the Embu Terrane seem to have intruded at relatively shallow crustal levels; this is indicated for instance by the exposure of cupula units affected by hydrothermal activity, as in the Mauá Granite (Filipov and Janasi, 2001) and by the presence of sinuous axial vapour cavities in the zircon grains from sample E-26 (Fig. 3). Eastward, in the Paraíba do Sul Domain, the typology and age of the granite magmatism seems to be similar to Embu. This is indicated by the U–Pb TIMS monazite age for the voluminous Rio Turvo peraluminous granite (579 ± 6 Ma), which has been interpreted to be derived from melting of the surrounding metasediments (Machado et al., 1996). This model could be interpreted as indicative that the Paraíba do Sul Domain corresponds to a deeper exposure level of the same terrane, where the main metamorphic event at 590–570 Ma is firmly established from U–Pb dating of monazite and titanite (Machado et al., 1996); however, no traces of the older ~800 Ma metamorphic event were reported so far, and this correlation is as yet unclear.

"Cordilleran-type" granite magmatism is recognized as an important component of the Oriental Terrane which, according to Heilbron et al. (2008), was accreted in a second "docking" event at ca. 580–550 Ma; its limits with the Embu and Paraíba do Sul domains are made through a high-grade shear zone named "Central Tectonic Boundary". The Rio Negro Complex, composed of orthogneisses of calc-alkaline affinity, is regarded as a magmatic arc initially developed in an intra-oceanic environment which later evolved to a continental margin "Cordilleran-type" arc (Heilbron et al., 2008; Tupinambá et al., 2000). Scarce U–Pb dating of the Rio Negro orthogneisses suggests that it was formed in two main periods (790 Ma and 635–620 Ma; Heilbron et al., 2008). As yet, it is unclear what is the volume and duration of arc magmatism in the Oriental Terrane. Available geochronological results confirm the perception expressed earlier by Campos Neto and Figueiredo (1995) that most of the granitic activity in this terrane occurred in the 590–565 Ma range. Among these are the voluminous granites making up the Serra dos Órgãos batholith (Tupinambá, 1999) and the most expressive granite occurrences in the eastern portion of the State of Rio de Janeiro, corresponding to expanded calc-alkaline, in parts of charnockitic affinity, interpreted by Campos Neto and Figueiredo (1995) as products of continental arc magmatism (e.g., the Bela Joana norite–enderbite–charnockite suite and the Angelim tonalite–granodiorite suite). Although, as commented above, a clear marker of the end of the magmatic arc setting in the Oriental Terrane seems still missing, most authors agree that younger (~565–560 Ma) plutons of peraluminous character such as those exposed in such scenic beauties as the Sugar Loaf in the city of Rio de Janeiro would be products of crustal recycling during the collisional stage that followed the end of subduction (e.g., Campos Neto and Figueiredo, 1995; Heilbron et al., 2008; Silva et al., 2005a). Interestingly, the Ubatuba Charnockite with similar age (~565 Ma TIMS U–Pb zircon age; C. Tassinari, personnal communication) in the western portion of the Oriental Terrane has "within-plate" chemical signature and could mark the end of the convergent tectonics related to the "Rio Doce" orogeny.

The present work demonstrates that granite magmatism with ages in the range 660–620 Ma is present in the Embu Terrane, represented by the Serra do Quebra-Cangalha batholith and the Santa Catarina Granite. Although their composition is not typical of arc-related granites, these occurrences have peculiar geochemical signatures that clearly demonstrate that they also do not fit easily into other "typical" tectonic environments; among them, their less negative εNd(t) compared to the younger granites is particularly significant (Alves, 2009). It is also important to recall that, as summarized above, the 590–580 Ma magmatism in the Oriental Terrane could be, in the vision of some authors, still connected to the development of a continental margin magmatic arc (e.g., Campos Neto and Figueiredo, 1995), responsible for the generation of important volumes of calc-alkaline plutons. Within this picture, the 590–580 Ma dominantly peraluminous granites from the Embu Terrane could be envisaged as part of an inner belt of crust-derived plutons much in a similar way to that developed east of the major belt of Cordilleran granites in North America (Miller and Bradfish, 1980). In this configuration, it could alternatively be related to the development of the magmatic arc developed further north in the Araçuaí belt, which intruded the Juiz de Fora Complex (Pedrosa-Soares et al., 2001), spans a time range similar to the arc magmatism in Oriental Terrane (640–580 Ma), but is in a different paleogeographic position. A third alternative would be that the Embu Terrane, characterized by some unique features such as the widespread ~800 Ma high-grade metamorphism and the essentially crust-derived nature of the 590–590 Ma granite magmatism, is an exotic terrane docked at the southeastern margin of the Paranapanema-São Francisco proto-continent through lateral dextral shear zones in a transpressional orogen.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.precamres.2013.01.018.

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