ABSTRACT: The Socorro Batholith is one of the most expressive granite manifestations associated with the Neoproterozoic evolution in SE Brazil, occupying large areas (~1,200 km²) in the southern portion of the Socorro-Guaxupé Nappe. A U-Pb zircon SHRIMP dating program was developed to determine the ages of the main components of this batholith, identified in previous detailed mapping projects. High-K calc-alkaline (HKCA) porphyritic biotite-hornblende granites with relatively low (60–67 wt%) SiO₂ are the most voluminous component of this and other large "syn-tectonic" batholiths in the SGN (Água Limpa and Pinhal-Ipuíuina) and neighboring domains located south of it in the Apiat and São Roque Domains of the Ribeira Fold Belt. Two samples collected in widely separated localities at the northern and southern part of the Socorro batholith yield similar ages of magmatic crystallization, respectively 610.1 ± 7.0 and 608.3 ± 6.6 Ma. A more fractioned (> 72 wt% SiO₂) granite reported in the literature as related to a younger event (“Socorro II magmatism”, as opposed to the previous “Socorro I” HKCA granites) yield a precise age that is clearly older (624.4 ± 3.6 Ma), and contemporary to anatectic granites and migmatites that were produced during a prolonged period of high-grade metamorphism (635–605 Ma) that affected the SGN. Our data thus indicates that at least part of the HKCA magmatism that constitutes the Socorro batholith post-dates the high-P metamorphism associated to continental collision, and may have been a source of heat and volatiles to the high-T metamorphism responsible for partial melting of the upper portions of the crustal section represented by the SGN. Two charnockitic rocks that show transitional contacts with granites of the Socorro batholith were also dated. The Socorro Charnockite is aged 641.6 ± 4.1 Ma, which overlaps those of regional orthogneisses (in part also of charnockitic character) considered as associated with a pre-collisional tectonics (subduction-related?). However, it is reported to transition to granites that are very similar to the HKCA granites of the Socorro batholith, which are yet undated. The Atibaia Charnockite has distinct geochemical affinity (lower mg# and Sr content; higher Zr), a younger age (633.3 ± 6.2 Ma), and may signal a different tectonic setting at the end of the period of plate consumption as yet poorly characterized.

KEYWORDS: zircon; U-Pb geochronology; SHRIMP; Socorro-Guaxupé Nappe; High-K calc-alkaline granite.

INTRODUCTION

One of the foremost features of the Neoproterozoic evolution of SE Brazil is the generation of voluminous granite magmatism of widely varied composition, whose ages spread for a large time interval (~800–500 Ma). Metaluminous, porphyritic (hornblende)-biotite granitoids (dominantly monzogranites, quartz monzonites and granodiorites) with I-type, high-K calc-alkaline (HKCA) character, are by far the most abundant granite type, and are the main components of some extensive batholithic masses with areas over 2,000 km² (Fig. 1). Although the tectonic significance of these HKCA granites is key to understanding the Neoproterozoic evolution of SE Brazil, their origin is still a matter of large uncertainties.

In fact, HKCA granites are known to be generated in various geodynamic environments (e.g., Barbarin 1999), occurring in both subduction-related and post-collisional settings. The occurrences in SE Brazil are usually associated in the literature to a continental-margin, subduction-related environment, in view of their huge volumes, deformed character and calc-alkaline character (e.g., Heilbron et al. 2004, 2017, Janasi & Ulbrich 1991, Vinagre et al. 2014). However, some authors argue that the plutonic products of convergent tectonics may be restricted to older (> 640 Ma) granitoids that were largely converted to orthogneiss and migmatite (Hackschacher et al. 2003), and thus the bulk of the HKCA granites could be post-collisional (Meira et al. 2015). Precise dating and careful association with geological features related to plate-margin
tectonics is thus key to correctly understanding the tectonic meaning of this magmatism.

Extensive geochronological surveys based on the U-Pb system in zircon and monazite by conventional TIMS have been carried out in some of the most expressive batholiths of SE Brazil, namely Três Corrêgos, Cunhaporanga (Gimenez Filho et al. 2000, Prazeres Filho et al. 2003) and Agudos Grandes (Janasi et al. 2001, Leite et al. 2007); more recently, in situ U-Pb dating of zircon by SHRIMP and LA-ICPMS was applied to the Serra da Água Limpa Batholith (Vinagre et al. 2014) and to the HKCA granites of the Sáo Roque Domain (Janasi et al. 2016).

The Socorro Batholith is one of the most expressive occurrences of HKCA in SE Brazil, spreading out for over 1,200 km² in the southern portion of the Socorro-Guaxupé Nappe, and was the subject of several mapping and geochemical studies in the 1980’s that revealed a wide variety of granites which were grouped in different associations, including, apart from the predominant HKCA porphyritic hornblende-biotite granites, several types of fractioned, pink granites, and also locally charnockites (Artur et al. 1993, Campos Neto et al. 1984a, Wernick et al. 1984a, 1984b). However, the geochronology of the batholith is restricted to determinations by the Rb-Sr system, which clearly results in unreliable ages (e.g., Tassinari 1988), and to two U-Pb zircon dates by TIMS reported by Topfner (1996) (629 ± 10 Ma), thus far considered as the best estimates of the ages of the predominant HKCA granite magmatism in the Socorro Batholith.

As part of an ongoing re-study of the Socorro Batholith, we selected five representative samples of the three main granite associations recognized in previous works for U-Pb SHRIMP dating (Socorro I or Bragança Paulista association, corresponding to the predominant HKCA porphyritic hornblende-biotite monzogranite; Socorro II or Salmão, a pink, coarse-grained biotite syenogranite; and the Charnockite association; nomenclature by Artur et al. 1993 and Campos Neto et al. 1984a). Our results reveal a wide (> 30 M.y.) interval for the batholith construction, and suggest that the granite associations may have been generated in a succession interval for the batholith construction, and suggest that the HKCA granite magmatism of the São Francisco Craton in the Ediacaran (Campos Neto & Caby 2000). Current tectonic models admit that the SGN exposes a continuous section of middle to lower crust that records events related to convergent tectonics which evolved from subduction to continental collision and finally was involved in post-collisional transtensional tectonics and then intruded by post-orogenic granites of A-type character (the Itu Granitic Province; Janasi et al. 2009). The post-collisional transtensional tectonics may be a reflection of the development of a younger orogenic belt located to the SE (the Ribeira Fold Belt, part of the Mantiqueira Province, an extensive Neoproterozoic-Cambrian orogenic system running parallel to the Atlantic coastline in Brazil (Heilbron et al. 2004, 2017). Geologic terranes located immediately south of the SGN and related to the Ribeira Belt (Apiaí and Sáo Roque domains) are also intruded by large volumes of “syn-tectonic” HKCA granites, and by post-orogenic granites of the Itu Granitic Province, which would thus straddle the limits between the SGN and Ribeira Belt. Some authors admit that the Apiaí and Sáo Roque domains correspond, together with the SGN, to the reworked margin of a “cratonic” terrane (the Paranapanema lithospheric block of (Mantovani & Brito Neves 2005). Domains located further E-SE in the Ribeira Belt (e.g., the Oriental terrane, Fig. 1) also bear significant volumes of Neoproterozoic granites, but the most voluminous “syn-tectonic” batholiths are typically younger (e.g., Heilbron et al. 2013), as is the post-orogenic granite magmatism (520–500 Ma; Valeriano et al. 2016).

The SGN is admitted by several authors to be related to the evolution of the southern portion of the Brasília Belt (Campos Neto & Caby 2000, Rocha et al. 2018). It would represent the active margin of Paranapanema Plate that was thrust over the passive margin of São Francisco paleocontinent (Campos Neto & Caby 2000) in a collisional setting. Orthogneisses dated by Hackspacher et al. (2003) at 660–640 Ma would represent arc magmatism that resulted from subduction of Neoproterozoic oceanic crust during early precollisional convergence and closure of a branch of either the Adamastor or Goianides paleo-ocean.

Neoproterozoic granitic magmatism in Socorro-Guaxupé Nappe

Extensive elongated granitic batholiths of high-K calc-alkaline character are typical of both the Ribeira belt and the Socorro-Guaxupé Nappe. The tectonic context in which these rocks were formed is still ambiguous, being accepted as products of active continental margin magmatic arcs (Campos Neto et al. 1984a, Heilbron et al. 2004, 2013, 2017, Janasi & Ulbrich 1991, Trouw et al. 2013), or considered belonging to a post-collision environment (Meira et al. 2015).
Large volumes of crustal granites throughout the crustal section are exposed in the Socorro-Guaxupé Nappe. Temperatures close to 1,000ºC were reached around 625 Ma in the deeper portions of Socorro-Guaxupé Nappe (at ~14 kbar), resulting in melting of deplet granulites and generation of charnockitic magmas (Janasi 2002). Similar age has been obtained for crustal granites generated at the temperature of biotite breakdown (~850ºC) by remelting of orthogneisses in the middle crust (biotite granite type Pinhal). At lower levels (in the southern portion of the Socorro Domain), garnet-biotite granites (Nazaret Paulista types), were generated by anatexis of paragneisses (or mixtures between ortho- and paragneisses), probably over a long period of time (ca. 25 M.y., between 635 and 610 Ma), as estimated by monazites dating in associated migmatites (Martins et al. 2009). Some large batholiths dominated by granitoids of high-K calc-alkaline occur in the SGN, Pinhal-Ipuína Batholith (Haddad 1995) in the northern portion, and Socorro (Artur et al. 1993) and Serra da Água Limpa batholiths (Vinagre et al. 2014) in the southern portion.

Granites of Socorro Batholith

The Socorro Batholith corresponds to an extensive area elongated in the N30E direction in the southern portion of SGN dominated by granitic rocks (ca. 60 x 25 km; total ca. 1,200 km²) (Fig. 2).

The predominant lithology in the batholith is a porphyritic hornblende-biotite granite with up to 4 cm alkali feldspar megacrysts set in a medium to coarse-grained matrix, commonly foliated, with high color index (10–20), and monzogranitic to quartz monzonitic modal composition. Two U-Pb zircon ages are reported in the literature, and indicate ages between 629 ± 3 (Topfner 1996) and 610 ± 10 Ma (Ebert et al. 1996) for the predominant Socorro I granites; no reliable age determinations are available for the other granite types from the batholith. The country rocks of the batholith are orthogneisses and paragneisses usually affected by migmatization. U-Pb zircon TIMS ages reported for the orthogneisses...
are in 660–640 Ma range (Hackspacher *et al.* 2003), and are seen as an upper limit to the ages of the Socorro granites. A recent LA-ICPMS dating program in the Serra da Água Limpa batholith, which seems to correspond to an eastern continuation of the Socorro Batholith, dated similar HKCA granites in the 645–630 Ma range (Vinagre *et al.* 2014).

The Socorro Batholith is intruded by post-orogenic granitic plutons, which are part of the Itu Granitic Province, constituted of granites of A-type or high-K calc-alkaline character and associated basic bodies (Janasi *et al.* 2009). These rocks may be envisaged as an “inboard reflection” of orogenic processes occurring at the Mantiqueira Orogenic System (Janasi *et al.* 2009). Besides the most voluminous bodies (Itu, Atibaia and Morungaba) the Guaripocaba stock is part of this province, and is intrusive in the area of the Socorro Batholith. The most robust ages for the Itu Province are ca. 580–570 Ma (Janasi *et al.* 2009), indicating that this magmatism occurred after a temporal hiatus, during which the SGN was raised.

### METHOD

**Whole-rock major and trace-element analyses**

X-ray Fluorescence was used to determine the major, minor and trace elements in whole rock samples. Large samples...
were adjusted to 100 g with 1% HNO₃. Analytical quality is eliminated by evaporation. After drying, the material is et al (Navarro. 2008).

The values obtained should be within 2σ of the certified values, and the duplicated samples within 1% of variation. The separation and concentration of zircon consisted of crushing, grinding, sieving, vibrating table, electromagnetic separation, heavy liquids and finally manual picking. The routine used at CPGeo is described by Sato et al. (2014) and consists of the following steps:

- rock samples (0.5 to 3 kg for granites and ~20 kg for mafic rocks) are crushed in a jaw crusher;
- crushed material is screened to separate a fraction of 100–250 mesh particle size, using a disk mill and a battery of sieves;
- the separated fraction is taken to a vibratory table to concentrate heavy minerals;
- magnetic minerals are removed with a hand magnet;
- minerals with different magnetic susceptibilities are concentrated in a Frantz-type magnetic separator, by varying the inclination and the intensity of the electromagnetic field;
- the least magnetic fractions are passed successively into bromoform (d = 2.85 g/cm³) and methylene iodide (d = 3.2 g/cm³) to further concentrate the heavy minerals of interest. Any remaining sulfides present in the concentrates are eliminated with HCl or HNO₃. About 50–100 zircon grains are separated by hand picking with the aid of a magnifying microscope, and then mounted on double sided adhesive tape and embedded in epoxy-type resin. The mount is then polished to expose the fresh surface of the grain trapped in the resin.

A previous study of cathodoluminescence (CL) images of each of the samples was necessary to choose the proper position of the spot during the pointed analyses by SHRIMP. After a thin layer of gold cover (2–3 nm) was added to the mounts, these images were obtained in a FEI Quanta 250 SEM spectrometer with a XMAX CL detector (Oxford Instruments). Operating conditions were: high voltage, 15 kV, distance, 16.9–17 mm, PMD detector, range of magnification, 95-250x.

**Zircon concentration, mounting and cathodoluminescence study**

The separation and concentration of zircon consisted of crushing, grinding, sieving, vibrating table, electromagnetic separation, heavy liquids and finally manual picking.
in Sato et al. (2014). During the run of every 5 determinations analyzed, the Temora-2 reference material (estimated age 416.78 ± 0.33 Ma; Black et al. 2004) was used as 206Pb/238U age reference, for calculation of common Pb correction factors and fractionation factors. Common lead corrections usually use 204Pb according to Stacey and Kramer (1975). Reference material SL13 (238 ppm) is used as U composition reference. Data are reduced with SQUID 1.6 software (Ludwig 2009) and ISOPLOTR 4 (Ludwig 2003) has been used for treatment of data to estimate ages and generate diagrams.

**U-Pb ZIRCON DATING**

**Porphyritic hornblende-biotite granite (Bragança Paulista-type, HKCA)**

**Sample petrography and geochemistry**

The porphyritic hornblende-biotite granites of HKCA character correspond to the Bragança Paulista association, which are the most voluminous rocks in the Socorro Batholith. We chose two samples from localities in the northern and southern portion of the batholith for U-Pb dating (Fig. 2), representing compositions with different degrees of fractionation.

Sample BRP-08 is from the vicinities of the Pedra Bela hill, and corresponds to a porphyritic hornblende-biotite granite with high color index (~22), with abundant and very large K-feldspar megacrysts averaging 3–4 × 1.5–2 cm (Fig. 3A) set in a massive, coarse matrix where plagioclase occurs as the only feldspar.

Sample ATB-13 is from a road next to the SP-095, NW of Bragança Paulista; compared to BRP-08, this sample has lower color index (~15), and the K-feldspar megacrysts are a little smaller and more elongated (average 2–3 × 1 cm); a slight solid-state foliation is evident, which is related to a tensional field and evidenced by the orientation of alkali feldspars.

Our geochemical dataset of the Bragança Paulista type granites (Tabs. 1 and 2) shows that they are relatively primitive, with 60–66 wt% SiO2, mg#~40, combining relatively high contents of MgO (2.5–1.5 wt%), CaO (4.5–3.2 wt%) and Fe2O3 (6.2–4.3 wt%) with high K2O (3.8–4.6 wt%), Ba (1,000–1,600 ppm) and Sr (540–800 ppm). BRP-08 with 61.7 wt% SiO2 and 2.0 wt% MgO is among the most unfractionated compositions, while ATI-13 with 66.3 wt% SiO2 and 1.5 wt% MgO groups with the most felsic Bragança Paulista-type granites (Fig. 4). Both samples have moderately fractionated REE patterns (La/Yb)N = 24-30 and discreet negative Eu anomalies (Fig. 5), that are more pronounced in the least fractioned sample (BRP = 08; EuN/Eu* = 0.70, versus 0.83 in ATB-13 (Eu* = (Sm x Gd)½).

**Zircon morphology and U-Pb dating**

Zircon crystals from sample BRP-08 are elongated with aspect ratios from 4:1 to 5:1, and lengths up to 400 µm (Suppl. data). CL images show typical oscillatory zoning, which is more pronounced in darker zones where small inclusions that are white in CL are present. Lighter cores with less evident zoning and a thin CL-bright outer rim, sometimes truncating the oscillatory zoning, occur in some crystals.

SHRIMP results from 21 spots yield essentially concordant ages (typical discordance ≤ 4%; Tab. 3) which, however, spread over the concordia for ca. 50 M.y. (584–635 Ma, excluding three extreme results: the two youngest and the oldest one). The weighted average 206Pb/238U age (Fig. 6) calculated by Isoplots is 610.1 ± 7.0 Ma (at 95% confidence), with a very high MSDW (6.1). Use of the Isoplots Unmix routine discriminates two age groups with 600.7 ± 3.9 Ma (eight samples) and 623.4 ± 4.8 Ma (six samples) (errors in calculated ages are reported as 2σ). A concordia age calculated

Figure 3. (A) Image of Bragança Paulista-type from the Pedra Bela hill. (B) Image of the dated sample of Salmão-type granite.
Table 1. Major and trace elements of granites from the Socorro Batholith by X-ray fluorescence.

|                | Salmão Granite | Bragança Paulista Granite | Socorro Charnockite | Atibaia Charnockite |
|----------------|----------------|---------------------------|---------------------|---------------------|
|                | BRP-03         | BRP-06A                   | BRP-06B             | BRP-07              |
| SiO₂           | 75.55          | 65.89                     | 64.77               | 64.59               |
| TiO₂           | 0.22           | 0.87                      | 0.86               | 0.93                |
| Al₂O₃          | 13.34          | 15.23                     | 14.63               | 14.74               |
| Fe₂O₃          | 1.29           | 4.47                      | 4.42               | 4.60                |
| MnO            | 0.02           | 0.07                      | 0.05               | 0.07                |
| MgO            | 0.29           | 1.66                      | 1.59               | 1.65                |
| CaO            | 1.45           | 3.57                      | 3.70               | 3.71                |
| Na₂O           | 2.81           | 3.09                      | 2.82               | 2.64                |
| K₂O            | 5.22           | 4.59                      | 4.08               | 4.54                |
| P₂O₅           | 0.04           | 0.33                      | 0.32               | 0.37                |
| LoI            | 0.46           | 0.78                      | 0.98               | 0.78                |
| Total (%)      | 98.68          | 98.56                     | 100.16             | 99.37               |
| Ba             | 541            | 1350                      | 1600               | 1622                |
| Ce             | 213            | 196                      | 179                | 189                 |
| Co             | < 6            | 7                        | 12                 | 8                   |
| Cr             | < 13           | 20                       | 24                 | 16                  |
| Cu             | < 5            | 9                        | 10                 | 12                  |
| Ga             | 19             | 25                       | 23                 | 21                  |
| La             | 73             | 61                       | 90                 | 82                  |
| Nb             | < 9            | 18                       | 14                 | 11                  |
| Nd             | 41             | 57                       | 62                 | 51                  |
| Ni             | < 5            | 11                       | 10                 | 9                   |
| Pb             | 30             | 21                       | 19                 | 16                  |
| Rb             | 185            | 135                      | 146                | 135                 |
| Sc             | < 14           | < 14                      | < 14               | < 14                |
| Sr             | 185            | 643                      | 783                | 748                 |
| Th             | 35             | 31                       | < 7                | 7                   |
| U              | 4              | 7                        | 10                 | 8                   |
| V              | 10             | 36                       | 74                 | 100                 |
| Y              | 5              | 8                        | 28                 | 31                  |
| Zn             | 22             | 30                       | 65                 | 90                  |
| Zr             | 159            | 197                      | 250                | 271                 |
| P₂O₅           | 0.04           | 0.33                      | 0.32               | 0.37                |
| LoI            | 0.46           | 0.78                      | 0.98               | 0.78                |
| Total (%)      | 98.68          | 98.56                     | 100.16             | 99.37               |

Table 2. Rare earth and additional trace elements of granites from the Socorro Batholith by ICPMS.

| Sample | La  | Ce  | Pr  | Nd  | Sm  | Eu  | Gd  | Tb  | Dy  | Ho  | Er  | Tm  | Yb  | Lu  | Hf  | Pb  | Th  | U   |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| BRP-03 | 75.85 | 135.69 | 14.23 | 44.21 | 6.25 | 1.13 | 2.75 | 0.33 | 1.24 | 0.18 | 0.39 | 0.05 | 0.31 | 0.05 | 4.70 | 33.05 | 36.17 | 1.56 |
| BRP-06 | 86.71 | 174.14 | 20.68 | 76.57 | 12.59 | 2.31 | 8.16 | 1.06 | 5.58 | 1.05 | 2.75 | 0.39 | 2.39 | 0.33 | 8.45 | 17.44 | 5.70 | 0.89 |
| BRP-12 | 63.47 | 129.80 | 14.32 | 52.26 | 9.04 | 2.13 | 5.84 | 0.83 | 4.52 | 0.85 | 2.24 | 0.35 | 2.04 | 0.29 | 5.40 | 17.08 | 6.74 | 0.42 |
| ATB-08 | 84.28 | 160.27 | 17.37 | 56.65 | 8.39 | 1.34 | 4.09 | 0.56 | 2.45 | 0.42 | 1.01 | 0.12 | 0.69 | 0.10 | 8.73 | 20.61 | 14.51 | 0.71 |
| ATB-13 | 65.27 | 120.23 | 15.26 | 45.41 | 7.85 | 1.76 | 5.18 | 0.71 | 3.59 | 0.64 | 1.62 | 0.25 | 1.36 | 0.20 | 6.80 | 18.64 | 9.08 | 0.89 |

ICPMS: inductively coupled plasma mass spectrometry.
for the first set yields 599.5 ± 3.6 (MSWD = 0.25) with a probability of fit of 0.62, while the concordia age for the second set is 620.1 ± 4.2 Ma, with higher MSWD (0.94) and lower probability of fit (0.33). No morphological or chemical differences exist between spots belonging to these two age groups, and some of the “older” dates correspond to spots located at the border of zircon crystals. We prefer therefore to admit the weighted average age of the whole set of analyses as the best estimate of the magmatic crystallization of this sample, in spite of the higher associated MSWD. Indeed, the Unmix routine can yield any chosen number of populations, but in this case no clear age gap is observed when the whole set of data is considered and no chemical or textural contrast exists between the different spots.

Zircons from sample ATB-13 have varied morphologies, with wide variation in aspect ratios, from 1.5:1 to 4:1 (Suppl. data). Most crystals are elongated, with lengths of 100–400 μm, and show oscillatory zoning, small granular inclusions of a CL-bright mineral, possibly apatite, occurring associated with some specific zones, and rare brighter cores. The shorter crystals show similar features, and more commonly have corroded cores of varied texture; one CL-bright homogeneous core corresponds to an inherited crystal.

Fourteen spots were analyzed, and yield nearly concordant ages (≤ 5% discordant, with two exceptions, Tab. 3). Spot 13.1 is an inherited core with a concordant 207Pb/206Pb age of 1,445
| Sample spot | Pb total (common) (%) | Pb rad ppm | Th ppm | U ppm | Th/U | 207Pb/235U 1σ | 206Pb/238U 1σ | Rho 207Pb/206Pb 1σ | 206Pb/238U Age (Ma) 1s | 207Pb/235U (% age) 1s | Discordant ATB – 08 (Atibaia Charnockite) UTM: 7447934 x 36105 23 K |
|-------------|----------------------|------------|--------|-------|------|----------------|----------------|----------------------|----------------------|------------------------|------------------------------------------------|
| ATB – 08    | 1.1                  | 0.05       | 0.85   | 1.99  | 0.01 | 1.51          | 0.76           | 0.62                 | 0.74                 | 0.002                  | 0.74                               |
|             | 2.1                  | -0.06      | 0.91   | 0.83  | 0.01 | 1.06          | 0.75           | 0.64                 | 0.71                 | 0.006                  | 0.75                               |
|             | 3.1                  | 0.05       | 1.02   | 0.36  | 0.01 | 1.05          | 0.72           | 0.64                 | 0.71                 | 0.006                  | 0.75                               |
|             | 4.1                  | -0.08      | 0.90   | 0.90  | 0.01 | 1.06          | 0.69           | 0.64                 | 0.71                 | 0.006                  | 0.75                               |
|             | 5.1                  | 0.04       | 1.02   | 0.36  | 0.01 | 1.03          | 0.72           | 0.64                 | 0.71                 | 0.006                  | 0.75                               |
|             | 6.1                  | 0.05       | 1.02   | 0.36  | 0.01 | 1.03          | 0.72           | 0.64                 | 0.71                 | 0.006                  | 0.75                               |
|             | 7.1                  | 0.00       | 1.02   | 0.36  | 0.01 | 1.03          | 0.72           | 0.64                 | 0.71                 | 0.006                  | 0.75                               |
|             | 8.1                  | 0.00       | 1.02   | 0.36  | 0.01 | 1.03          | 0.72           | 0.64                 | 0.71                 | 0.006                  | 0.75                               |
|             | 9.1                  | 0.00       | 1.02   | 0.36  | 0.01 | 1.03          | 0.72           | 0.64                 | 0.71                 | 0.006                  | 0.75                               |
|             | 10.1                 | 0.00       | 1.02   | 0.36  | 0.01 | 1.03          | 0.72           | 0.64                 | 0.71                 | 0.006                  | 0.75                               |
|             | 11.1                 | 0.00       | 1.02   | 0.36  | 0.01 | 1.03          | 0.72           | 0.64                 | 0.71                 | 0.006                  | 0.75                               |

(Note: The table continues with similar entries for each sample spot, showing detailed values for Pb total, Pb rad, Th, U, Th/U, 207Pb/235U, 206Pb/238U, Rho 207Pb/206Pb, 206Pb/238U Age, 207Pb/235U (% age), and Discordant.)
| Sample | Pb total (common) (%) | Pb rad ppm | Th ppm | U ppm | Th/U 207 Pb/235U 1σ | 206 Pb/238U 1σ | Rho 207 Pb/206 Pb 1σ | Age (Ma) 1σ |
|--------|-----------------------|------------|--------|-------|---------------------|-----------------|----------------------|--------------|
| BRP – 03 Salmão Granite | 5.1 | -0.01 | 1.161 | 0.956 | 0.689 | 0.87 | 0.87 | 0.060 | 0.751 |
| | 2.1 | 0.03 | 1.154 | 0.600 | 0.847 | 0.73 | 0.72 | 0.053 | 0.771 |
| | 3.1 | 0.01 | 1.081 | 0.625 | 0.861 | 0.68 | 0.67 | 0.100 | 0.972 |
| | 4.1 | -0.01 | 1.250 | 0.735 | 0.906 | 0.85 | 0.84 | 0.101 | 0.681 |
| | 5.1 | -0.02 | 0.900 | 0.735 | 0.906 | 0.85 | 0.84 | 0.061 | 0.772 |
| | 6.1 | 0.05 | 0.847 | 0.722 | 0.831 | 0.72 | 0.72 | 0.100 | 0.972 |

| Sample | Pb total (common) (%) | Pb rad ppm | Th ppm | U ppm | Th/U 207 Pb/235U 1σ | 206 Pb/238U 1σ | Rho 207 Pb/206 Pb 1σ | Age (Ma) 1σ |
|--------|-----------------------|------------|--------|-------|---------------------|-----------------|----------------------|--------------|
| BRP – 08 Bragança Paulista | 5.1 | -0.12 | 0.847 | 0.681 | 0.85 | 0.84 | 0.061 | 0.972 |
| | 1.1 | 0.10 | 0.847 | 0.681 | 0.85 | 0.84 | 0.061 | 0.972 |
| | 2.1 | 0.12 | 0.847 | 0.681 | 0.85 | 0.84 | 0.061 | 0.972 |
| | 2.2 | 1.91 | 0.847 | 0.681 | 0.85 | 0.84 | 0.061 | 0.972 |
| | 3.1 | 0.18 | 0.847 | 0.681 | 0.85 | 0.84 | 0.061 | 0.972 |
| | 4.1 | 0.20 | 0.847 | 0.681 | 0.85 | 0.84 | 0.061 | 0.972 |
| | 5.1 | 0.24 | 0.847 | 0.681 | 0.85 | 0.84 | 0.061 | 0.972 |

Table 3. Continuation.
Table 3. Continuation.

| Sample spot | Pb total (common) (%) | Pb rad ppm | Th ppm | U ppm | Th/U | 207Pb/206Pb Age (Ma) | 1σ 206Pb/203Pb (Ma) | 1σ 206Pb/235U | 1σ 206Pb/238U Age (Ma) | 1σ Rho 207Pb/206Pb | 1σ Rho 207Pb/235U | Discordant |
|-------------|-----------------------|------------|-------|-------|------|-----------------------|----------------------|------------------|------------------------|---------------------|---------------------|------------|
| BRP – 12 Socorro Charnockite | 0.08 | 23.6 | 0.08 | 271 | 0.84 | 0.845 | 1.765 | 0.101 | 0.982 | 0.156 | 0.061 | 1.132 |
| | 1.1 | 0.01 | 18.4 | 0.50 | 0.18 | 1.900 | 0.098 | 0.082 | 1.456 | 0.082 | 1.900 | 0.18 |
| | 11.1 | 0.01 | 11.2 | 0.50 | 0.18 | 1.900 | 0.098 | 0.082 | 1.456 | 0.082 | 1.900 | 0.18 |
| | 12.1 | 0.01 | 12.2 | 0.50 | 0.18 | 1.900 | 0.098 | 0.082 | 1.456 | 0.082 | 1.900 | 0.18 |
| | 13.1 | 0.01 | 13.2 | 0.50 | 0.18 | 1.900 | 0.098 | 0.082 | 1.456 | 0.082 | 1.900 | 0.18 |
| | 14.1 | 0.01 | 14.2 | 0.50 | 0.18 | 1.900 | 0.098 | 0.082 | 1.456 | 0.082 | 1.900 | 0.18 |
| | 15.1 | 0.01 | 15.2 | 0.50 | 0.18 | 1.900 | 0.098 | 0.082 | 1.456 | 0.082 | 1.900 | 0.18 |
| | 16.1 | 0.01 | 16.2 | 0.50 | 0.18 | 1.900 | 0.098 | 0.082 | 1.456 | 0.082 | 1.900 | 0.18 |
| | 17.1 | 0.01 | 17.2 | 0.50 | 0.18 | 1.900 | 0.098 | 0.082 | 1.456 | 0.082 | 1.900 | 0.18 |

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Porphyritic biotite-syenogranite (Salmão-type)

Sample petrography and geochemistry

The porphyritic biotite-syenogranite corresponds to the Salmão association (Campos Neto et al. 1984a) or the Socorro II magmatism of Artur et al. (1993). These granites form plutons in different portions of the batholith, with dimensions varying from 2 to 25 km³.

Sample BRP-03 was collected in the southern portion of the batholith (Fig. 2) and corresponds to an inequigranular porphyritic pink-colored biotite syenogranite with a color index around 6 and alkali feldspar megacrysts measuring, on average, 4 × 1.5 cm (Fig. 3B). Accessory minerals include apatite, zircon, opaque minerals and monazite.

The geochemical data show high contents of SiO₂ (73.6 wt%), K₂O (5.2 wt%), Th (35 ppm) and U (4 ppm) (Fig. 7); mg# is ~30. In comparison to the other samples dated, it has the lowest contents of Fe₂O₃ (1.3 wt%), MnO (< 0.02 wt%) and MgO (0.3 wt%). The REE pattern is very fractionated, with (La/Yb)N = 166 with a negative anomaly of Eu (Eu/Eu* = 0.7) (Fig. 5).

Zircon morphology and U-Pb dating

Zircons from sample BRP-03 can be divided into two morphologically distinct populations. One has elongated prismatic shape with up to 300 µm length, and 3:1 aspect ratio. The cores are heterogeneous, without zoning or exhibiting inconspicuous and irregular zoning, and are typically darker than rims. The other population has more rounded shapes and lengths up to 200 µm, with some cores, in CL images (Suppl. data), with a bright appearance.

Three cores yield inherited ages, but spot 14.1 is strongly discordant and will not be further considered. Spot 12.1 is 98% concordant, and yields a 207Pb/206Pb age of 1,777 ± 42 Ma; spot 7.1 is 12% discordant, and its 206Pb/238U age is similar within error (1,675 ± 98 Ma).

Four of the other 13 points are > +10% discordant, and as such show 206Pb/238U that are too young. The remaining nine spots yield a weighted average 206Pb/238U age (Fig. 6) of 626.6 ± 6.4 Ma with high MSWD = 2.4. Spot 15.1 has the highest age and is not part of a coherent age group with the other eight spots. Excluding it, the weighted average is 624.7 ± 3.6 Ma (2σ) with a lower MSWD (1.04) and a probability of fit of 0.46. These eight samples yield a Concordia age (Fig. 8) of 624.4 ± 3.6 Ma (MSWD = 0.24), which is considered the magmatic crystallization age of sample BRP-03.

Charnockites

Sample petrography and geochemistry

Charnockites were described as a marginal facies with transitional contacts to porphyritic granites associated to the Socorro I magmatism nearby the city of Socorro (Artur 2003, Wernick et al. 1984a), occurring as elongated bodies with a maximum extension of 20 km. Sample BRP-12 was collected in this region, and is a foliated, porphyritic charnockite with dark green colour, and alkali feldspar as 2 × 1 cm megacyrst, and as a matrix mineral with plagioclase, quartz, orthopyroxene, clinopyroxene, biotite and hornblende.

The Atibaia Charnockite is a small NE-elongated body (3 × 0.5 km) in the southern portion of the Socorro Batholith (Fig. 2). Sample ATB-08 is medium-to coarse-grained, foliated, with greenish-brown color and monzogranitic composition. Mafic minerals are clinopyroxene, orthopyroxene, amphibole and traces of biotite; accessory minerals are zircon, apatite and opaque minerals.

Our geochemical data (Fig. 4) shows important differences between the two charnockite occurrences. The Socorro charnockite sample is relatively primitive, and its geochemical signature is very similar to the Bragança Paulista-type granites, with 61.6 wt% SiO₂, 4.6 wt% CaO, 2.2 wt% MgO and mg# ~ 43, combining relatively high contents of K₂O (3.7%), Ba (1,300 ppm), Sr (800 ppm) and a fractionated REE pattern ([La/Yb]N = 82) with poorly developed negative Eu anomaly (Eu/Eu* = 0.84) (Fig. 5). The Atibaia charnockite has higher contents of SiO₂ (70 wt%), K₂O (5.8 wt%), and Zr (402 ppm) and much lower Sr (170 ppm); the REE patterns are moderately fractionated ([La/Yb]N = 32.3) with a more pronounced negative Eu anomaly (Eu/Eu* = 0.62) (Fig. 5). This chemical signature is
similar to neighboring garnet-bearing biotite granites (Fig. 5), and different from both Bragança Paulista and Salmão-type granites.

Zircon morphology and U-Pb dating
Zircon crystals from sample BRP-12 have different sizes and shapes, and can be divided into two populations, based

Figure 6. Weighted average of $^{206}\text{Pb}/^{238}\text{U}$ ages of dated zircon spots.
on morphological and textured grain differences. The first is elongated, prismatic, with lengths of 200–350 μm; in CL images (Suppl. data), they show rims with oscillatory zoning and cores with dark gray to white shading. Crystals from the second population are 150–200 μm in length, with cores typically brighter (lower U) than the rims, some having a shiny appearance. In this case, the rims have little obvious zoning.

Sixteen points were analyzed and are ≤ 6 % discordant, with four exceptions that were excluded from age calculations; spot 14.1 has a high analytical error and was also excluded (Tab. 3). The remaining 11 results spread along the Concordia for a wide time interval (206Pb/238U ages = 615–667 Ma). As a result, the weighted average has a large error and MSWD (640 ± 11 Ma; 95% conf.; MSWD = 7.8), and no Concordia age is obtained from this set of data. Exclusion of the oldest and the two youngest 206Pb/238U ages defines a coherent group of 8 samples, which yields a weighted average (Fig. 6) 206Pb/238U age of 642.0 ± 6.7 Ma (95% confidence), with a much higher MSWD = 7.6 and very low probability of fit (0.006). Excluding the two results that are > 5 % discordant yields a weighted average 206Pb/238U age of 633.3 ± 6.2 Ma (2σ) with MSWD = 1.6 and probability of fit = 0.996. A Concordia age (Fig. 8) obtained from these 10 results yields an age of 630.3 ± 5.7 Ma, with high MSWD (5.1) and low probability of fit (0.024). All these ages are coincident within error; the weighted average (Fig. 6) 206Pb/238U age of 633.3 ± 6.2 Ma is admitted as the best estimate of the age of this sample.

**DISCUSSION**

**Age of granitic magmatism in Socorro Batholith**

Five samples of the most typical granite types of the Socorro Batholith were chosen for U-Pb dating by SHRIMP in this study. The samples consist of porphyritic granites related in previous works to the Bragança Paulista and Salmão suites (respectively, Socorro I and Socorro II associations of Artur et al. 2013) and two charnockites that form small occurrences described as transitional to granites from the batholith. The five ages obtained here seem part of a continuum and suggest a chronological sequence from the Socorro Charnockite (641.6 ± 4.1 Ma) to the Atibaia Charnockite (633.3 ± 6.2 Ma), Salmão-type granite (624.4 ± 3.6 Ma), and then the Bragança Paulista-type granites (610.1 ± 7.0 Ma and 608.3 ± 6.6 Ma). This sequence contradicts some of the assumptions made in the literature.

The Socorro Charnockite is described as transitional with the Socorro I (Bragança Paulista-type) granites and yet has a much older age. It is possible that the granites described as transitional to the Socorro Charnockite (which remain so far undated) are indeed of the same age, and in fact their geochemical signature (Wernick et al. 1984a) is very similar to the Bragança Paulista type granites, but our data suggest that the Socorro charnockites (and eventually their opx-free equivalents) may belong to an older association.

The fact that the dated “Salmão-type” granite is older than the two Bragança Paulista type granites may appear surprising, since this type of granite is reported as younger in the literature (“Socorro II” association), based on field work (Artur et al. 1993, 1994, 1996, Wernick et al. 1997, Wernick & Menezes 2001, Artur 2003, Campos Neto et al. 1984b). Again, older HKCA (Bragança Paulista-type) granites may exist, and this is clear from the U-Pb zircon TIMS
Figure 8. Concordia ages of dated samples, with an additional figure from sample BRP-03 indicating the points with inherited ages. Data for BRP-08 do not yield a Concordia age, and in this figure only the graph with age distribution are shown.
age reported by Topfner (1996) for a sample with typical Bragança Paulista affinity (629 ± 3 Ma). While the scrutiny of the data for this sample in the original work does not show any suggestions that a different interpretation could be offered for its age, we observe that some other ages reported in that work were shown to be ~20 Ma older than the ages obtained for the same plutons in a recent SHRIMP and LA-ICPMS dating program (Janasi et al. 2016), and this was attributed to the presence of tiny inclusions of inherited zircon in the multigrain fractions used in the TIMS study. Our ages for the two Bragança Paulista-type granites are identical within error, and coincide with the age reported by Ebert et al. (1996) to a sample collected in the southeastern portion of the batholith (610 ± 10 Ma).

Except in sample BRP-03 (Salmão-type granite), inheritance is uncommon in the studied samples; in fact, no inherited zircon was identified in the two charnockite samples and a single one was found in one of the Bragança-Paulista type granites (BRP-13). This suggests that the effect reported by Janasi et al. (2016) in the São Roque granites should not be effective here. The spread of ages over the concordia for up to 50 Ma (also recorded in similar granites in the region, see for instance Vinagre et al. 2014) may reflect other two causes: the presence of antecrysts (i.e., crystals from the same magmatic system previously crystallized and cannibalized by the magma that formed the dated pulse) or slightly younger lead-loss events (as demonstrated by several recent reports of U-Pb zircon ages dated by TIMS after chemical abrasion; e.g., Almeida et al. 2018). At the moment, we cannot detect these effects, and thus we admit that both may respond for part of the spread. TIMS dating of selected crystals after chemical abrasion would certainly be a valuable tool to further improve the geochronology of some samples.

Correlations with other batholiths of HKCA affinity in SE Brazil

The Socorro Batholith is one of the major expressions of Neoproterozoic granitic magmatism in SE Brazil and is comparable in volume to other important batholiths dominated by HKCA granites such as Agudos Grandes, Três Córregos, Cunhaporanga and Serra da Água Limpa. Figure 9 compares the ages obtained in this work with data obtained by the U-Pb method in zircon for these batholiths.

Only recently in situ methods (SHRIMP and LA-ICPMS) have been used to date these granites, and as reported by Janasi et al. (2016), at least in the case of the granites from the São Roque Domain, the new in situ results have shown systematically younger ages, which raised the suspicion that some ages obtained by TIMS may be older than the true magmatic age (by as far as 20 M.y.) due to the presence of tiny inclusions of inherited zircon in multigrain fractions used for dating. A similar situation was observed in the geochronology of HKCA granites from the Três Corregos and Cunhaporanga granites, where part of the U-Pb TIMS ages older than 610 Ma presented in preliminary reports (Prazeres Filho et al. 2003) were revised to younger values (610–590 Ma) after SHRIMP dating (Prazeres Filho 2006). In fact, important amounts of zircon inheritance are reported in samples of HKCA granites from these batholiths, particularly those intruding metasedimentary sequences in the Ribeira Belt (Três Córregos, Cunhaporanga and Agudos Grandes; e.g., Gimenez Filho et al. 2000, Janasi et al. 2001, Prazeres Filho et al. 2003, Leite et al. 2007), and in situ methods seem more adequate to obtain their true age of magmatic crystallization.

Figure 9 shows that the best estimates of magmatic crystallization ages available for HKCA granites from the Ribeira Belt indicate that the greatest volume of these granites was generated in the 610–590 Ma period. In the Agudos Grandes batholith, Leite et al. (2007) suggested that the typical HKCA granites forming elongated intrusions are slightly older than equivalents more contaminated with middle crust material that form plutons with subcircular shape in plant, referred to as “late-orogenic”, whose ages are in the 605–600 Ma interval. In the São Roque Domain, typical HKCA granites also tend to be slightly older than occurrences with peraluminous or subalkaline character dated at ~590 Ma (Janasi et al. 2016).

Age determinations for the HKCA magmatism in the Socorro-Guaxupê are less abundant in the literature, and the results of LA-ICPMS U-Pb dating reported for the Serra da Água Limpa Batholith by Vinagre et al. (2014) indicate an older interval for the HKCA granite magmatism (645–630 Ma; Fig. 9). This partly overlaps the range of ages determined for the magmatic orthogneisses admitted to be subduction-related by Hackspacher et al. (2003) (660–640 Ma). Our new data indicates that important volumes of Bragança Paulista-type granites were generated at ca. 610 Ma in the Socorro Batholith (see also the age reported by Ebert et al. 1996), i.e., contemporaneous with the peak of HKCA magmatism in the nearby (Apiaí and São Roque) domains of the Ribeira Belt.

Inferences on sources and tectonic environment

A reassessment of the petrogenesis of the southern part of the Socorro Batholith is the subject of a current project using additional elemental and isotope geochemistry data, and is not the focus of the present article. A few considerations can be made considering

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the whole-rock geochemical and geochronological data presented here.

The oldest age obtained here is that of the Socorro Charnockite, which has a HKCA geochemical signature very similar to the Bragança Paulista-type granites. These dry, high-temperature, relatively primitive (~62 wt% SiO_2) are not typical products of partial melting of the continental crust, and may have connections with mantle-derived basic magmatism, which is also suggested by the common presence of mafic enclaves.

The age obtained for the Atibaia Charnockite is ca. 10 Ma younger, and the chemistry of this rock (and also of associated granites, Fig. 4) is indeed indicative of a different source and perhaps also of a change in tectonic setting. The relatively low mg# ~ 27 combined with high Zr (~400 ppm) and low Sr (< 180 ppm) is indicative of a non-calc-alkaline character, and perhaps a closer affinity to the São José do Rio Pardo mangerite-charnockite association present in the northern part of the NESG and dated at 623.3 ± 3.1 Ma (Janasi 2002).

The high-grade metamorphism that affected the metasupracrustal sequences of the SGN has been shown to have lasted for a period as long as 25 M.y., between 635 and 610 Ma, based on U-Pb and chemical dating of monazite and zircon from migmatites (Martins et al. 2009, Rocha et al. 2017). This coincides with the range of ages of the Socorro granites, with the possible exception of the Socorro Charnockite. The Atibaia Charnockite may be a product of partial melting of a dry, granulitic source, during this high-grade metamorphism, as suggested for the São José do Rio Pardo association. Similarly, the fractionated (~73 wt% SiO_2) Salmão-type granite dated here is probably a product of crustal melting, as suggested by its moderately peraluminous character, trace-element signature (e.g., high Th and LREE contents) and abundance of inherited zircon. Indeed, it shares important compositional attributes with the regional anatetic granites of Nazaré Paulista type, and is coeval with the oldest occurrences of these granites (e.g., 623.6 ± 1.6 Ma; U-Pb TIMS monazite age reported by Janasi (1999).

The ~610 Ma ages determined for the Bragança Paulista-type HKCA granites (this work; Ebert et al. 1996) indicate that their emplacement was coeval with the late stages of regional high-grade metamorphism which is associated to partial melting of fertile crustal protoliths, possibly under...
Table 4. Results of U-Pb isotope determinations of Três Córregos, Cunhaporanga, Serra da Água Limpa, Agudos Grandes and São Roque Domain.

| Sample   | Unit       | Rock type       | Mineral     | Analytical Method | Age | Error | Reference                      |
|----------|------------|-----------------|-------------|-------------------|-----|-------|--------------------------------|
| **Socorro Batholith** |           |                 |             |                   |     |       |                                |
| 1. BRP – 12 | Socorro  | Charnockite   | Zircon     | SHRIMP             | 641 | 4     | This study                      |
| 2. ATB – 08 | Atibaia  | Charnockite   | Zircon     | SHRIMP             | 633 | 6     | This study                      |
| 3. BRP – 03 | Salmão   | Bt syenogranite | Zircon     | SHRIMP             | 624 | 4     | This study                      |
| 4. ATB - 13 | Bragança  | Bt syenogranite | Zircon     | SHRIMP             | 608 | 6     | This study                      |
| 5. BRP – 08 | Bragança  | Hbl-bt granite | Zircon     | SHRIMP             | 610 | 7     | This study                      |
| 6. H3        | Bragança  | Granite        | Zircon     | TIMS              | 610 | 10    | Ebert et al. 1996              |
| 7.           | Bragança  | Granite        | Zircon     | TIMS              | 629 | 3     | Topfner 1996                   |
| 8. H621      | Piracaia  | Milonitic granitic gneiss | Zircon     | TIMS              | 642 | 1     | Hackspacher et al. 2003        |
| 9. H705B     | Piracaia  | Orthogneiss    | Zircon     | TIMS              | 655 | 13    | Hackspacher et al. 2003        |
| 10. H623A    | Paraíso Complex | Granulite | Zircon     | TIMS              | 646 | 7     | Hackspacher et al. 2003        |
| **Serra da Água Limpa** |           |                 |             |                   |     |       |                                |
| 10. RDTM 62  | Facies 3  | Porphyritic granite | Zircon     | LA-ICPMS          | 667 | 10    | Vinagre et al. 2014            |
| 11. RDPA 44 (SALB) | Facies 3  | Porphyritic granite | Zircon     | LA-ICPMS          | 645 | 5     | Vinagre et al. 2014            |
| 12. RDPA 46 (SALB) | Facies 3  | Porphyritic granite | Zircon     | LA-ICPMS          | 630 | 12    | Vinagre et al. 2014            |
| 13. VAC 10 (SALB) | Facies 4  | Porphyritic granite | Zircon     | LA-ICPMS          | 631 | 7     | Vinagre et al. 2014            |
| 14. RDIT 41 (SALB) | Facies 5  | Qtz-syenite     | Zircon     | LA-ICPMS          | 634 | 8     | Vinagre et al. 2014            |
| **Agudos Grandes** |           |                 |             |                   |     |       |                                |
| 15. PD - 513f | Turvo    | Ms-Bt leucogranite | Monazite   | TIMS              | 610 | 1     | Janasi et al. 2001             |
| 16. PD - 526 | Ibiúna    | Hbl-Bt monzogranite | Zircon     | TIMS              | 610 | 2     | Janasi et al. 2001             |
| 17. PD - 462 | Piedade  | Ms-Bt granite   | Monazite   | TIMS              | 601 | 2     | Janasi et al. 2001             |
| 18. PD - 474b | Piedade  | Bt granite      | Zircon     | TIMS              | 604 | 8     | Janasi et al. 2001             |
| 19. PD - 420 | Piedade  | Bt granite      | Zircon     | TIMS              | 605 | 7     | Janasi et al. 2001             |
| 20. PD - 498 | Roseira  | Bt granite      | Monazite   | TIMS              | 600 | 4     | Leite et al. 2007              |
| 21. PD - 2266 | Serra dos Lopes | Bt granite | Monazite   | TIMS              | 604 | 3     | Leite et al. 2007              |
| 22. PD - 2154 | Pilar do Sul | Ms-Bt granite | Monazite   | TIMS              | 600 | 4     | Leite et al. 2007              |
| **Três Córregos (E)** |           |                 |             |                   |     |       |                                |
| 23.E - 3     | Barra do Chapéu | Foliated granite | Zircon     | TIMS              | 610 | 3     | Gimenez Filho et al. 2000      |
| 24.MN - 15   | Barra do Chapéu | Hbl-Bt orthogneiss | Zircon     | TIMS              | 608 | 5     | Gimenez Filho et al. 2000      |
| 25.S - 1     | Saival    | Hbl-Bt granite  | Zircon     | TIMS              | 605 | 2     | Gimenez Filho et al. 2000      |
### Table 4. Continuation.

| Sample     | Unit             | Rock type          | Mineral | Analytical Method | Age   | Error | Reference               |
|------------|------------------|--------------------|---------|-------------------|-------|-------|-------------------------|
| Três Córregos (W) |                  |                    |         |                   |       |       |                         |
| 26. HP - 06 | Paina            | Hbl-Bt tonalite    | Zircon  | SHRIMP            | 645   | 10    | Prazeres Filho 2005     |
| 27. HP - 07 | Arrieiros - Cerro Azul | Hbl-Bt granodiorite | Zircon  | SHRIMP            | 610   | 3     | Prazeres Filho 2005     |
| 28. HP - 121| Arrieiros - Cerro Azul | Granodiorite       | Zircon  | TIMS              | 617   | 2     | Prazeres Filho et al. 2003 |
| 29. HP - 44 | São Sebastião    | Hbl-Bt qtz monzonite | Zircon  | SHRIMP            | 601   | 22    | Prazeres Filho 2005     |
| 30. HP - 44 | São Sebastião    | Hbl-Bt qtz monzonite | Zircon  | TIMS              | 604   | 4     | Prazeres Filho et al. 2003 |
| Cunhaporanga |                  |                    |         |                   |       |       |                         |
| 31. HP - 03 | Ribeirão Butiá | Monzogranite       | Zircon  | TIMS              | 591   | 3     | Prazeres Filho 2006     |
| 32. HP - 437| Ribeirão Butiá-Pitangui | Qtz-monzodiorite   | Zircon  | SHRIMP            | 601   | 7     | Prazeres Filho 2006     |
| 33. HP - 21 | Piraí do Sul     | Monzogranite       | Zircon  | TIMS              | 601   | 7     | Prazeres Filho et al. 2003 |
| São Roque Domain |              |                    |         |                   |       |       |                         |
| 34. SR -07 | São Roque        | Monzogranite       | Zircon  | SHRIMP            | 604   | 3     | Janasi et al. 2016      |
| 35. MD42B  | Cantareira       | Syenogranite       | Zircon  | SHRIMP            | 592   | 4     | Janasi et al. 2016      |
| 36. MD24   | Fazenda Itaíyé  | Monzogranite       | Zircon  | SHRIMP            | 598   | 4     | Janasi et al. 2016      |
| 37. JP-18  | Vila dos Remédios | Qtz-syenite        | Zircon  | SHRIMP            | 590   | 4     | Janasi et al. 2016      |
| 38. TICO-2 | Tico-Tico        | Granite            | Zircon  | LA-ICPMS          | 591   | 4     | Janasi et al. 2016      |
| 39. CANT-6 | Cantareira       | Granite            | Zircon  | LA-ICPMS          | 599   | 4     | Janasi et al. 2016      |
| 40. TAP-1  | Taipas           | Granite            | Zircon  | LA-ICPMS          | 602   | 6     | Janasi et al. 2016      |
| 41. ITQ-2  | Itaqui           | Granite            | Zircon  | LA-ICPMS          | 594   | 5     | Janasi et al. 2016      |

SHRIMP: Sensitive High Resolution Ion Microprobe. TIMS: Thermal Ionization Mass Spectrometry. LA-ICPMS: laser ablation inductively coupled plasma mass spectrometry.

Water-fluxed regime (Martins 2006). It can therefore be speculated that the intrusion of large volumes of high-temperature, relatively primitive, HKCA granites may be in part responsible for the influx of heat and volatiles that facilitated widespread melting in the upper levels of the presently exposed crustal section of the SGN. The young ages of these Bragança Paulista-type granites seem difficult to reconcile with models that admit a pre-collisional setting for the HKCA magmatism, and indeed high-pressure metamorphism diagnostic of collisional setting is, at least in part, older (Reno et al. 2009). The evolved isotope signature and enriched geochemical signature of these HKCA granites is indicative that they are, at least in part, the products of crustal recycling. The few inherited zircon cores identified in this work show ~1.4-1.8 Ga ages that overlap the Sm-Nd model ages reported for the SGN (e.g., Janasi 1999), which is consistent with the idea that the reworked crust is distinct, and younger, than that forming the nearby Apiá and São Roque Domains in the Ribeira Belt.

**CONCLUSIONS**

Our U-Pb zircon SHRIMP dating program determined the ages of the main components of the Socorro Batholith, a major component of the allochthonous Socorro-Guaxupé Nappe. Two samples of HKCA porphyritic biotite-hornblende granites of relatively primitive (60–67 wt% SiO₂) that are the most voluminous component of the batholith were dated, and yielded similar results (Pedra Bela sample BRP-08 in the northern portion of the batholith, 610.1 ± 7.0 Ma and Bragança Paulista sample ATB-13 in the southern portion, 608.3 ± 6.6 Ma). These ages are similar to U-Pb zircon ages recently obtained by *in situ* methods in similar rocks (HKCA granites) in other large batholiths in neighboring domains (Apiá...
and São Roque) from the Ribeira Belt, but younger than the U-Pb zircon LA-ICPMS ages reported for the HKCA granites of the Serra da Água Limpa Batholith, located immediately east of the Socorro batholith (645–630 Ma).

A more fractioned (> 72 wt% SiO₂) “Salmão-type” granite reported in the literature as related to a younger event (“Socorro II magmatism”) yielded a precise age that is clearly older (624.4 ± 3.6 Ma) than the two HKCA samples. This age is similar to that of the oldest anatectic granites and migmatites that were produced during a prolonged period of high-grade metamorphism (635–605 Ma) that affected the SGN. Our data thus indicates that at least part of the HKCA magmatism of the Socorro batholith post-dates the high-P metamorphism associated to continental collision, and may have been a source of heat and volatiles to the high-T metamorphism responsible for partial melting of the upper portions of the crustal section represented by the SGN.

Two charnockitic rocks that show transitional contacts with granites of the Socorro batholith were also dated. The Socorro Charnockite has an age of 641.6 ± 4.1 Ma, which overlaps those of regional orthogneisses (in part also of charnockitic character) considered as associated with pre-collisional tectonics (subduction-related?). However, it is reported to transition to granites that are very similar to the HKCA granites of the Socorro Batholith, which are yet undated. The Atibaia Charnockite is younger (633.3 ± 6.2 Ma) and has distinct geochemical affinity (lower mg# and Sr content; higher Zr), which may signal a different tectonic setting at the end of the period of plate consumption as yet poorly characterized.

ACKNOWLEDGEMENTS

Financial support for this work was provided by Fapesp through Grant 2015/01817-6 (to VAJ). LGRS acknowledges a Scientific Initiation scholarship by CNPq. VAJ is a CNPq Productivity Researcher (Grant 305661/2014-0). Kei Sato at CPGeo is acknowledged for qualified support in obtaining and processing geochronological data. A careful review by Claudio Valeriano, Stefano Zincone, Rodrigo Vinagre and the associated editor Umberto Cordani were very helpful to improve the manuscript.

SUPPLEMENTARY DATA

Supplementary data associated with this article can be found in the online version: Supplementary data A1-A5.

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