Zircon U-Pb and Lu-Hf record from high-grade complexes within the Mantiqueira Complex: first evidence of juvenile crustal input at 2.4-2.2 Ga and implications for the Palaeoproterozoic evolution of the São Francisco craton

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ABSTRACT: The Mantiqueira Complex together with the Mineiro Belt and Juiz de Fora Complex, characterize a long-lived system of oceanic and continental magmatic arcs. The proposed accretion of these terranes in the Rhyacian resulted in the closure of the Minas Basin, a fundamental turning point for the geology of this area. Understanding this event is critical for determining the evolution of the South American continent. Despite its importance, there is a paucity of zircon U-Pb and Lu-Hf data available for the Mantiqueira Complex and no data from two high-grade complexes within the later. U-Pb zircon data were obtained from interpreted metasediments of those two complexes, the granulite facies Acaíaca Complex and Pedra Dourada Granulite. Four targeted samples yield cores with ages between 3.5 to 2.2 Ga and a large proportion of metamorphic grains and rims at ca. 2.1-2.0 Ga. The similarity between the detrital zircon signatures of the Acaíaca Complex and Pedra Dourada Granulite, and the Archaean inheritance of the Mantiqueira Complex, indicates that these three units are related. Potentially the Acaíaca Complex and

Pedra Dourada Granulite either source the Mantiqueira Complex or the Mantiqueira intrusive suites rework the protoliths of the Acaíaca Complex and Pedra Dourada Granulite. Hf-in-zircon data indicate two discrete sources for both the Acaíaca Complex and Pedra Dourada Granulite. An Archaean source (model ages of 3.2-2.6 Ga), which is consistent with the suggested origin of the Mantiqueira Complex as recycled Archaean crust sourced from the São Francisco Craton and reworked during the ca. 2.1 Ga Transamazonian orogeny. A second more juvenile source (model ages of 2.4-2.2 Ga) recorded exclusively within the more mafic samples is identical in age and Hf to that found in the Juiz de Fora Complex. This could indicate a close link between the Mantiqueira and Juiz de Fora Complexes in the period 2.2 to 2.0 Ga. Alternatively, these juvenile zircons may represent an as yet unidentified juvenile portion of the Mantiqueira arc.

The results of this study are consistent with the prevailing theories for formation of the Mantiqueira Complex as a continental arc with cumulative proportion curves indicating an active-margin type depositional setting.

KEYWORDS: U-Pb ZIRCON, TRANSAMAZONIAN OROGENY, Hf ISOTOPES, MANTIQUEIRA COMPLEX, JUVENILE SIGNATURE

1. Introduction

Numerous recent studies have been conducted investigating tectonic links between, as well as the formation processes of, the Mineiro Belt, the Juiz de Fora Complex and the Mantiqueira Complex, particularly focussing of the time interval from the Siderian to Cambrian (i.e. Aguilar et al., 2017; Alkmim and Teixeira, 2017; Teixeira et al., 2017; Degler et al., 2018; Moreira et al., 2018; Barbosa et al., 2019; Cardoso et al., 2019; Kuribara et al., 2019). This time period is significant because it encompasses the 2450-2200 Ma magmatic shutdown

(Mineiro Belt; Moreira et al., 2018), the Rhyacian-Orosirian Transamazonian orogeny that affected all of these units as well as the São Francisco cratonic basement (Alkmim and Marshak, 1998; Aguilar et al., 2017; Alkmim and Teixeira, 2017; Carvalho et al., 2017; Cutts et al., 2018; 2019), followed by the Brasiliano event at 600-490 Ma, which reactivated already existent structures, making it difficult to determine the timing and significance of earlier events (Chemale et al., 1994; Alkmim and Marshak, 1998;; Brueckner et al., 2000; Noce et al., 2007; Heilbron et al 2010; Aguilar et al., 2017; Cutts et al., 2018). These three units, the Mineiro Belt (MB), Mantiqueira Complex (MC) and Juiz de Fora Complex (JFC), are all considered to be fragments of the Palaeoproterozoic orogeny (Transamazonian orogeny), which also resulted in the inversion and closure of the Minas Basin. The structure separating the Mantiqueira and Juiz de Fora Complexes, the Abre Campo Shear zone (Fig. 1), has been interpreted by many workers either to have formed during the Brasiliano event or to have formed in the Palaeoproterozoic as a suture and reactivated during the Neoproterozoic (Machado et al., 1996). The first interpretation is based on the presence of deep-ocean correlatives of the Macaúbas Group being rooted within the Abre Campo shear zone, in addition to Brasiliano-aged shear zones (Brueckner et al., 2000; Alkmim et al., 2006; Kuribara et al., 2019), whereas the second is based on the distinction between the terranes to each side of the shear zone, composed of juvenile Palaeoproterozoic granitoids to the east and mostly reworked Palaeoproterozoic granitoids to the west (Noce et al., 2007; Heilbron et al 2010; Alkmim and Teixeira, 2017). These observations have prompted at least one study to suggest that the MC and JFC only amalgamated in the Brasiliano, along a Brasiliano-aged structure (Kuribara et al., 2019; c.f. Cutts and Lana, 2019).

This study targets two high-grade complexes adjacent to the southern São Francisco Craton (SFC) of Brazil – the Acaiaca Complex and Pedra Dourada Granulite. These units both consist of granulite facies meta-igneous and metasedimentary rocks and both outcrop within

the amphibolite facies, exclusively orthogneiss Mantiqueira Complex. However, the two complexes have been mapped as different units due to their higher metamorphic grade and the presence of aluminous rock types (Marinho et al., 2016; Medeiros Júnior et al., 2016). The relationship between these units and the Mantiqueira Complex, as well as to each other is presently uncertain due to a paucity of outcrop. The Pedra Dourada Granulite has previously been interpreted to be intrusive into the Mantiqueira Complex (Peres et al., 2004; Marinho, 2014; Cutts et al., 2018), however, none of the cited works has directly observed this contact. The Mantiqueira Complex has been investigated using zircon U-Pb and whole-rock Sm-Nd (Noce et al., 2007), and more recently, zircon U-Pb combined with Lu-Hf (Kuribara et al., 2019). The Acaiaca complex has only been the target of metamorphic studies (Cutts et al., 2018; Medeiros Júnior et al., 2016), whereas some minor detrital zircon work has been conducted on the Pedra Dourada Granulite (Marinho, 2014). Both the Mineiro Belt and Juiz de Fora Complex have been the target of combined zircon U-Pb and Lu-Hf studies (MB - Moreira et al., 2018; JFC - Degler et al., 2018; Kuribara et al., 2019). The objective of this study is to evaluate the detrital zircon record preserved within the Pedra Dourada Granulite and Acaiaca Complex in order to compare with the inherited zircon record of the Mantiqueira Complex. This will allow us to determine the relationship between the two higher grade complexes in addition to their relationship with the amphibolite facies Mantiqueira Complex. The zircon record in these granulite facies rocks hosted in the MC will then be compared to the Lu-Hf and zircon record of the Mineiro Belt and JFC to determine the presence of a genetic relationship between any of these units. This can then be used to evaluate the proposed tectonics models for this region from the Siderian to Cambrian.

2. Geological setting

The Mantiqueira Complex is considered to contain the easternmost fragments of the Archaean crust of the southern São Francisco craton, which experienced extensive reworking during the Palaeoproterozoic (e.g., Teixeira, 1996; Heilbron et al., 2000; Teixeira et al., 2000; Duarte et al., 2004, 2005; Noce et al., 2007; Heilbron et al., 2010; Fig. 1). The complex is heterogeneous and includes several calc-alkaline gneiss–migmatitic suites with amphibolite layers. The latter consist predominantly of banded biotite-amphibole orthogneisses. Alkaline felsic plutons and younger felsic and mafic dykes intruded the Mantiqueira Complex between ca. 2180 Ma and ca. 2040 Ma. Available Rb–Sr and U–Pb isotopic data reveal a complex and protracted evolution for the magmatic arc plutons (e.g., Fischel et al., 1998; Ragatky et al., 1999; Brueckner et al., 2000; Heilbron et al., 2001; Silva et al., 2002; Noce et al., 2007; Heilbron et al., 2010; Kuribara et al., 2019). According to these authors, composite zircons from the Mantiqueira gneisses record magmatic crystallization ages from ca. 2203 to 2041 Ma in their rims and a large amount of inherited Archaean zircon cores dated between ca. 3200 Ma and ca. 2600 Ma. These data, together with zircon T_{DM} model ages ranging from 3200 Ma to 2900 Ma and strongly negative whole rock epsilon-Nd values ($\epsilon Nd(t) = -9$ to -12) suggest that the Palaeoproterozoic rocks were derived from crustally-contaminated magmas in an active-margin setting (Noce et al., 2007; Heilbron et al., 2010). More recently, Kuribara et al. (2019) conducted U-Pb zircon and Lu-Hf work on the Mantiqueira Complex and obtained a more limited range of inherited ages (2.61–2.67 Ga) and highly evolved Lu-Hf with model ages of 3.6–3.2 Ga.

The eastern extent of the MC is marked by the 300 km long Abre Campo Shear zone (Fig. 1). This shear zone represents a major structural discontinuity, and gravimetric and magnetic anomaly (Haralyi and Hasui, 1982; Alkmim et al., 2006; Noce et al., 2007; Degler et al., 2018). It separates the largely amphibolite facies MC from the granulite facies JFC suggesting that it is a Palaeoproterozoic suture (Degler et al., 2018; Alkmim and Teixeira,

2017). However, deep-ocean correlatives of the Neoproterozoic Macaúbas Group root in the Abre Campo shear zone, indicating that the Abre Campo shear zone delineates a Brasiliano suture developed during closure of the oceanic portion of the Macaúbas basin. Brasiliano shear zones also root into the Abre Campo shear zone, steepening it (Brueckner et al., 2000; Alkmim et al., 2006). Thus if it is a Palaeoproterozoic structure, it was reworked during the Brasiliano orogeny.

The JFC mainly comprises granulite facies juvenile granitic orthogneisses (enderbites and mafic rocks) with magmatic ages of 2400 to 2100 Ma, which are portrayed as the assemblage of an intra-oceanic magmatic arc (Machado et al., 1996; Fischel et al., 1998; Silva et al., 2002; Noce et al., 2007; Heilbron et al., 2010; Degler et al., 2018). Degler et al. (2018) obtained magmatic ages of 2195-2107 Ma for the JFC and T_{DM} of 2.0-2.5 Ga and correlated the JFC with the Pocrane Complex as a juvenile to transitional magmatic arc. In another recent publication, Kuribara et al. (2019), also worked on the JFC, obtaining magmatic ages of 2.38 and 2.05-1.96 Ga with T_{DM} of 2.2-3.4 Ga. This is the only study to have found Archaean input for the JFC.

To the west of the Mantiqueira reworked cratonic margin, is the southern São Francisco craton. The SFC comprises a major N-S trending Archaean core that is fringed by Palaeoproterozoic orogenic belts at its northeastern and southern ends, and almost entirely covered by Proterozoic (<1.8 Ga) and Phanerozoic sedimentary units (Fig. 1; Almeida et al., 1981; Teixeira et al., 2000; Barbosa and Sabaté, 2004; Alkmim and Martins-Neto, 2012). The southernmost sector of the craton exposes a relatively small portion of the Palaeoproterozoic orogen, which encompasses the region of the Quadrilátero Ferrífero (QF; Figs. 1, 2). The QF has a dome-and-keel geometry involving keels of Archaean to Palaeoproterozoic supracrustal rocks of the Rio das Velhas Supergroup (ca. 2900-2730 Ma), the Minas Supergroup (ca. 2600-2100 Ma) and the Itacolomi Group (ca. 2100-2000 Ma; Marshak et al., 1997; Farina et

al., 2015, 2016). The domes consist of Archaean granitoid-gneiss complexes that fall into three age groups (3220-3200, 2930-2850 and 2800-2760 Ma; Lana et al., 2013).

The Mineiro Belt consists of plutonic suites ranging in age from 2.47-2.0 Ga with associated supracrustal sequences containing carbonaceous phyllites, gondites, quartzites, metagreywackes and mafic to ultramafic metavolcanics (Avila et al., 2010, 2014; Barbosa et al., 2015; Moreira et al., 2018). The Mineiro Belt is separated from the Archaean São Francisco craton by the NE-SW trending Jeceaba-Bom Sucesso Lineament, and the NW-SE trending Congonhas Lineament (see Fig. 1 of Moreira et al., 2018). The suture to the SE of the belt has yet to be found. Generally the granitoid suites of the Mineiro Belt have juvenile signatures with T_{DM} of 2.3-2.6 Ga with minor Archaean inheritance (Avila et al., 2010, 2014; Seixas et al., 2012, 2013; Teixeira et al., 2015; Moreira et al., 2018). However, the supracrustal rocks of the Mineiro Belt, which were deposited between 2.3-2.1 Ga contain a significant contribution of Archaean detritus (Teixeira et al., 2012, 2015; Avila et al., 2014).

The Acaíaca Complex (AC) consists of felsic, mafic, ultramafic and aluminous granulites with lower-grade gneisses and mylonites. The rocks are highly deformed with mafic, felsic and aluminous granulites frequently occurring interbanded on a cm to mm scale. The mafic and felsic granulites have previously been interpreted as orthogneisses, with the aluminous granulites being interpreted as metasediments (Medeiros Júnior et al., 2016). The AC occurs as a NS-trending body in the hanging wall of a shallow dipping and W-verging thrust affecting the Mantiqueira Complex. A petrological and geochronological investigation carried out in the complex has yielded a U-Pb monazite age of ca. 2060 Ma for estimated peak-metamorphic P - T conditions of ca. 800 °C and 5-10 kbar (Medeiros Júnior, 2016; Medeiros Júnior et al., 2016).

The Pedra Dourada Granulite (PDG; originally called the Córrego Pedra Dourada Granulite, Brandalise, 1991) consists of granulite-facies metaigneous and metasedimentary rocks. These rocks occur as one large and numerous smaller bodies occurring within the Mantiqueira gneisses. These rocks have been interpreted as intrusive into the Mantiqueira Complex (see Peres et al., 2004). However, no exposure of this intrusive contact has ever been described and outcrops are limited to creek bed exposures. Similarly to the AC, the Pedra Dourada Granulite consists of mafic and felsic granulites that have been interpreted as orthogneisses and aluminous granulites interpreted to be metasediments (Marinho et al., 2016). Again, all of these lithologies are highly deformed and banded on a cm to mm scale. The Pedra Dourada Granulite is interpreted to have undergone a high-grade metamorphic event reaching peak conditions of 716-620 °C at 7 kbar (Jordt-Evangelista et al., 1994) or 550-680°C at 7-11 kbar (Rettinger et al., 1998). A later event resulted in overprinting at lower grade conditions (Peres et al., 2004). *P-T* conditions of 750–800 °C and 5–7 kbar with slow cooling along a near-isobaric path and a corresponding monazite age of ca. 2015 Ma were obtained for both the Acaiaca Complex and Pedra Dourada Granulite (Cutts et al., 2018). A zircon age of ca. 2070-2040 Ma for the granulite-facies event was obtained from the Pedra Dourada Granulite (Marinho, 2014). Detrital zircon data from one aluminous granulite sample of the Pedra Dourada Granulite yielded ages between 2250-3402 Ma, with the youngest age being interpreted as the maximum deposition age of the unit (Marinho, 2014).

2.1 Metamorphism

The available geochronological data suggest that an amphibolite-facies metamorphic event overprinted the Archaean gneisses and greenstone belt, as well as the Palaeoproterozoic supracrustal rocks in the QF in the time interval of 2098 to 1989 Ma (e.g., Belo de Oliveira

and Teixeira, 1990; Machado et al., 1992; Babinski et al., 1995; Machado et al., 1996; Schrank and Machado, 1996a,b; Marshak et al., 1997; Noce et al., 1998; Brueckner et al., 2000; Vlach et al., 2003, Aguilar et al., 2017).

As mentioned above, the Pedra Dourada Granulite and Acaiaca Complex experienced granulite facies metamorphism at ca. 2015 Ma (Cutts et al., 2018) or ca. 2060 Ma (Medeiros Júnior, 2016; Medeiros Júnior et al., 2016). The Mantiqueira Complex is also suggested to have experienced a metamorphic event at ca. 2100 Ma based on zircon U-Pb SHRIMP data (Silva et al., 2002; Heilbron et al., 2010).

Units of the QF were locally affected by greenschist-facies metamorphism and deformation structures currently associated with the Neoproterozoic Brasiliano event (e.g., Chemale et al., 1994; Alkmim and Marshak, 1998), this resulted in resetting of zircon to produce lead-loss trends with intercepts of ~650-550 Ma (Lana et al., 2013; Carvalho et al., 2017). The Mantiqueira Complex, on the other hand, was intensively deformed and metamorphosed under amphibolite facies conditions in the Neoproterozoic (at 580-540 Ma; Silva et al., 2002; Heilbron et al., 2001, 2010; Duarte et al., 2005; Noce et al., 2007; Silva et al., 2016; Cutts et al., 2018). Cutts et al. (2018) obtained *P-T* conditions of 8-9 kbar and 650 °C at 600- 550 Ma based on U-Pb monazite dating of amphibolite facies samples from the Mantiqueira Complex and the Dom Silvério Group, a Neoproterozoic deep marine succession overlaying the Mantiqueira Complex (Peres et al., 2004). In addition, Sm-Nd garnet-plagioclase-whole rock isochrons obtained from the Dom Silvério Group indicates amphibolite facies metamorphism at ca. 550 Ma (Brueckner et al., 2000).

The supracrustal rocks of the Mineiro Belt record two metamorphic episodes at ca. 2.19 and 2.13 Ga (Avila et al., 2010, 2014; Barbosa et al., 2015; Teixeira et al., 2015; Alkmim and Teixeira, 2017). Some zircon rims and titanite grains also have 2050 Ma ages, interpreted as a

thermal overprint during the belt collapse (Moreira et al., 2018). The western sector of the Mineiro Belt was not strongly affected by the Neoproterozoic overprint and the only evidence is based on Pb-loss trends with lower intercepts on concordia diagrams at ca. 500 Ma.

In contrast, the JFC experienced granulite facies metamorphism during the Brasiliano event, producing leucosomes of garnet-bearing charnokite and metamorphic zircon ages of 620-520 Ma (Kuribara et al., 2019), 570-600 Ma (Noce et al., 2007), and 604-570 Ma (Heilbron et al., 2010). Breuckner et al. (2000) obtained garnet isochron ages of samples from the JFC of 570-560 Ma with Sm-Nd model ages of ca. 2000 Ma. Degler et al. (2018) obtain metamorphic ages of ca. 590 Ma and 2095 Ma for the JFC.

A synthesis of data from the Mantiqueira Province (this extends from 33°S in Uruguay to 15°S in Brazil; Bento dos Santos et al., 2015) suggests that Brasiliano metamorphic ages fall into three groups: pre-, syn- and post-orogenic periods at 670-595 Ma, 620-550 Ma and 560-490 Ma respectively (Bento dos Santos et al., 2015). Other workers indicate that the collisional episodes in the Mantiqueira Province are diachronic with the oldest episodes being recorded in the south of the province at 790 to 700 Ma, followed by collisions in the southern Brasilia orogen and Dom Feliciano orogen (in southern Brazil and Uruguay) at ca. 630-600 Ma and finally collision in the Ribeira and Araçuaí orogens from ca. 580-520 Ma (Heilbron et al., 2004).

3. Sampling sites

3.1 Acaiaca Complex

Samples from the Acaiaca Complex were obtained from an abandoned (at the time of sampling) quarry, which is the type locality of the Acaiaca Complex (Grid ref. SAD69, 23K 0696285/ 7743102; Fig. 2). This outcrop features pervasively foliated migmatites, diatexites,

and mafic and felsic granulites (Fig. 3A). The mafic and felsic granulites occur as centimetric to metric bands which are locally bent or interrupted by felsic injections containing coarse garnet grains (up to 5 cm in diameter). In addition, the outcrop features a pegmatite that crosscuts the banding and a diabase that crosscuts both the banding and the pegmatite (see also Medeiros Júnior et al., 2016). Two samples were obtained from aluminous mafic and felsic banded granulites at this location. Both samples are banded with Acai 2 being dominated by mafic bands and Acai 3 being dominated by felsic bands. Sample Acai 2 contains the minerals garnet, plagioclase, biotite, K-feldspar, quartz and orthopyroxene with minor zircon, monazite and apatite. Sample Acai 3 contains clinopyroxene, orthopyroxene, biotite, garnet, plagioclase, K-feldspar and quartz with minor zircon, apatite and monazite. Garnet is texturally late, appearing to grow at the expense of pyroxene and plagioclase. Samples Acai 2 (4437) and Acai 3 (4438) were used for zircon U-Pb geochronology utilising grains obtained via mineral separation. Lu-Hf isotopic analysis was conducted on the same spots (where possible) that the U-Pb ages were obtained from.

3.2 Pedra Dourada Granulite

Samples from the Pedra Dourada Granulite within the Mantiqueira Complex were collected in an outcrop next to the Mascarenhas power plant (Grid ref. SAD69, 23K 0721755/7767476; Figs. 2, 3B). The outcrop hosts a range of highly-deformed rock types including diatexites, mafic and felsic granulites, all with garnet-bearing leucosomes (Fig. 3B). The sample obtained here is a stromatic metatexite featuring interlayered mafic and felsic aluminous granulites (Fig. 3B). Sample Masc 1 (4435) favours the mafic portion of the rock, whereas Masc 2 (4436) favours the more felsic granulites. As with the previous locality, both samples contain mafic and felsic bands but sample Masc 1 is dominated by mafic bands, and Masc 2 is dominated by the felsic portion. Mineralogy is garnet, biotite, plagioclase, orthopyroxene, K-feldspar and quartz. Clinopyroxene occurs exclusively within the mafic bands. Minor

amphibole is observed replacing orthopyroxene. The accessory minerals present include zircon, apatite and monazite. Both samples are used for zircon U-Pb geochronology utilising grain separates, with Lu-Hf isotope analysis targeting the same spots used for the U-Pb ages.

4. Analytical methods

4.1 Zircon U-Pb geochronology

Zircon grains were separated, mounted in epoxy resin and imaged using cathodoluminescence (CL) imaging on a JEOL 6510 scanning electron microscope housed at the Universidade Federal de Ouro Preto. The CL images were used to examine morphological characteristics of zircon grains and avoid cracks, inclusions and damaged areas during the analysis of grains. Zircon U-Pb analyses were carried out at the Universidade Federal de Ouro Preto using a Thermo-Finnegan Neptune multi-collector ICP-MS coupled with a Photon-Machines 193 nm excimer laser system (LA-MC-ICP-MS). Data acquisition followed the method described by Lana et al. (2017). For U-Pb measurements, the magnet is settled on a virtual mass (~ 223.2) in the centre of the array and all relevant masses are measured simultaneously (^{202}Hg , $^{204}(\text{Pb} + \text{Hg})$, ^{206}Pb , ^{207}Pb , ^{208}Pb , ^{232}Th and ^{238}U). Data collection consists of 550 cycles (or sweeps of ~ 0.1 s each) of all the relevant masses and ratios. A 15 s background is collected prior to 40 s of sample acquisition, with a typical analysis time of 55 seconds. A spot size of 20 μm was used with a 6 Hz repetition rate and laser fluence of 1-2 $\text{J}\cdot\text{cm}^{-2}$.

The data was processed offline using an in-house spreadsheet modified from Gerdes and Zeh (2006) that includes corrections for background, downhole fractionation, instrumental mass bias drift and common Pb. Analyses were conducted over several analytical sessions. The GJ-1 zircon standard (Jackson et al., 2004) was used as a primary standard for this study with the Plešovice zircon standard ($^{206}\text{Pb}/^{238}\text{U} = 337$ Ma, $^{207}\text{Pb}/^{235}\text{U} = 337$ Ma and $^{207}\text{Pb}/^{206}\text{Pb} = 339$

Ma; Sláma et al., 2008) being used as a secondary standard. Plešovice analyses collected over the duration of the study give weighted average results of: $^{206}\text{Pb}/^{238}\text{U} = 338 \pm 1$ Ma, $^{207}\text{Pb}/^{235}\text{U} = 338 \pm 1$ Ma and $^{207}\text{Pb}/^{206}\text{Pb} = 342 \pm 3$ Ma ($n=32$).

All zircon data is given in Supplementary Table 1. Data was plotted using Isoplot v.4.15 (Ludwig, 2011). Individual concordia ages and probability of concordance were also utilised to evaluate the reliability of the data (i.e. Rossignol et al., 2018; Zimmerman et al., 2018). However, this method was found to remove some populations so we have also presented all data within 10% concordant.

4.2 Lu-Hf isotope analysis

Lu–Hf analyses were carried out at the Universidade Federal de Ouro Preto using a Thermo-Finnigan Neptune multi-collector ICP-MS coupled to a Photon-Machines 193 nm excimer laser system (LA-MC-ICP-MS), following the methods of Gerdes and Zeh (2006, 2009). Data (154 analyses, Supplementary Table 1) were collected in static mode during 60 s of ablation with a spot size of 50 μm . The spots were drilled with a repetition rate of 6 Hz. Typical signal intensity was ca. 10 V for ^{177}Hf . The isotopes ^{172}Yb , ^{173}Yb and ^{175}Lu were simultaneously monitored during each analysis step to allow for correction of isobaric interferences of Lu and Yb isotopes on mass 176. The accuracy and external reproducibility were verified by analyses of the standard zircons GJ-1 (Jackson et al., 2004), Plešovice (Sláma et al., 2008) and Blue Berry (Santos et al., 2016), which yielded $^{176}\text{Hf}/^{177}\text{Hf}$ of 0.2820079 ± 0.0000085 ($n = 24$), 0.2824717 ± 0.0000042 ($n = 22$), 0.281664 ± 0.000013 ($n = 29$) respectively (all errors are $\pm 2\sigma$ SD). These ratios are in good agreement with the accepted ratios data of 0.282000 ± 0.000005 (GJ-1), 0.282482 ± 0.000013 (Plešovice), and 0.281674 ± 0.000018 (Blue Berry).

5. Results

5.1 Zircon U-Pb geochronology

5.1.1. Sample Acai 2

Zircon grains in this sample are usually between 100-200 μm in size, sub-rounded and equant to elongate (Fig. 4A). CL response is mixed with some very bright and dark grains, in some cases these are cores/rims of individual grains (Fig. 4A, grains 21 and 66). Grains have variable zoning with some unzoned (or it is too dark or bright to see, i.e. spots 16 and 21), others have distinct cores and rims (i.e. spots 30 and 74) and the remainder have sector or soccerball type zonation (i.e. spots 11, 60, 27 and 28; Fig. 4A). Thirty-nine analyses were conducted on zircon grains from this sample. Two analyses were strongly discordant (67% and 21%), whereas the remaining 37 are all within 10% concordant (98-106%). Using the method of Zimmerman et al. (2018) with individual calculated concordia ages, twelve of the thirty-nine analyses have a concordance probability of less than 10%. This leaves twenty-seven analyses (Fig. 5A). There does seem to be a relationship between textural setting and age with most of the older ages originating from textural cores (or CL dark grains; Fig. 4A, Supplementary Table 1).

When all data is plotted on a probability density plot (using the $^{207}\text{Pb}/^{206}\text{Pb}$ ages) most of the data lies between 2000-2500 Ma, although there is a small older group at ca. 2600-2700 Ma. The largest groups are at 2050 Ma, 2150, 2290 and 2400 Ma (Fig. 5A). If only the most concordant analyses are used ($n=27$, blue curve, Fig. 5A), there is a large, narrow peak at ca. 2058 Ma. The bulk of these analyses are from sector zoned grains or rims thus this peak is interpreted to represent the metamorphic age of the sample. This is also consistent with the age of ca. 2060 Ma obtained by Medeiros Júnior et al. (2016). Three analyses are younger than this group at ca. 2000 Ma, 1900 Ma and 1550 Ma. The remainder of the data lies

between 2150-2420 Ma. The largest groups are at 2150 Ma, 2260, 2360 and 2420 Ma (Fig. 5A).

5.1.2. Sample Acai 3

Zircon grains in this sample are generally 200-300 μm in size and vary from subrounded to euhedral. Grains are commonly equant but can also be elongate (Fig. 4B). Most grains have a moderate CL response and contain sector zoning (or soccer ball type zonation, i.e. 7 and 37). A few grains preserve eroded cores that are surrounded by sector or unzoned rims (i.e. grains 50 and 78). In these cases, the CL response is usually quite different between the core and rim. The core domains can be quite small but seem to also have either no zonation or sector zonation with only a few instances suggesting oscillatory zonation (Fig. 4B, spot 78).

Forty-seven U-Pb analyses were obtained from this sample and all are within 10% concordant (range from 96% to 108%). Obtained $^{207}\text{Pb}/^{206}\text{Pb}$ ages range from 1680 to 2500 Ma and there is no relation between Th/U ratio and age (Supplementary Table 1).

While the core domains seem to be generally older, there is a large amount of overlap in age with rim ages and those obtained from apparently metamorphic grains (Supplementary Table 1). When all data is plotted on a probability density plot (using the $^{207}\text{Pb}/^{206}\text{Pb}$ ages, $n=47$, black curve, Fig. 5B) most of the data lies between 2500-2000 Ma with larger groups at 2050-2150 Ma, 2200, 2300 and 2400 Ma (Fig. 5B).

The individual concordia ages indicated twelve analyses with a probability below 10%, leaving 35 analyses. Of these, obtained $^{207}\text{Pb}/^{206}\text{Pb}$ ages range from 1930 to 2480 Ma and there is no relation between Th/U ratio and age (Table 1). When all data is plotted on a probability density plot (using the $^{207}\text{Pb}/^{206}\text{Pb}$ ages, $n=35$, blue curve, Fig. 5B), the youngest large peak occurs at 2066 Ma with the bulk of analyses in this group coming from sector zoned grains or rims. This likely represents the metamorphic age of the sample and is the

same as the age obtained from sample Acai 2 and the monazite age of Medeiros Júnior et al. (2016). Other major peaks occur at 2090, 2130, 2210, 2314 and 2420 Ma (Fig. 5B).

5.1.3 Sample Masc 1

Zircon grains in this sample can be up to 200 μm in size but are usually 100 or less (Fig. 4C). Grains are subrounded and can be elongate, but are more frequently equant. CL response is extremely variable even within a single grain (i.e. spots 24, 41 and 43) making these grains difficult to image. Most grains have sector or soccerball type zoning. Cores are common, very rarely these seem to preserve oscillatory zonation. More often, cores are white or black with no identifiable zonation. Sixty U-Pb analyses were obtained from this sample. Four analyses were extremely reversely discordant ($>110\%$) so they are not included here. The obtained $^{207}\text{Pb}/^{206}\text{Pb}$ analyses from the remaining analyses ($n=54$) range from 3584 Ma (109%; also 3505 Ma with 103% conc.) to 1211 Ma ($^{206}\text{Pb}/^{238}\text{U}$ age, 96% conc.). There are two younger analyses at 1093 and 358 that are discordant (87 and 72% conc. respectively). When the data is plotted on a probability density plot (using the $^{207}\text{Pb}/^{206}\text{Pb}$ ages, excluding the youngest analysis, $n=53$) most of the data lies between 1800-2700 Ma with larger groups at 2100 Ma, 2300, 2700, 3200 Ma and 3500 Ma (Fig. 5C). Analyses which target cores give older ages (>2000 Ma) while those that target rims preserve younger ages (<2500 Ma; Fig. 5C; Supplementary Table 1).

When individual concordia ages are determined, 32 analyses are found to have less than 10 % probability of concordance, leaving only 28 analyses. The obtained $^{207}\text{Pb}/^{206}\text{Pb}$ analyses from the remaining analyses range from 1980 to 2730 Ma. When the data is plotted on a probability density plot (using the $^{207}\text{Pb}/^{206}\text{Pb}$ ages, blue curve, Fig. 5C) most of the data lies between 2000-2500 Ma with larger groups at 2097 Ma, 2123, 2180, 2320 and 2480 Ma (Fig. 5C). The bulk of the younger peaks (2097 Ma, 2123 Ma and 2180 Ma) consist of analyses

acquired from unzoned grains and rims (Supplementary Table 1). Several analyses that give ca. 2120 and 2180 Ma ages occur as cores (although sector zoned) with thin, black rims that could not be dated, whereas the youngest group is found as rims or sector zoned grains that have no rims (i.e. analyses 50 and 51; Fig. 5). Thus, it is likely that the ca. 2097 Ma group represents the metamorphic population in this sample.

5.1.4 Sample Masc 2

Zircon grains in this sample can be up to 500 μm in size but are usually around 300 μm (Fig. 4D). Grains are subrounded to subangular and elongate to equant. CL response is only slightly variable and grains contain sector or soccerball zonation (i.e. spots 81 and 82). In some cases there are clear cores and rims with unzoned rims truncating the zoning of the core (i.e. spots 76 and 71). In other grains cores seem to be embayed prior to rim growth (see Fig. 4D, spots 46 and 39). Thirty-five U-Pb analyses were collected from this sample with one analysis being greater than 10% discordant (80%) while the remainder are 95%-108%. The obtained $^{207}\text{Pb}/^{206}\text{Pb}$ ages range from 2500 to 1874 Ma. When plotted on a probability density plot (using the $^{207}\text{Pb}/^{206}\text{Pb}$ ages, black curve, $n=34$, Fig. 5D), there are two large peaks at 2135 Ma and 2080 Ma, there are also three minor peaks at ca. 2200 Ma, 2260 Ma and 2300 Ma. There is one analyses at 2500 Ma. These small groups of older analyses often come from embayed cores (i.e. spots 39 and 46). Rims, unzoned grains or sector zoned grains generally give ages corresponding to the younger peak (ca. 2080 Ma; i.e. spots 82 and 69), potentially indicating that this is the age of metamorphism of the sample, however both younger groups are found as cores (i.e. analyses 69 and 48). When individual concordia ages are determined, 8 analyses have a probability less than 10, leaving 27. This reduces the age range to 2310 to 1874 Ma but doesn't significantly alter the

probability density plot (Fig. 5D, blue curve, $n=27$). There are still two large peaks at 2135 and 2080 Ma, there are also two minor peaks at ca. 2200 Ma and 2300 Ma (Fig. 5D).

5.2 Lu-Hf isotope analyses

The initial $^{176}\text{Hf}/^{177}\text{Hf}$ ranges from 0.2807 to 0.2816 (Fig. 6A) and was calculated based on the measured $^{207}\text{Pb}/^{206}\text{Pb}$ concordant ages of 154 concordant to sub-concordant zircons from the four investigated samples. Lu-Hf isotope analyses were obtained from the same domains, in most cases, directly on the U-Pb spots. In a few instances, the Lu-Hf spot clearly sampled a younger domain. These analyses are indicated in Table 1 with an asterix. For these analyses, the initial $^{176}\text{Hf}/^{177}\text{Hf}$ was determined using the average metamorphic age of the sample (2100 Ma for sample Masc 1 and 2080 Ma for sample Acai 2; see Supplementary Table 1). In summary, these ratios seem to fall in two bands. One diffuse band at 0.2808-0.2812 and a second more discrete band at 0.2816. These two bands are seen as crustal evolution trends in the $\square\text{Hf}(t)$ diagram (Fig. 6B). The first trend gives mostly subchondritic $\square\text{Hf}(t)$ values of -27 to +2, with variations in Hf model age (T_{DM}) of 3500 to 2800 Ma. The second group gives exclusively superchondritic $\square\text{Hf}(t)$ values of +2 to +10 with variations in Hf model age (T_{DM}) of 2500 to 2250 Ma.

6. Discussion

6.1 Metamorphism and maximum depositional age

Given the high proportion of metamorphic zircon grains present, determining the maximum deposition age is problematic. Marinho (2014) proposed a maximum deposition age of 2250 Ma based on the age of the youngest interpreted detrital analysis.

The zircon grains in this study proved difficult to image, in many cases having alternating CL bright and dark bands (Fig. 4), however in most of the samples, analyses obtained from grain cores start from ca. 2100 Ma, with the bulk of the peaks below this age being made up of interpreted metamorphic grains. Other workers in the Mantiqueira Complex have suggested crystallization ages of the gneisses from ca. 2200-2040 Ma (Fischel et al., 1998; Ragatky et al., 1999; Brueckner et al., 2000; Heilbron et al., 2001; Silva et al., 2002; Noce et al., 2007; Heilbron et al., 2010). In the samples of this study, there are a few dated cores that yield ages between 2050 and 2100 Ma. These cores are surrounded by thin rims, analytically difficult to date, but that offer the possibility to represent the metamorphic age. Considering the oldest monazite ages of 2015 Ma for the same complexes (Cutts et al., 2018), it is plausible that the MDA lies between 2050 and 2100 Ma. However, the previous study that investigated metamorphic monazite from the Acaíaca Complex and Pedra Dourada Granulite interpreted the monazite ages to date cooling from peak conditions or be a result of fluid dissolution-reprecipitation processes (Cutts et al., 2018). Sample Acaí 2 produces a concordia age of ca. 2050 Ma from interpreted metamorphic grains and has only one clear metamorphic peak at ca. 2055 Ma (Fig. 7). The remaining samples all present at least two potentially metamorphic peaks at ca. 2070-2090 Ma and 2130-2140 Ma. Existing data from the Pedra Dourada Granulite (Marinho, 2014) and the Mantiqueira Complex has only one peak at ca. 2040-2050 Ma, similar to sample Acaí 2. Although, Noce et al. (2007) found crystallization ages of ca. 2137 and ca. 2020-2070 Ma for Mantiqueira gneisses and 2120 and 2080 Ma for the Juiz de Fora Complex. Degler et al. (2018) found crystallization age of 2107-2195 Ma for the Juiz de Fora Complex.

Thus, the metamorphic zircon data presented in this study suggests at least two zircon (and melt) producing metamorphic events within the AC and PDG. The ca. 2050-2090 Ma ages may better represent the age of peak metamorphism of the ca. 750-800 °C and 6 kbar event of

Cutts et al. (2018). The nature of the older ca. 2130-2140 Ma event is uncertain but may be a result of magmatism as the Mantiqueira Complex is proposed to be a continental arc at this time (Noce et al., 2007). In this sense, the ca. 2130 Ma would represent the onset of the convergent stages within the Palaeoproterozoic orogeny, whereby a reasonable proportion of the magmatism produced was juvenile, corresponding to the juvenile 2.4-2.2 Ga zircon population found in the AC and PDG. This suggestion is consistent with the contemporaneous juvenile magmatism in the Minas accretionary orogeny to the south in the Mineiro Belt (Teixeira et al., 2015; Moreira et al., 2018). The overall evolved signature of the Mantiqueira Complex is attained as the orogen evolves, with the melting of sediments with older crustal input (not necessarily Archaean, but possibly Palaeoproterozoic) marking the convergent to collisional stage transition with higher reworking rates.

Due to the distinctive nature of the older ca. 2130 Ma event, we use a MDA of 2100 Ma for the AC and PDG, although an MDA of 2250 Ma was used for the data of Marinho (2014). It is reasonable to suggest a younger MDA given the presence of some ca. 2100-2050 Ma cores surrounded by undated rims. The rims potentially represent a metamorphic event and overgrowth in the presence of melt. The protolith of the migmatites, therefore, contained ca. 2100 Ma zircon grains later involved and not completely consumed during the partial melt event.

All of the samples present some analyses that are younger than the interpreted metamorphic ages, which vary from ca. 1950 to 1260 Ma. In many cases, when concordia ages are determined, the probability of concordance for these grains is lower than 10% (see Supplementary data table). The investigation by Heilbron et al. (2010) on the Mantiqueira Complex indicated a large degree of Brasiliano resetting. Potentially these younger analyses are the result of Brasiliano age partial lead loss.

6.2 Sources and related units

When the detrital zircon spectra from all of the investigated samples are compared (Fig. 7), it appears that the two Acaiaca Complex samples are dominated by 2500-2200 Ma detritus with no Archaean input. The Pedra Dourada Granulite samples are also dominated by 2500 to 2200 Ma detritus but have a minor Archaean component as well (Fig. 7). In contrast, previous work on the Pedra Dourada Granulite (Marinho, 2014) found dominantly Archaean detritus with minor 2500-2250 Ma detrital input. This is similar to the age of inherited zircon been found in the Mantiqueira Complex (Fig. 7; Noce et al., 2007). Additionally Heilbron et al. (2010) found six inherited grains at 2890-2300 Ma, showing that the Mantiqueira Complex also has Palaeoproterozoic sources. It should be noted that both of the mafic samples investigated (Acai 2 and Masc 1) did contain Archaean populations. Plausibly if a larger sample set were investigated (similar to the 135 analyses of Marinho, 2014) this population would be larger. Altogether, we suggest that the detrital zircon spectra of both the Pedra Dourada Granulite and Acaiaca Complex are similar to each other and also to the inherited zircon present within the Mantiqueira Complex. This would indicate that the PDG and AC represent a higher metamorphic grade unit which either sources the Mantiqueira Complex or has an equivalent source to the Mantiqueira Complex.

The Sabará Group is also plotted on Figure 7. This unit is the uppermost unit of the Minas Supergroup. It has a depositional age of 2120 (Martinez Dopico et al., 2017) or 2036 Ma (Dutra et al., 2019), thus it is time equivalent to AC and PDG but occurring within the Minas Basin. The Sabará Group contains a large proportion of detritus with Palaeoproterozoic ages (2.3-2.05 Ga) and a slightly smaller group with late Archean ages (2.5-3.0 Ga; Fig. 7). This large proportion of Palaeoproterozoic detritus is similar to what is found in the AC and PDG (Fig. 7).

514 The Hf data shows the presence of two different sources of zircon for both the Acaiaça
515 Complex and Pedra Dourada Granulite, with the younger of these sources only being present
516 in the more mafic samples (Fig. 6). The high-grade of the rocks makes interpretation of the
517 mafic components difficult. These could represent juvenile intrusives into a sedimentary
518 sequence, which were then deformed and metamorphosed at high grade, or their protoliths
519 contained additional mafic sediments with juvenile isotopic compositions. To explain these
520 grains, we either need a source of juvenile detrital zircons or a related suite of rocks.
521 Alternatively, during the presence of a higher volume of melt (i.e. late stages of
522 migmatization), a magma mingling with a more mafic, juvenile component may have
523 occurred. The juvenile signature would then derive from mafic components crystallised
524 slightly later in the system. For clarification, the mafic portions could not be the melanosome
525 portion of the migmatite, as they have a younger source compared to the more felsic samples.
526 When the Mantiqueira Complex Nd data from Noce et al. (2007) is plotted on a plot of ϵ_{Hf}
527 vs $^{207}\text{Pb}/^{206}\text{Pb}$ age (Fig. 8, orange band), it matches the Hf data of the older group, which also
528 corresponds to the ages of magmatic events within the SFC (Rio das Velhas I and II, and
529 Mamona; Farina et al., 2016) and overlaps with data obtained from sedimentary sequences in
530 the Quadrilátero Ferrífero (red field in Fig. 8; Albert et al., 2016). This indicates that the SFC
531 is a suitable source for this older population of zircons, with later reworking recrystallizing
532 the grains but not changing the Hf signature. Kuribara et al. (2019) also obtained Hf data
533 from Juiz de Fora Complex (red x symbols, Fig.8) and Mantiqueira Complex (blue x
534 symbols, Fig. 8). The MC data of Kuribara et al. (2019) overlaps with the more evolved
535 source obtained in this study, although it seems to be more limited range, with a T_{DM} of 3.6 to
536 3.2 Ga. The authors attribute these old model ages to recycling of Eoarchaean crustal
537 components (using a $^{177}\text{Lu}/^{178}\text{Hf}$ of 0.015 to determine TDM, rather than 0.0113) but it is
538 unclear whether the São Francisco Craton is considered a possible source (see Kuribara et al.,

2019). While no 3.6 Ga crust has been found in the present exposure of the SFC, Hf studies from the SFC have identified detrital grains as old as 3.88 Ga and Hf model ages of 4.0-3.0 Ga for the Maquiné Group (Moreira et al., 2016) and model ages of up to 3.65 Ga for the Minas Supergroup (Martinez Dopico et al., 2017). This indicates that the São Francisco Craton is a suitable source for all of the older detritus found within the Mantiqueira Complex. The source of the more juvenile group of zircons is more enigmatic. Potentially the Juiz de Fora complex, a proposed oceanic arc separated from the Mantiqueira Complex by an ocean, could be a source. Alternatively some of the intervening oceanic crust may have provided the zircons. It is also plausible that there is a hitherto unknown juvenile component in the Mantiqueira arc, which produced these juvenile zircons, either occurring as intrusives into a sedimentary sequence or magma mixing during high-grade metamorphism. Zircon and Hf data is available from the Juiz de Fora Complex (green plus symbols on Figure 8; Degler et al., 2018) and this appears to be consistent with the juvenile population (model ages of 2.2-2.4 Ga, and 2.3-2.7 Ga, their samples RC101 and M-03 respectively). The JFC data of Kuribara et al. (2019) overlaps with the data obtained from this study with T_{DM} ages of 2.4-2.25 Ga, 2.8-2.65 Ga, and 3.45-3.2 Ga. Nd data was also obtained from the JFC by Noce et al. (2007) producing model ages of 2.4-2.2 Ga. Altogether, this would suggest that the Juiz de Fora Complex is an appropriate source for the more juvenile population. Another possible source could be the 2.4-2.2 Ga Mineiro Belt, when plotted on an ϵ_{Hf} vs $^{207}Pb/^{206}Pb$ age plot, the Mineiro Belt samples plot in between those of the QF and the JFC (blue fields, Figure 8; Moreira et al., 2018). Thus, while the Mineiro Belt rocks do overlap some of the AC and PDG data, a more juvenile source similar to the Juiz de Fora complex is required. In fact, the low zircon ϵ_{Hf} values presented in the Mineiro Belt are derived from discordant U-Pb analyses and most of the ca. 2.1 Ga igneous populations have a chondritic signature.

The Sabará Group, the uppermost unit in the Minas Basin, also has a large contribution of Palaeoproterozoic detritus and the Hf record of this is similar to the samples of this study, the Juiz de Fora Complex and the Mineiro Belt (Martinez Dopico et al., 2017; Fig. 8). This unit also contains sediments from the QF that were not reworked (these analyses occur in the QF field of Albert et al., 2016; Fig. 8).

6.3 Tectonic setting

As mentioned above, the proposed tectonic setting for the Mantiqueira Complex is a continental arc or active margin based mostly on the geochemistry of orthogneisses within the Mantiqueira Complex (Duarte et al., 2004, 2005; Noce et al., 2007; Heilbron et al., 2010). Also, the Mantiqueira Complex is dominated by magmatic rocks (ca. 2.2-2.04 Ga; Noce et al., 2007; Heilbron et al., 2001, 2010), which record crustal recycling (containing large suites of Archaean xenocrystic zircon; see Noce et al., 2007). Since detrital zircon spectra reflect the basin environment in which they are deposited (Cawood et al., 2012, 2013), the detrital zircon spectra of this study can be used to additionally investigate the appropriateness of this setting and the proposed tectonic evolution of the Mantiqueira Complex (Fig. 9A)

Figure 9a shows a plot of the distribution of the difference between the measured crystallization age (CA) for a detrital zircon grain and the depositional age (DA) of the sediment for the samples investigated in this study in addition to the detrital zircon data of Marinho (2014) and from the Sabará Group (Martinez Dopico et al., 2017; Dutra et al., 2019). As a proposed active margin, we would expect to see a large amount of detrital zircons having a similar age to the deposition age of the strata. This is the case for the samples from this study (Fig. 9) but not for the sample of Marinho (2014) which plots within the collisional

setting (Cawood et al., 2012). The data from the Sabará Group plots in both the convergent and collisional fields (Fig. 9A). Considering the location of our samples, their depositional age and their convergent margin setting, and high metamorphic grade, it is feasible that the AC and PDG are arc related sediments previously thought to have not been preserved (Aguilar et al., 2017). The Sabará Group is proposed to record the closure of the Minas basin with a change in source from the QF to the Mineiro and Mantiqueira arcs (Dutra et al., 2019), has a signal that records both the active margin and basin settings

The metasedimentary rocks of the Mineiro Belt show a contrasting feature compared to the MC samples. Most of the detrital zircon populations come from Archean domains, likely to the north (SFC), and the youngest peaks at 2.1 Ga close to the MDA are secondary. This suggests that the sediments within the Mineiro Belt were deposited in a tectonic setting akin to a passive margin (Moreira et al., 2018).

The evident crustal reworking in the MC, at least to the east of the QF, could be derived from a Cordilleran-arc to forearc-type setting, likely built upon the margins of the São Francisco palaeocontinent, in which Palaeoproterozoic juvenile magmatism and old Archean crust were available sources for the crustal-mantle mixed signatures (Fig. 9B, C). The metasediments deposited as a foreland basin of the Palaeoproterozoic orogeny show similar detrital zircon spectra compared to our studied samples (Martinez Dopico et al., 2017). It suggests a convergent setting, with high rates of sedimentation, followed by metamorphism and closure of the Minas Supergroup basin in the context of the amalgamation of the Minas accretionary orogeny (Fig. 9B; Teixeira et al., 2015).

The model presented in Figure 9 is consistent with previous models proposed by Noce et al. (2007), Heilbron et al. (2010), Aguilar et al. (2017) and Cutts et al. (2018), but contrasts with more recent models for the region, which have either connected the Mantiqueira Complex

with the Mineiro Belt (the west Rhyacian – Orosirian orogenic system; see Fig. 8 of Degler et al., 2018), or propose that all the block evolved independently until the Brasiliano event (ca. 600 Ma; see Fig. 15 of Kuribara et al., 2019).

7. Conclusions

The results of this study indicate that the Acaiaca Complex and Pedra Dourada Granulite are effectively higher grade equivalents of the Mantiqueira Complex. The Hf in zircon data from the AC and PDG is the first data indicating more than one source terrain for the Mantiqueira Complex. Deposition of this sequence likely occurred in an arc to fore-arc setting, receiving evolved detritus from the São Francisco Craton as well as more juvenile input potentially from the adjacent Juiz de Fora Complex.

The results of this study indicate a Palaeoproterozoic link between the Mantiqueira and Juiz de Fora Complexes with both complexes either having the same source of juvenile material or the JFC being the source of juvenile material present in the MC. This contrasts with previous studies which have either linked the MC with the Mineiro Belt (Degler et al., 2018) or entirely separated all of the complexes (Kuribara et al., 2019).

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FIGURE CAPTIONS:

1. A. Geological map of the São Francisco craton. The location of panel B is indicated by the dashed box. The grey letters indicate the Neoproterozoic orogenic belts: B – Brasiliano; R – Ribeiro; A - Araçuaí. B. Simplified geological map of the study region adapted from Giraldo et al. (2019) and Heilbron et al. (2010). The rectangle indicates the region shown in Figure 2. ACSZ – Abre Campo shear zone; ANS – Andrelandia Nappe System; E – Embu Terrane; G – Guaxupe Nappe; P – Passos Nappe; PS – Paraíba do Sul Terrane; S – Socorro Nappe.
2. A detailed geological map of the study area: the Quadrilátero Ferrífero and the bordering Mantiqueira Complex to the east. The sampled locations are indicated on this map with black spots. Adapted from Farina et al. (2015).
3. A. The Acaiaca Complex field site where the Acai samples were obtained. This is the type locality for the Acaiaca Complex, showing the variability of rocks within the complex. This photo illustrates the fine-scale banding of the mafic and felsic

granulites. Medeiros Júnior et al. (2016) also present a field image of this location illustrating the crosscutting pegmatite and diabase. The inset shows large garnet grains present in leucosomes at this location (coin is 21 mm in diameter). B. Sample location of the Pedra Dourada Granulite where the Masc samples were obtained. The left hand image illustrates the cm-scale mafic and felsic granulite banding at the sample site (similar to what is observed in the Acaia Complex; feet are 11 cm wide).

4. A) Zircon cathodoluminescence images from sample Acai 2. For each spot in all samples, analysis numbers, concordia ages (if the analysis was found to have >10% probability of concordance, i.e. Zimmerman et al., 2018; Rossignol et al., 2018) or $^{207}\text{Pb}/^{206}\text{Pb}$ ages and $\square\text{Hf}$ values are indicated. Hf spots are dashed and U-Pb spots are not. $\square\text{Hf}$ analyses that are marked with an asterix did not sample the same domain as the U-Pb analysis so these $\square\text{Hf}$ values are determined using the average metamorphic age for the sample. Analyses without a $\square\text{Hf}$ value listed either could not be analysed or the analysis failed. B) Zircon cathodoluminescence images for sample Acai 3. C) Zircon cathodoluminescence images for sample Masc 1. D) Zircon cathodoluminescence images for sample Masc 2.
5. A) Concordia plot of sample Acai 2 ($n=37$, within 10% concordant; $n=27$, with greater than 10% probability of concordance). All illustrated analyses are with 10% concordant. For all samples, analyses given in blue correspond have greater than 10% probability of concordance (e.g. Zimmerman et al 2018). For all samples, the inset is a probability density plot for all the analyses within 10% concordant (black curve). The blue curve indicates spots that have a greater than 10% probability of concordance (i.e. Zimmerman et al 2018). B) Concordia plot of all concordant analyses from sample Acai 3 ($n=47$, within 10% concordant; $n=35$ with greater than

10% probability of concordance). C). Concordia plot of sample Masc 1, excluding 6 discordant analyses, and one analysis that was significantly younger ($n=53$, analyses within 10% concordant; $n=28$, analyses with greater than 10% probability of concordance). D) Concordia plot of concordant (within 10%) from sample Masc 2 ($n=34$, analyses within 10% concordant; $n=27$, analyses with greater than 10% probability of concordance).

6. A. $^{176}\text{Hf}/^{177}\text{Hf}_{(\text{initial})}$ versus $^{207}\text{Pb}/^{206}\text{Pb}$ age diagram showing all data from the Acaia Complex and Pedra Dourada Granulite. Analyses in grey are those that have concordia ages with less than 10% probability of concordance. B. $\square\text{Hf}_{(\text{t})}$ versus $^{207}\text{Pb}/^{206}\text{Pb}$ age diagram showing the results of detrital zircon of this study. The small arrow indicates the evolution of average continental crust with $^{176}\text{Lu}/^{177}\text{Hf}=0.0113$. The vertical grey bands indicate the main magmatic (Rio das Velhas I, Rio das Velhas II, Mamona; Farina et al., 2016) and metamorphic events (2.1-1.8 Ga Transamazonian orogeny; Alkmim and Marshak, 1998). For calculation of $\square\text{Hf}_{(\text{t})}$, CHUR and the depleted mantle evolution trend (DM), the CHUR constants of Bouvier et al. (2008; $^{176}\text{Hf}/^{177}\text{Hf}=0.282785$ and $^{176}\text{Lu}/^{177}\text{Hf}=0.0336$) and T_{DM} constants of Blichert-Toft and Puchtel (2010; $^{176}\text{Hf}/^{177}\text{Hf}=0.283294$ and $^{176}\text{Lu}/^{177}\text{Hf}=0.03933$) were used. Analyses in grey are those that have concordia ages with less than 10% probability of concordance. Symbols used for each sample are Acai 2 – black squares, Acai 3 – white triangles, Masc 1 – black triangles, Masc 2 – white circles.

7. Probability density diagrams showing the $^{207}\text{Pb}/^{206}\text{Pb}$ age spectra of the four samples of this study, then the combined $^{207}\text{Pb}/^{206}\text{Pb}$ age spectra for the Pedra Dourada Granulite (PDG) and Acaia Complex (AC). The range has been limited

to 1800-3700 Ma although some samples do contain grains younger than this. The second summary diagram of PDG and AC spectra is limited only to analyse with a probability of concordance greater than 90% (Rossignol et al., 2018, Zimmerman et al., 2018). The dashed line indicates the interpreted MDA for the samples of this study (2100 Ma). The black line represents the metamorphic peak (ca. 2050 Ma). For comparison, data from other studies is also shown for the Mantiqueira Complex (MC, 1 - Noce et al., 2007; 3 – Kuribara et al., 2019), the Pedra Dourada Granulite (PDG, 2 - Marinho, 2014) and Sabará Group (S, 4 – Martinez Dopico et al., 2017; Dutra et al., 2019).

8. A plot of ϵ_{Hf} vs $^{207}\text{Pb}/^{206}\text{Pb}$ age for all the samples of this study with additional data from the Mantiqueira Complex (orange field; converted from ϵ_{Nd} data of -9 to -13 of Noce et al., 2007 using Vervoort et al., 1999; blue 'x' symbols, Kuribara et al., 2019), Juiz de Fora Complex (green plus symbols; Degler et al., 2018; red 'x' symbols, Kuribara et al., 2019), Quadrilátero Ferrífero (red field; Albert et al., 2016), Sabará Group (orange dash symbols; Martinez Dopico et al., 2017) and Mineiro Belt (blue fields; Moreira et al., 2018). The vertical grey bands indicate the main magmatic (Rio das Velhas I, Rio das Velhas II, Mamona) and metamorphic events (2.1-1.8 Ga Transamazonian orogeny; Alkmim and Marshak, 1998). Analyses in grey are those that have concordia ages with less than 10% probability of concordance. Symbols used for each sample are Masc 1 – black triangles, Masc 2 – white circles, Acai 2 – black squares, Acai 3 – white triangles. The arrows indicate the Hf crustal evolution trends for average continental crust ($^{176}\text{Lu}/^{177}\text{Hf}$ of 0.0113) and average mafic crust ($^{176}\text{Lu}/^{177}\text{Hf}$ of 0.022).

9. A. Plot of the difference between the measured crystallization age for a detrital zircon grain and the age of sedimentation based on cumulative proportion curves (Cawood et al., 2012) for the four samples of this study (dashed thin black lines) and the data of all the samples merged together (thick black line). The data of Marinho (2016) is given in blue. The orange line represents data from the Sabará Group (Martinez Dopico et al., 2017; Dutra et al., 2019). B. Tectonic model for the deposition and metamorphism of the Acaiaca Complex, Pedra Dourada Granulite and Mantiqueira Complex (adapted from Cutts et al., 2018). C. Simplified geological map of the region after Giraldo et al. (2019).

A

B

A. Acai 2

B. Acai 3

C. Masc 1

D. Masc 2

A

B

C

D