The ancestry and magmatic evolution of Archaean TTG rocks of the Quadrilátero Ferrífero province, southeast Brazil

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ABSTRACT

Combined LA-ICP-MS and SHRIMP U–Pb ages from Quadrilátero Ferrífero (QF) province reveals for the first time three main periods of TTG magmatism in the southern part of the São Francisco Craton (Brazil). These periods – described here as the Santa Barbara (SB), Rio das Velhas I (RVI) and Rio das Velhas II (RVII) events – embody a significant part of a protracted tectonomagmatic history of the Craton, spanning from 3220 to 2770 Ma. The initial stages of TTG magmatism (the SB event) led to formation of a core of Palaeoarchaeoan TTG crust via magmatic additions of juvenile felsic rocks into mafic–ultramafic rocks, at ca. 3212–3210 Ma. The following event (RVI event) saw the growth of this Palaeoarchaeoan core into a more composite, polydeformed continental segment through magmatic additions of juvenile TTG rocks and tectonic accretion of mafic–ultramafic greenstone belt terrains. Our U–Pb data and regional constraints suggest that much of the TTG crust exposed in the QF region today was produced during the RVI event, between 2930 and 2900 Ma. The final stages of TTG crust production (RV II event) were marked by convergence-related magmatism, affecting an extensive Palaeo- to Mesoarchaeoan continental block (The RVI block). The timing and duration of the latest TTG event coincides with the felsic volcanism and deposition of turbiditic wackes of the main greenstone belt sequence.

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1. Introduction

The Quadrilátero Ferrífero (QF) province, in the Southern São Francisco Craton, exposes a large segment of Palaeo- to Neoproterozoic continental crust that served for many years as type locality for understanding early crustal evolution in South America (Figs. 1 and 2) (e.g., Teixeira and Figueiredo, 1991; Machado and Carneiro, 1992; Machado et al., 1992, 1996; Teixeira et al., 1996; Carneiro et al., 1997; Noce et al., 1998, 2005; Hartmann et al., 2006; Romano et al., 2013). The Archaean history of this segment spans about 600 My, and can be subdivided into two fundamentally distinct stages. The first stage, lasting more than 400 My, involved the emplacement of voluminous Tonalite–Trondjemite–Granodiorite (TTG) magmas and extrusion of mafic and ultramafic rocks between 3200 and 2770 Ma (e.g., Teixeira et al., 1996). The TTG magmatism led to the construction of a regionally extensive sialic crust containing several greenstone belt occurrences (e.g., Teixeira et al., 1996). The second stage was marked by high-grade ductile deformation, partial melting of the TTG–greenstone crust, and concomitant

emplacement of voluminous potassic granitoids between 2750 and 2600 Ma (Machado et al., 1992; Teixeira et al., 1996; Campos et al., 2003; Romano et al., 2013). This period of intra-crustal melting saw the emergence of a stable continental platform that was rigid enough to sustain the deposition of thick Palaeoproterozoic sequences, including extensive banded iron formation units of the QF mining district (Romano et al., 2013).

Specifically for the TTG rocks, limited zircon U–Pb TIMS data suggest that the main TTG magmatism was coeval with extrusion of several felsic volcanic units of the main greenstone belt (the Rio das Velhas Greenstone Belt) between 2770 and 2780 Ma (Machado et al., 1992; Noce et al., 1998). The age dataset, together with previous Sm–Nd TDM model ages, also indicate that this magmatic event involved partial melting of sialic crust older than 3000 Ma (Carneiro et al., 1997; Teixeira et al., 1996). However, U–Pb zircon age data from the earliest TTG rocks, which could provide clues to the first emergence of continental crust, have not been fully explored. The >3000 Ma ancestry of the TTG crust is mainly indicated by Rb–Sr and Pb–Pb model ages (Teixeira et al., 1996) and indirectly via detrital zircon ages from the greenstone belt rocks and overlying supracrustal sequences (Machado et al., 1992, 1996; Noce et al., 2005; Hartmann et al., 2006). The detrital age dataset is characterized by main peaks at 2700–2730 Ma, 2770–2800 Ma and 2900 Ma,

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Fig. 1. Simplified map of the Southern São Francisco Craton showing the main Palaeo- to Neoarchaean terrain and adjacent Proterozoic belts.

Fig. 2. Geological map of the Quadrilátero Ferrífero province. Previously published U–Pb ages of some relevant granitoid rocks are indicated (ages are compiled from Machado et al., 1992; Machado and Carneiro, 1992; Romano, 1989; Noce et al., 1998; Romano et al., 2013).

and a minor subset of grains recording older ages from 3200 Ma to 3800 Ma. Evidence for TTG crust older than 2780 Ma is limited to sporadic samples in the ca. 25,000 km² of the Quadrilátero Ferrífero and surrounding gneiss-granitoid terrains (Fig. 2). Significantly, changes in magmatic regime that potentially occurred in the Archaean are difficult to observe because of the complex and protracted history of these TTG rocks.

Field observations combined with high resolution zircon U–Pb age data from the TTG rocks would place important constraints on the timing of the magmatism, deformation and metamorphism in the southern part of the São Francisco Craton. This would lead to a much richer understanding of the process occurring during construction of one of the oldest segments of continental crust in South America. In this paper, a number of new SHRIMP and LA-ICP-MS zircon U–Pb ages (14 samples) are combined with published U–Pb age data to provide a comprehensive dataset for the ages of the TTG crust in the Southern part of the São Francisco Craton. We aim to constrain the ancestry and the main pulses of TTG magma production across the entire province, and to place the periods of TTG production into a broader geodynamic context that may highlight the processes of Archaean crustal growth in South America.

2. Regional geology

The stratigraphic framework of the QF comprises two main components: amphibolite-facies granitoid-gneiss complexes, and a polydeformed, low-grade supracrustal sequence. The cover succession includes Archaean rocks of the Rio das Velhas Supergroup and Palaeoproterozoic metasedimentary sequences of the Minas Supergroup and the Itacolomi Group (Dorr et al., 1957; Dorr, 1969).

The Rio das Velhas Group is subdivided into Nova Lima and Maquiné Groups (Dorr, 1969). The early work by Ladeira (1980) and Zucchetti et al. (2000a,b), Baltazar and Zucchetti (2007) attribute the onset of the Rio das Velhas to extrusion of massive komatiites to pillowed komatiitic basalts. The massive komatiites are characterized by spinifex textures, layers with cumulus olivine/intercumulus orthopyroxene and a level of lahar-type breccia (Zucchetti et al., 2000a,b). The pillowed units are intercalated with chemical carbonaceous sediments, consistent with a submarine environment for the volcanism (Schränk et al., 1990). This period of mafic volcanism and carbonate precipitation was followed by submarine deposition of pelites, banded iron formation and subordinate cherts, which are in turn capped with a volcanoclastic sequences of conglomerate-graywacke, sandstone-graywacke and pelite-graywacke. Three felsic volcanic events mark the final deposition of the Nova Lima Group at ca. 2792 ± 11, 2773 ± 7 and 2751 ± 9 Ma (Machado et al., 1992, 1996; Noce et al., 2005). Overlying the Nova Lima Group is a 2000 m thick clastic unit of marine and fluvial sediments of the Maquiné Group. According to Dorr (1969) this group comprises a flysch to molasse-type sequence, consisting of a coarsening upward succession of wackes that also became cleaner (more quartz rich) and conglomeratic towards the top. Contact relationships between the Nova Lima and Maquiné are often overprinted by fault zones, but gradational and discordant contacts have been observed (Dorr, 1969, and references therein). Although limited, the available detrital zircon U–Pb age data suggest that a continental block ranging in age from 3260 to 2877 Ma was the main source of the Maquiné sediments (e.g., Machado et al., 1996).

The Minas Supergroup was deposited over the Rio das Velhas Supergroup and the granitoid-gneiss terrain (Fig. 2). It is subdivided into the Tamanduá, Caraça, Itabira, Piracicaba and Sabará Groups (Dorr, 1969). The Tamanduá and Caraça Groups, at the base of the Supergroup, are made up of alluvial sandstones, conglomerates, and shales that grade upward into coastal marine pelites (Dorr,

1969; Renger et al., 1995; Alkmim and Martins-Neto, 2012). Zircon U–Pb detrital age data suggest that the Caraça and Tamanduá sediments derived predominantly from erosion of TTG and potassic granitoid sources and that the maximum age of deposition is ca. 2600 Ma (Machado et al., 1996; Hartmann et al., 2006). The sedimentation of the Caraça shallow-water pelites was followed by a major transgression that records a period of chemical sedimentation. This event led to the accumulation of the marker bed of the QF, the Lake Superior-type Cauê Banded Iron Formation, and was subsequently followed by the deposition of ca. 2400 Ma stromatolite-rich carbonates (Dorr, 1969; Babinski et al., 1995). The carbonates are in contact with marine sandstones and pelites of the Piracicaba Group. This unit records a similar zircon U–Pb detrital age to the Caraça Group and most probably was derived from erosion of the TTG and potassic granitoids of the QF basement (Machado et al., 1996). The stratigraphy of the Minas sequence is completed by the Sabará Group. The Sabará Group comprises a thick pile of turbidites, volcanic tuffs, and diamictites derived from much younger 2100 Ma sources (Dorr, 1969; Renger et al., 1995; Machado et al., 1996).

The Itacolomi Group is the youngest unit in the QF supracrustal sequence. The Group comprises an up to 2000 m-thick pile of alluvial sediments that is separated from the Minas Supergroup by a regional unconformity. While the Minas sedimentary rocks are portrayed as passive margin to syn-orogenic deposits that record the operation of a Wilson cycle along the southern margin of the São Francisco Craton, the Itacolomi Group is viewed as an intermontane molasse accumulated during the collapse phase of the Rhyacian orogeny (Marshak et al., 1992; Alkmim and Marshak, 1998; Alkmim and Martins-Neto, 2012).

2.1. The granitoid-gneiss complexes

The granitoid-gneiss complexes of the QF, on which this study is focused, are exposed in the core of domal structures such as the Bação, Belo Horizonte, Caeté, Santa Bárbara, and Bonfim (Fig. 2). The domes expose several phases of TTG gneisses and plutons, which are in turn intruded by voluminous sheets and bodies of potassic granitoids (Fig. 2). The TTG assemblage range from hornblende + biotite + plagioclase + quartz tonalites to plagioclase + K-feldspar + biotite + quartz granodiorites (Carneiro, 1992; Noce, 1995; Endo, 1997). These rocks record a period of high-grade metamorphism, with formation of a penetrative amphibolite-facies foliation and local development of banded/stromatic migmatites (Carneiro, 1992; Noce, 1995; Endo, 1997). This foliation underwent a complex succession of folding and refolding, which testify to the polyphase deformation history of Archaean rocks in the Southern São Francisco Craton.

Exposures of the Belo Horizonte, Bação, Bonfim and Santa Bárbara complexes show a number of different trondhjemitic phases with well-preserved intrusive relationships. Moreover, all these complexes are characterized by the presence of metre to kilometre-scale greenstone remnants that are in tectonic contact with the TTG bodies (e.g., Figs. 2 and 4). Both TTG and greenstones record similar polyphase deformation histories. The complex foliation pattern is in striking contrast with the commonly smooth, and, in most places, low metamorphic grade foliation trajectories observed in the overlying Palaeoproterozoic supracrustal sequence (e.g., Alkmim and Marshak, 1998). The gneisses are intruded by comparatively small, 2780–2770 Ma TTG plutons, which are known as the Caeté Trondhjemitic and Samambaia Tonalite (e.g., Machado and Carneiro, 1992; Machado et al., 1992), in the Caeté and Bonfim complexes respectively (Fig. 2). These younger trondhjemitic phases are less abundant and are distinguished from the older gneisses by their more massive, undeformed nature, lacking a penetrative planar fabric. Likewise, granitoids of the younger 2750–2600 Ma potassic

granitoid suite, widely distributed across Southern São Francisco Craton (Romano et al., 2013), are significantly less deformed than the TTG phases. This structural contrast between the TTG gneisses and younger granitoids is a clear indication that the tectonic climax with multiple TTG magmatism and polyphase high-grade deformation in the Southern São Francisco Craton occurred prior to 2750–2770 Ma.

Previous zircon U–Pb TIMS data indicate a range in ages from 2920 Ma to 2772 Ma for the TTG assemblage. Early zircon U–Pb TIMS work by Machado and Carneiro (1992) in the Bonfim TTG gneisses identified two subconcordant zircon populations with apparent ages of ca. 2920 Ma and 2770 Ma. Noce et al. (1998) obtained a zircon U–Pb upper concordia intercept TIMS age of 2860 ± 14 Ma from a migmatite in the Belo Horizonte dome. This intercept age was interpreted to reflect the timing of the oldest yet recognized high-grade metamorphism and partial melting of >2900 Ma TTG crust. However, this age was based on a limited number of highly discordant grains (Fig. 2). The only two ages that were substantially accurate and precise were obtained from the 2772–2778 Ma Caeté and Samambaia granitoids. These ages overlap within error with ages from the volcanic rocks in the Archaean supracrustal sequence of the QF (Machado et al., 1992; Noce et al., 2005).

The Archaean TTG rocks were subsequently intruded by numerous 2750 and 2700 Ma potassic granitoids that form km-scale batholiths or thick granitoid sheets around the margins or in the interior of the complexes (Figs. 2 and 3). Recent zircon U–Pb age data indicates that this granitoid event marked the stabilization of the TTG crust and the development of a rigid cratonic nucleus (The Southern São Francisco Craton – Fig. 1) that supported the development of the supracrustal rocks of the QF. Outside this Archaean block, the crystalline and supracrustal rocks to the south and east of the QF were affected by two Proterozoic orogenic systems. For instance, the southern margin of QF (Fig. 1) is bounded by a km-wide, arcuate corridor of high-grade, polydeformed Archaean TTG rocks, elongated greenstone belt remnants and numerous 2300–2000 Ma granitoids phases (Teixeira and Figueiredo, 1991; Alkmim and Marshak, 1998; Machado et al., 1996; Teixeira et al., 1996, 2000; Noce, 1995; Teixeira et al., 2008). Known as the Mineiro Belt, this corridor developed as a consequence of plate convergence and collision along the margin of the Archaean core of the São Francisco Craton during the 2100 Ma Transamazonian event. Similarly, the eastern margin of the province was affected by the 600–500 Ma Araçuá orogeny (Almeida et al., 1981; Pedrosa-Soares et al., 2001; Alkmim et al., 2006), during the assembly of West Gondwana by the end of the Neoproterozoic (the Brasiliano event).

3. Geochronology

In order to record the full spectrum of the TTG magmatic events in the southern part of the São Francisco Craton, we collected 14 samples from the main crystalline complexes around the Quadrilátero Ferrífero area, including the Belo Horizonte, Bação, Bonfim and Santa Bárbara complexes as well as one TTG sample from the Mineiro Belt. The selection of a large number of samples is justified because it was not always possible to correlate the various TTG units based on field relationships, mineralogy and petrography. Thus, the sampling protocol was aimed at obtaining a substantial amount of U–Pb age data (of the magmatic phases) over an extensive area of TTG crust.

The TTG samples contained zircon grains that range from slightly hazy to milky and opaque (Fig. 3). Such characteristics are usually attributable to zones of high uranium that have undergone alteration. According to Machado et al. (1992) and Machado and Carneiro (1992), zircons from the TTG rocks in the QF are largely

altered and rich in mineral inclusions (Fe-oxides). The white to milky grains are observed in both magnetic and non-magnetic fractions, but non-magnetic fractions yielded subfractions that were somewhat translucent to partly translucent grains. A close inspection of the partly translucent grains revealed that the cores were usually better preserved than the rims. Machado et al. (1992) also observed that the majority of the milky white grains were fragile and would disintegrate instantly during air abrasion. This is likely a result of intense chemical weathering and leaching of the U-rich areas within the grains. Likewise, our previous experience with these zircons (e.g., Romano et al., 2013) shows that the milky white grains did not cope well with the laser (during the ablations), because of their poorly preserved crystalline structure (i.e., most of these grains were quickly pulverized and yielded unreliable U–Pb data).

In this study, only the translucent and partly translucent grains were selected for SHRIMP and LA-ICP-MS analysis. The SHRIMP and LA-ICP-MS analysis were carried out at the Australian National University and Universidade Federal de Ouro Preto, respectively. See Appendix for details on the methodology and instrumentation. The results of the SHRIMP and LA-ICP-MS analyses of samples and secondary standards can be found in Electronic Supplement. The LA-ICP-MS and SHRIMP data were reduced using the ISO-PLLOT/SQUID program (Ludwig, 2001a,b) with ages calculated and plotted on Concordia diagrams using the IsoplotEx 2.46 program. Uncertainties given for individual analyses (ratios and ages) are at the 1 sigma level. All uncertainties in the calculated intercept or Concordia ages are reported at 2 sigma confidence limits, unless stated otherwise. For the probability density diagrams and histograms, the Age Display set of Excel™ macros were used (Sircombe, 2004).

3.1. Results

3.1.1. Bação complex

Located in the central part of the QF (Fig. 2), the 25 km-wide Bação dome exposes a crystalline complex that predominantly consists of potassic granitoids and TTG rocks. A number of greenschist-to amphibolite-facies greenstone belt remnants are found in the eastern portion of the dome (Fig. 4a). The TTG rocks are especially well exposed on the periphery of the dome, and are characterized by the alternation of trondhjemitic and tonalitic bands. Locally, these bands are crosscut by potassic granitoid sheets that are intruded predominantly parallel or subparallel to the gneissosity. Previous studies have dated two samples of potassic granitoids at 2744 ± 10 Ma and 2717 ± 5 Ma (Fig. 4a), consistent with the main potassic magmatic episodes between 2700 Ma and 2750 Ma (Romano et al., 2013). In this study, we obtained ages of eight samples of TTG's spread across the dome (Samples D04, D06, D7A, D7B, MP-1, SG-1, SG-2 and D12). Refer to Electronic Supplements for results of individual SHRIMP and LA-ICP-MS analyses.

Sample D06 (UTM: 628831/7748456) was extracted from a banded trondhjemitic, exposed along railway cuttings in the south-central part of the Bação dome, a few kilometres from Engenheiro Correia (Fig. 4a). The rock displays a strong vertical foliation defined by biotite and quartz aggregates, and mm-wide leucocratic (plagioclase + quartz) bands (Fig. 4b). Locally, the foliation is accentuated by elongated (cm-long) biotite-amphibolite enclaves. Zircons from this sample are generally stubby, with round terminations and range in colour from light to dark brown. CL-images reveal complex internal structures with rather bright cores surrounded by dark, structureless overgrowths. The zircon cores are generally round, show resorbed rims, and preserve some oscillatory zoning (Fig. 3). SHRIMP analyses on eight of these cores gave concordant to subconcordant points (1–8% discordant) with apparent ages of ca. 2900 Ma. A regression through these points define a Pb-loss Discordia with

Fig. 3. Cathodoluminescence images of zircons analyzed in this study.

an upper intercept age of 2925 ± 8 Ma (MSWD = 0.67) (Fig. 5a). This age is interpreted as the crystallization age of the sample. Three other analyses on fairly altered cores gave discordant points with large internal errors – these analyses were discarded. Analyses of the structureless dark overgrowths gave points with rather younger apparent ages than those in the magmatic cores. They were also marked by low Th/U ratios, which could characterize them as metamorphic overgrowths or recrystallization domains. They define a Pb-loss Discordia line with a lower intercept of 429 ± 15 Ma and upper intercept of 2794 ± 15 Ma (MSWD = 3.1) (Fig. 5a).

Sample MP-1 (UTM: 622543/7747051) comes from a trondhjemitic gneiss that is exposed in the southwestern periphery of the dome, near Mata Porcos stream (Fig. 4a). This rock records a strong vertical gneissosity defined by oriented biotite and cm-wide

leucocratic bands. Locally, the gneiss is intruded by undeformed, layer-parallel leucogranite bands (Fig. 4c). Similar to Sample D06, this sample contained zircons that are round to stubby, with round terminations and range in colour from light pink to brown. They have concentrically zoned, CL-bright cores surrounded by dark structureless rims. The cores range from round to irregular and may show resorbed rims (Fig. 3). LA-IPM-MS analyses of the least altered cores gave concordant to highly discordant points that plot along a Pb-loss line with upper intercept age of 2903 ± 12 Ma (MSWD = 3.2). The structureless rims were relatively more altered relative to the core. A large number of spot analyses on the altered, milky white rims yielded unreliable U–Pb ratios (due to discordancy) were discarded. Only seven of these points, placed on somewhat pristine areas of the grains, gave a Discordia line with an

Fig. 4. (a) Simplified geological map of the Bação dome showing localities and ages (white boxes) of TTG samples investigated in this study. The ages in grey boxes are from two samples of potassic granitoids dated by Romano et al. (2013). (b) Field photograph of the Engenheiro Correia banded gneiss (D06; Eng. Correia), showing gneissosity and cm-wide leucocratic bands. (c) Detailed image from the foliated trondhjemite in the southwestern periphery of the dome (MP-1; Mata Porcos). The gneiss is intruded by foliation-parallel leucogranite sheets. (d) Representative image of the banded trondhjemite sampled in the Serrinha Quarry (D07; Serrinha), western margin of the dome. (e) Detailed image of amphibolite collected near São Gonçalo town (SG1; São Gonçalo). Note the amphibolite is cross cut by leucogranite sheets. (f) Representative image of the trondhjemitic gneiss exposed in the southeastern part of dome (D04; Cachoeira do Campo). All ages are shown in (a) are interpreted as crystallization ages; otherwise labelled as (M) for metamorphic age.

upper concordia intercept age of 2770 ± 29 Ma (MSWD = 4.2). This age is identical (within error) to the metamorphic age obtained for the Engenheiro Correia gneiss (Sample D06). We suggest that this sample crystallized at 2903 ± 12 Ma and experienced a metamorphic event at 2770 ± 29 Ma.

Samples D07A and D07B (UTM: 620152/7749497) were collected in a quarry outcrop (Serrinha Quarry) in the southwestern portion of the Bação dome (Fig. 4a). The quarry exposes strongly banded, light coloured trondhjemite gneiss that records a vertical compositional banding (Fig. 4d). Both biotite and plagioclase-rich bands are locally intruded by numerous leucogranite sheets that vary in width from several millimetres to a few metres. Sample D07A was extracted from a homogenous trondhjemite gneiss, which is interpreted to be oldest phase of the TTG gneiss in this quarry. Zircons from this sample are prismatic to stubby, with round terminations, ranging in length from 100 to 200 μm . CL-images reveal complex core and rim structures (Fig. 3). Most grains show irregular cores, surrounded by dark or bright structureless rims. SHRIMP spot analyses on twelve of the cores gave subconcordant to concordant points, plotting along a Pb-loss Discordia that

intercepts the upper concordia at 2918 ± 9 Ma (MSWD = 1.6) (Fig. 5c). Twelve analyses on the structureless rims gave very discordant points, with substantially younger apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages of ca. 2600–2780 Ma. A regression line through these analyses intercept the Concordia at 661 ± 110 Ma and 2775 ± 39 Ma (MSWD = 8.8) (Fig. 5c). Our interpretation is that this rock crystallized at ca. 2918 ± 10 Ma and was metamorphosed at around 2775 Ma.

Sample D07B was extracted from a 50 cm wide medium-grained, leucocratic band of the TTG gneiss. This band crosscuts the trondhjemite gneiss, but locally it is intruded parallel to the main foliation. Zircons from this sample are prismatic, ranging in length from 50 to 200 μm . CL-images reveal internal oscillatory zoning (Fig. 3). A few grains showed complex, structureless cores surrounded by oscillatory rims. SHRIMP analyses on the oscillatory overgrowth grains gave apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 2600 and 2800 Ma. Thirteen of the most concordant to subconcordant points give a precise $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2774 ± 11 Ma (MSWD = 3.2) (Fig. 5d). We suggest that this age is the best approximation of the crystallization age of the sample. Two analyses on cores of these

Fig. 5. U–Pb Concordia diagrams of SHRIMP and LA-ICP-MS analyses from TTG gneisses from the Bação Complex, Southern São Francisco Craton.

grains were concordant to sub-concordant and gave a $^{207}\text{Pb}/^{206}\text{Pb}$ mean age of 2931 ± 12 Ma (MSWD = 3.0). We interpret these cores as inherited, most likely from the host TTG gneiss.

Sample SG-1 (UTM: 625589/7755071) comes from an amphibolite intrusion near São Gonçalo town (Fig. 4a and e). The host TTG rock is compositionally similar to the banded gneisses sampled

previously. Both TTG gneiss and amphibolite are strongly foliated and are crosscut by numerous phases of potassic granitoid sheets (Fig. 4e). Sample SG-1 contained a number of translucent grains with well-defined oscillatory zoning in CL images (Fig. 3). The grains were less complex than the ones described above: except for a couple of grains that contained zoned cores with resorbed

terminations. Two analyses on the cores were fairly discordant with apparent ages of 2894 ± 21 Ma and 2903 ± 22 Ma (Fig. 5e). Thirteen analyses on the other zoned grains gave a well-defined concordia age of 2778 ± 8 Ma (MSWD = 0.73) (Fig. 5e). Sample SG-2 comes from the cross cutting potassic granitoid sheet. This rock consists dominantly of plagioclase, quartz, K-feldspar and biotite, similar in many aspects to the vertical sheets described in Romano et al. (2013). The zircons were translucent to partly translucent and showed well-defined oscillatory zoning in CL images. Twenty points in these grains define a Pb-loss regression which intercept the Concordia at 609 ± 130 Ma and 2730 ± 7 Ma (MSWD = 2.2) (Fig. 5f). The older age (upper intercept) is identical to several samples of potassic granitoids (see Romano et al., 2013 and references therein) and is here interpreted as the crystallization age of the sample.

Sample D12 (UTM: 0625664/7762166) represents a large body of weakly foliated granodiorite that is exposed a few kms away from the northern border of the dome, to the northwest of the Itabirito town (Fig. 4a). This sample yielded milky white, heavily fractured zircons, ranging in size from 80 to 300 μ m. CL-images show well-zoned internal structures, rimmed by structureless dark rims (Fig. 3). SHRIMP analyses show that the rims are richer in U relative to the zoned cores (Th/U < 0.2), and yielded the most discordant results. No reliable age data was obtained from these rims. Nine analyses on the zoned cores yielded concordant to subconcordant results that defined a Pb-Discordia with an upper intercept age of 2764 ± 10 Ma (MSWD = 0.9) (Fig. 5g). This age is slightly younger than the previous crystallization ages, but it overlaps (within error) with the 2774 ± 11 Ma age obtained for Sample D07A (Fig. 5c), from the Serrinha Quarry, southwest of Itabirito. It is interpreted as the crystallization age of the sample.

Sample D04 (UTM: 0637825/7750333) was collected from a quarry outcrop in the southeastern sector of the Bação dome, a few kilometres from the town Cachoeira do Campo (Fig. 4a). It represents a banded trondhjemitic gneiss, characterized by vertical, mm- to cm-wide leucocratic and mesocratic bands. The mesocratic bands are rich in plagioclase and biotite, whereas the leucocratic bands contain predominantly plagioclase, quartz and minor microcline. The gneiss is locally cross-cut by subvertical sheets of potassic granitoids that are intruded subparallel to the gneiss vertical banding (Fig. 4f). This sample yielded a number of milky white to dark brown zircons that are of poor quality for U–Pb dating. Totally altered, milky white grains were discarded. The remaining 10–15% of the separate contained subhedral to anhedral, partly translucent zircons, with broad zones of intense alteration and radiation damage. The least altered zircon grains or areas within grains were targeted for analysis. Twenty SHRIMP analyses gave a poorly constrained Pb-loss Discordia regression line due to severe Pb-loss disturbance (highly discordant points). No intercept age was attempted. Five of these points are, however, concordant or near-concordant (>96%) to give confidence in a $^{207}\text{Pb}/^{206}\text{Pb}$ age calculated from these selected data. A $^{207}\text{Pb}/^{206}\text{Pb}$ weighted mean age of 2795 ± 7 Ma (MSWD = 0.92) was obtained for these datapoints (Fig. 5h). This 2795 ± 7 Ma age is interpreted as the crystallization age of the sample.

3.1.2. Belo Horizonte Complex

The Belo Horizonte Complex corresponds to the largest segment of TTG crust in the study area (Fig. 6a). It was initially investigated by Machado et al. (1992) and Noce (1995). The majority of the exposures consist of strongly banded gneisses (Fig. 6b and c) with dominant amphibolite-facies foliation. Two main trondhjemitic phases that record a strong solid state foliation occur along the southeastern margin of the domal structure. The dominant phase is a fine-grained trondhjemitic consisting of plagioclase, biotite, quartz and minor microcline (Fig. 6d). The penetrative fabric is

mainly defined by the preferred orientation of biotite and stretched plagioclase. This fine-grained phase alternates with a porphyritic trondhjemitic that contains a similar mineralogy but with cm-size, strongly stretched plagioclase porphyroclasts. The only sample previously dated from this complex comes from the central part of the structure (Noce, 1995; Noce et al., 1998). These authors obtained a TIMS zircon U–Pb upper intercept age of 2860 ± 14 Ma from a migmatite. However, this age was obtained from fairly discordant grains, due to the strong metamict nature of the zircons.

We have attempted to date the banded gneiss (Sample D14) in the central part of the Belo Horizonte dome and the trondhjemitic phases in the southeast: the fine-grained (sample CO-1) and coarse-grained (Sample CO-2) phases. However, sample CO-2 yielded only milky white grains that gave very poor U–Pb age data. No data reduction was attempted. Likewise, sample CO-2 (UTM: 662232/7758014) contains a large number of short prismatic zircons with structureless cores (Fig. 3), surrounded by zoned rims. LA-ICP-MS analyses on the cores gave unreliable U–Pb data, with high U concentrations – these analyses were discarded. Data obtained from the magmatic rims were substantially more consistent, with 12 points plotting around a Pb-loss Discordia that intercepts the concordia at ca. 700 Ma and 2900 Ma. Two points were identified as an outlier from this group, with a significantly lower $^{207}\text{Pb}/^{206}\text{Pb}$ ratios. As these points were sited side-by-side within the same zircon, this discrepancy is attributed to local heterogeneity resulting from variable early radiogenic Pb-loss. Ten other points define a Pb-loss cord that intercepts the Concordia at 747 ± 150 Ma and 2919 ± 12 Ma (MSWD = 2.3) (Fig. 7a). We interpret the 2919 ± 12 Ma age as the crystallization age of the sample.

Sample D14 (UTM: 0592565/7792672) represents a banded gneiss from the western parts of the Belo Horizonte dome, well exposed on a road cut a few km from Betim (Fig. 6c). This gneiss is intruded by several vertical sheets of potassic granitoids. The sample contains milky white to dark brown zircons, which vary from prismatic to slightly stubby, all with round terminations. The grains are predominately dark in CL images due to high U content (Fig. 3). Some bright complex cores are observed but the relationship with the overgrowth is difficult to constrain. SHRIMP spot analyses in the cores seem to indicate one single population that crystallized at around 2800 Ma. The data points are dispersed along a line which does not pass through the origin but has a lower intersection with the Concordia curve at approximately 500 Ma. Eight of the most concordant data points have $^{207}\text{Pb}/^{206}\text{Pb}$ ages, which are identical within error, and give $^{207}\text{Pb}/^{206}\text{Pb}$ weighted mean age of 2783 ± 23 Ma (MSWD = 2.9) (Fig. 7b). This age is identical to three other Rb/Sr ages of 2803 ± 80 Ma, 2790 ± 90 Ma and 2798 ± 73 Ma obtained for TTG gneiss in the same area (western part of the dome) (Teixeira et al., 1996). We interpret the 2783 ± 23 Ma age as the best estimate of the crystallization age for this sample. Two concordant/subconcordant points that were too young relative to the main 2783 Ma population gave a $^{207}\text{Pb}/^{206}\text{Pb}$ weighted mean age of 2716 ± 9 Ma, which is rather close to the ages obtained for the potassic granitoids (Romano et al., 2013). However, these two points came from one grain, which is compositionally distinct from the rest of the population. We believe that this is a case of sample contamination, given the banded nature of this rock, or a result of authigenic growth during emplacement of the potassic granitoids.

3.1.3. Bonfim Complex

The Bonfim Complex comprises the second largest segment of TTG crust in the Southern São Francisco Craton (Fig. 6a). The Bonfim dome exposes TTG gneisses in the core and a thick sheet of potassic granitoids on its periphery (Romano et al., 2013). The basement gneisses record a N–S trending, subvertical foliation that is marked by complex, polyphase history of folding. This gneissosity is cross-cut by the 2780 Ma Samambaia tonalite (Machado and Carneiro,

Fig. 6. (a) Sample localities and ages of TTG rocks dated in this study. (b), (c) Representative images of the banded TTG gneiss from the western and southwestern part of the Belo Horizonte dome. (d) Detailed image of the foliated fine-grained and coarse-grained (porphyritic) gneisses of the Belo Horizonte Complex, exposed near Cocaís town (CO-1; Cocaís). (e) Banded trondhjemite from the northern part of the Bonfim dome (D11; Brumadinho). (f) Detailed image of the TTG samples in the southern part of the Santa Bárbara dome (CAM-1 and CAM-2). All ages are shown in (a) are interpreted as crystallization ages; otherwise labelled as (M) for metamorphic age and (In) for inherited.

1992) and numerous phases of vertical potassic granitoid bodies. Zircon U–Pb age data from Machado and Carneiro (1992), Noce (1995) and Romano et al. (2013) indicate that almost all potassic granitoid phases range in age from 2700 to 2730 Ma, except for two small occurrences that seemingly record an age of 2614–2615 Ma.

Sample D11 (UTM: 0588164/7770431) represents a banded tonalitic gneiss exposed along a road cut in the northern sector of the complex, a few kilometres south of a large batholith of potassic granitoid (Fig. 6a). The gneiss records strong subvertical foliation that is intruded by multiple foliation-parallel leucocratic sheets. As shown in Fig. 6e, the gneiss foliation is represented by aligned biotite and amphibole crystals as well as elongated quartz + plagioclase pods of potassic granitoid melt. Zircons from the sample are prismatic with round terminations. They range in colour from milky white to light brown. Partly transparent zircons (~10% of the fraction) record well-defined oscillatory zones, typical of magmatic zircons, which in turn are truncated by thin bright overgrowths. Fifteen SHRIMP U–Pb analyses on the magmatic zones of these zircons gave a Pb-loss Discordia line that

intercepts the Concordia at 537 ± 55 Ma and 2895 ± 13 Ma (MSWD = 1.9) (Fig. 7c). We interpret this age as the crystallization age of the sample. Analyses on the rims gave significantly younger ages and slightly lower Th/U ratios. These analyses define a Discordia line that intercepts the Concordia at 479 ± 25 Ma and 2749 ± 10 Ma (MSWD = 1.0). This age is within error of the age of the potassic granitoids, and reflects the crystallization of the foliation-parallel leucogranite sheets (Fig. 6e).

3.1.4. Santa Bárbara Complex

The Santa Bárbara dome in the eastern part of the QF (Fig. 6a) is the only segment of TTG crust that has not been mapped in detail. One of only a few outcrop localities in the dome exposes two phases of strongly foliated, locally banded TTG gneiss (Fig. 6f). One phase is coarse-grained, light grey that intrudes a rather fine-grained, biotite-rich trondhjemite phase (Fig. 6a). The two phases were sampled (Samples CAM-1 and CAM-2; UTM: 625589/7755071). Both contained very similar looking grains with well-preserved magmatic zoning (Fig. 3). They are euhedral, rather ellipsoidal in shape,

Fig. 7. U–Pb Concordia diagrams of SHRIMP and LA-ICP-MS analyses from TTG gneisses from the Belo Horizonte, Bonfim and Santa Bárbara complexes, Southern São Francisco Craton, and one sample from the reworked basement from the Mineiro Belt.

multi-faceted and strongly zoned. No clear core-rim structure was observed. Thirty-one LA-ICP-MS analyses on the centre and border of zircons from Sample CAM-1 seem to represent one single population. These points define a Pb-loss Discordia line that intercepts

upper Concordia at circa 3200 Ma. Twenty-three of these grains gave a concordia age of 3210 ± 8 Ma (MSWD = 0.95) (Fig. 7d). Sample CAM-2 yielded similar results. Thirty-five grains were analyzed via LA-ICP-MS. The analyses define a Discordia regression line that

intercepts the upper Concordia at ca. 3210 Ma. Nineteen concordant grains gave a concordia age of 3212 ± 9 Ma (MSWD = 0.84) (Fig. 7e). These ages indicate that these phases were co-magmatic and that they crystallized between 3210 and 3212 Ma.

3.1.5. Reworked basement of the Mineiro Belt

The Mineiro Belt evolved as a marginal belt to the southern end of the Archaean nucleus of the São Francisco Craton. To the south of the Quadrilátero Ferrífero, the belt includes a large area of reworked Archaean TTG and potassic granitoid rocks that is largely intruded by several 2300–2100 Ma Palaeoproterozoic granitoid plutons and mafic bodies, also with <2100 Ma supracrustal sequences present (Fig. 1) (Teixeira and Figueiredo, 1991; Teixeira et al., 2000; Noce et al., 2007; Seixas et al., 2012).

One sample of a coarse-grained massive trondhjemite (Sample D09; Fig. 6a; UTM: 0639642/7730692), located a few hundreds of metres from the contact with the greenstone belt/supracrustal rocks of the QF (Serra de Ouro Branco; Fig. 6a), was chosen as representative of the reworked basement rocks of the Mineiro Belt. This sample yielded translucent to partly translucent grains, many of which were coated with a few μm -width rims of alteration. CL-images show structureless, bright cores surrounded by CL-bright overgrowths. Four spot analyses on the cores gave apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages ranging from 3211 to 2846 Ma. They define a Pb-loss Discordia that intercepts the upper Concordia at 3219 ± 13 Ma (MSWD = 1.09) (Fig. 7f). Spot analyses on the overgrowths gave significantly younger ages, and define a regression line that passes through the Concordia at 2898 ± 7 Ma (MSWD = 1.4). We interpret this age the crystallization age.

4. Summary

Previous studies have made a case that the TTG crust in and around the Quadrilátero Ferrífero experienced a complex polyphase magmatic evolution prior to the emplacement of km-scale batholiths of potassic granitoids (see also, Machado and Carneiro, 1992; Machado et al., 1996; Teixeira et al., 1996; Carneiro et al., 1997; Noce et al., 1998, 2005). In contrast to the rather undeformed nature of the potassic granitoids, the TTG rocks record field evidence of multiple stages of magmatic intrusion (Carneiro et al., 1997; Noce et al., 1998) and a complex pattern of amphibolite-facies foliation. After careful examination of the zircon morphology and internal structures we were able to obtain by SHRIMP and LA-ICP-MS methods a concise U–Pb age dataset for 14 samples. When combined with previously published zircon U–Pb age data, the results indicate a protracted magmatic evolution for the TTG crust (Table 1), with at least three main periods of TTG magmatism and one metamorphic event (Table 1). The magmatic events are hereafter referred to as the Santa Bárbara (3220–3200 Ma), Rio das Velhas I (RV I, 2930–2900 Ma) and Rio das Velhas II (RV II, 2800–2770 Ma) events (Table 1).

The Santa Bárbara event is marked by the emplacement of the 3212 ± 9 and 3210 ± 8 Ma TTG rocks in the SB complex and the 3219 Ma rock in the Mineiro Belt (Fig. 6). Although these rocks are the only direct evidence of Palaeoarchaeoan crustal evolution in the area, Sm–Nd model ages from the TTG rocks (Teixeira et al., 1996) and detrital zircons from the main greenstone belt (see Machado et al., 1992, 1996) may indicate the existence of other fragments of Palaeoarchaeoan TTG crust in the province. For instance, a compilation of the detrital zircon dataset from Machado et al. (1996) and Hartmann et al. (2006) shows a large number of Palaeoarchaeoan detrital grains, defining a spectrum from 3600 to 3000 Ma (Fig. 8). Zircon separates from the Minas and Rio das Velhas clastic sediments yielded more than 30 grains ranging in age from 3250 to

3200 Ma. This compilation suggests that older sources >3300 Ma may have existed prior to the deposition of the Minas Basin.

The Rio das Velhas I (RV I) event is represented by the 2930–2900 Ma TTG gneisses exposed in Bação, Belo Horizonte, and Bonfim domes as well as in the Mineiro Belt (Table 1). The widespread distribution of the ca. 2900 Ma rocks (Figs. 4 and 6), together with the inherited ages in TTG rocks that crystallized at ca. 2700 Ma (RV II event: Table 1), indicate that much of the Southern São Francisco crust was already formed by 2900 Ma. Likewise, the detrital zircon dataset is particularly marked by a large number of ca. 2900 Ma grains, confirming the widespread preservation of the RV II TTG crust at the time of accumulation of the Rio das Velhas and Minas clastic sediments.

The Rio das Velhas II event took place between 2800 Ma and 2760 Ma. Six samples of TTG gneisses from the Caeté, Bação, Bonfim and Belo Horizonte complexes (Figs. 4 and 6), and one amphibolite sample from the Bação dome record crystallization ages that fall within this range (Table 1). Significantly, many of the rocks of the RV I record metamorphic ages that overlap (within error) with the magmatic ages of the RV II. We suggest that the entire crust around the QF was affected by magmatism and amphibolite-facies metamorphism at 2770–2800 Ma. The widespread occurrence of RVII ages in the QF is consistent with a magmatic event of similar magnitude to the RV I event.

5. Implications for Archaean crustal development

The generation of Archaean TTG rocks is a matter of a long standing debate. Geochemical evidence support the view that Archaean TTG assemblages form in arc settings, being thus ancient equivalents of modern subduction-related magmatic assemblages (e.g., Martin, 1993; Smithies et al., 2003, 2005; Rapp et al., 2003; Moyen et al., 2007; Foley et al., 2002). Considering the differences in the geochemical signatures of Archaean TTG suites and post-Archaean arc-related granitoids, several authors postulate that TTG magmas were generated through the melting of subducting oceanic slabs (e.g., Martin, 1999; Rapp et al., 2003). Alternatively, Archaean TTG suites are also viewed as a product of delamination of the base of oceanic plateaus (Bédard, 2006), i.e., not related to consumption of the oceanic lithosphere. Likewise, different models have been proposed for the generation of Archaean greenstone belt successions and their juxtaposition with the TTG crust. For instance, in the models that predict TTG generation through subduction-related magmatism, the greenstone belts are invariably interpreted as intra-oceanic thrust belts (oceanic terranes), sandwiched between the TTG-dominated sialic blocks (e.g., De Ronde and De Wit, 1994; De Wit, 1998; Percival et al., 2001; Windley and Garde, 2009). Although the modes of tectonic accretion remain unclear, evidence exists that blocks with different geological histories have amalgamated to form a number of Archaean granite-greenstone terrains (Nutman et al., 1989, 2002; Kusky and Polat, 1999; Percival et al., 1994, 2001; Smithies et al., 2003, 2005; Windley and Garde, 2009; Stott and Mueller, 2009; Lana et al., 2010a,b, 2011).

Terrains like the Barberton Terrain in South Africa (Anhaeusser, 1969, 1984; Armstrong et al., 1990) seem to include relatively small continental blocks that were amalgamated at some point in the Archaean (Armstrong et al., 1990; De Ronde and De Wit, 1994; Lowe, 1994; Kroner et al., 1996; De Wit, 1998; Kisters et al., 2010). Sedimentological features, structure, and age data variations across the Barberton Greenstone Belt, indicated to previous workers the presence of at least two distinct terranes separated by a major tectonic discontinuity (Armstrong et al., 1990; De Wit et al., 1992; De Ronde and De Wit, 1994; De Ronde and Kamo, 2000; Lowe, 1994). Significantly, in the Barberton setting the isotopic signatures of syntectonic TTG intrusives are invariably in favour of emplacement

Table 1
Summary of ages for TTG rocks in the Southern São Francisco Craton.

Sample	Rock type		Method	Inherited age	Crystallization age	Metamorphic age	References
3200–3220 Ma magmatic/volcanic event							
CAM-1	Cachoeira camargo Trondhjemitic gneiss	Santa Barbara	LA-ICP-MS		3210 ± 8 Ma (MSWD = 0.95)		This study
CAM-2	Cachoeira camargo Trondhjemitic gneiss	Santa Barbara	LA-ICP-MS		3212 ± 9 Ma (MSWD = 0.84)		This study
2900–2930 Ma magmatic/volcanic event							
D06	Eng. Correia Banded trondhjemite	Baço	SHRIMP		2925 ± 8 Ma (MSWD = 0.67)	2794 ± 15 Ma (MSWD = 3.1)	This study
MP-1	Eng. Correia Trondhjemite band	Baço	LA-ICP-MS		2902 ± 12 Ma (MSWD = 3.2)	2770 ± 29 Ma (MSWD = 4.2)	This study
	Alberto Flores Gneiss Banded trondhjemite	Bonfim	TIMS		2920 ± 5 Ma	2772 ± 6 Ma	Machado and Carneiro (1992)
D07A	Serrinha Trondhjemite band	Baço	SHRIMP		2918 ± 10 Ma (MSWD = 1.6)	2775 ± 39 (MSWD = 8.8)	This study
D11	Brumadinho Banded trondhjemite	Bonfim	SHRIMP		2895 ± 13 Ma (MSWD = 1.9)	2749 ± 10 Ma (MSWD = 1.0)	This study
D09	Serra de Ouro Branco Trondhjemite	Mineiro Belt	SHRIMP	3219 ± 13 Ma (MSWD = 1.09)	2898 ± 7 Ma (MSWD = 1.4)		This study
CO-1	Cocais Foliated trondhjemite	Belo Horizonte	LA-ICP-MS	3258 ± 14 Ma	2919 ± 12 Ma (MSWD = 2.3)		This study
2760–2800 Ma magmatic event							
D07B	Caete Trondhjemite gneiss	Caete	TIMS		2776 ± 6 Ma		Machado et al. (1992)
	Serrinha Leucocratic band	Baço	SHRIMP	2931 ± 12 Ma (MSWD = 3.0)	2774 ± 11 Ma (MSWD = 3.2)		This study
SG-1	São Gonçalo Amphibolite	Baço	LA-ICP-MS	>2903 ± 22	2800 ± 8 Ma (MSWD = 0.73)		This study
D12	Itabirito Granodiorite	Baço	SHRIMP		2764 ± 10 Ma (MSWD = 0.9)		This study
D04	Caixoeira do Campo Trondhjemite gneiss	Baço	SHRIMP		2795 ± 7 Ma (MSWD = 0.92)		This study
D14	Betin Banded Gneiss	Belo Horizonte	SHRIMP		2783 ± 23 Ma (MSWD = 2.9)		This study
	Samambaia Tonalite	Bonfim	TIMS		2778 ± 3 Ma		Machado and Carneiro (1992)
2750–2800 Ma volcanic event in the Rio das Velhas Greenstone Belt							
FR-38	Rio das Velhas Group Volcanic rocks	Supracrustals	TIMS	2883 ± 6 Ma	2776 ± 26 Ma		Machado et al. (1992)
	Rio das Velhas Group Volcanic rocks	Supracrustals	SHRIMP	>3000 Ma	2792 ± 11 Ma		Noce et al. (2005)
MZ-53	Rio das Velhas Group Volcanic rocks	Supracrustals	TIMS	2928 ± 14 Ma	2751 ± 11 Ma		Noce et al. (2005)
SS-144	Rio das Velhas Group Volcanic rocks	Supracrustals	TIMS	3035 ± 5 Ma	2777 ± 7 Ma		Noce et al. (2005)

Fig. 8. Detrital zircon ages compiled for the supracrustal rocks of the Quadrilátero Ferrífero (Includes Rio das Velhas and Minas Supergroups; see Machado et al., 1996; Hartmann et al., 2006). Data for the Itacolomi and Sabara Groups are not included. The main peaks correspond to the magmatic ages recorded in the magmatic events in and around the QF province. The magmatism is subdivided into Santa Bárbara, Rio das Velhas and Potassic Granitoid event. See discussion for details.

in continental arc settings prior or during terrain amalgamation (Schoene et al., 2008, 2009).

The Quadrilátero Ferrífero province constitutes an area equivalent or slightly smaller than that occupied by the Barberton Terrain. Features recorded in the Rio das Velhas greenstone belt are consistent with intra-oceanic mafic–ultramafic magmatism, responsible

for development of pillowed basaltic lavas, and their intercalation with carbonate and banded iron formation sediments (e.g., Ladeira, 1980; Zucchetti et al., 2000a,b; Baltazar and Zucchetti, 2007). However, in contrast to other greenstone belt provinces, blocks with distinct tectonomagmatic histories cannot be identified judging the fact that the granitoid-gneiss complexes (e.g., Bação,

Fig. 9. A simplified model for the generation of Archaean TTG crust during the RVI and RVII events in the QF region. In this model we propose that the Santa Barbara complex represents a relic of a much wider segment of Palaeoarchaeon TTG crust in the region. (A–B) This segment grew through magmatic and tectonic addition of TTG felsic magmas and tectonic accretion of greenstone belt material. (C) The TTG production resulted from partial melting at the base of the RV I crust with high-grade metamorphism and emplacement of the RV II granitoids between 2770 and 2800 Ma. This model also accounts for the sedimentation of the clastic sediments and emplacement of the volcanic rocks in the Rio das Velhas Greenstone Belt.

Belo Horizonte, Bonfim) record identical magmatic events: they were affected by both RVI and RV II TTG events.

Our zircon U–Pb data shows that the magmatic evolution of the TTG crust began as early as 3200 Ma with the emplacement of the 3210 Ma Santa Bárbara TTG rocks (samples CAM-1 and CAM-2) and a reworked granitoid in the Mineiro Belt (sample D9). We observed that 3250–3200 Ma zircons occur as inherited components in a limited number of samples, but they represent a significant subset in the detrital spectra of the greenstone belt clastic succession (Maquiné Group; Machado et al., 1996 – Fig. 8) and the Palaeoproterozoic Minas Supergroup (Machado et al., 1996; Hartmann et al., 2006). A possible explanation for this fact is that the QF province began with a large segment of >3200 Ma Palaeoarchaeoan TTG crust and that this segment was either partly consumed (reworked) or partly eroded during tectonic denudation and intermittent magmatic activities at ca. 2930–2900 Ma (RVI event), 2800–2770 Ma (RV II event) and 2750–2700 (potassic granitoid event). Given that these Palaeoarchaeoan zircons do not show any evidence metamorphic overgrowth (Table 1), we suggest that Santa Barbara complex represent a well preserved core of this Palaeoarchaeoan crust, developed through additions of juvenile TTG magmas into mafic–ultramafic greenstone belt rocks. This core served as the main building block that grew through tectonic accretions of younger, 2900 Ma TTG terrain (Figs. 9a and b).

Evidence for the 2930–2900 Ma RV I TTG magmatism is present in almost all granitoid–gneiss complexes, surrounded by the Rio das Velhas Greenstone Belt – namely the Bação, Bonfim and Belo Horizonte complexes, as well as in the reworked basement of the Palaeoproterozoic Mineiro Belt (Figs. 4 and 6). Such a spatial distribution of RV I rocks testifies to the regional extent of the Neoproterozoic TTG production, encompassing ca. 70% of the QF area (Figs. 2, 4 and 6). The RVI event is possibly linked to the first emergence of a regional continental lithosphere in the Southern São Francisco Craton (Fig. 9b). This process may have involved not only additions of TTG magmas in the Palaeoarchaeoan crust, but also tectonic accretion of mafic and ultramafic rocks that are represented by the basal units of the Rio das Velhas Supergroup and by greenstone belt remnants around the margin of the Southern São Francisco Craton.

The 2800–2770 RVII magmatic event overlaps in age with the extrusion of felsic volcanic units and fluvial/turbiditic sedimentation on top of mafic–ultramafic lavas of the Rio das Velhas greenstone belt (Table 1). Primary sedimentary/volcanic structures within the most preserved part of the belt link the RV II felsic volcanic units with alluvial–fluvial lithofacies which, in turn, change abruptly to turbiditic deposits of submarine fans (Upper Nova Lima and Maquiné Groups). Both felsic volcanism and the turbiditic sedimentation are interpreted to mark the initial stages of a subduction episode ca. 2800 Ma (Baltazar and Zucchetti, 2007). The clastic sediments and volcanoclastics contain a number of detrital zircons ranging in age from 3200 to 2780 Ma (Machado et al., 1996; Hartmann et al., 2006) suggesting that all previously described components of the QF TTG crust served as sources during their deposition. Significantly, published negative $\varepsilon_{\text{Nd}}(t)$ values calculated for the 2770 Ma amphibolites and tonalities, and late 2700 Ma potassic granites indicate that older (>2900 Ma) sialic crust participated in their petrogenesis (Teixeira et al., 1996). According to Teixeira et al. (1996), intrusive 2770 Ma tonalites and late potassic granites are marked by different negative $\varepsilon_{\text{Nd}}(t)$ values, suggesting that different proportions of sialic material participated in their origin. Thus, it is likely that the RVII TTG rocks and associated volcanic rocks were emplaced in volcanic–arc systems developed around the margins of the 3220–2900 Ma continental block (Fig. 8b). This explains the fact that a number of 2900 Ma zircons (RV I zircons) record metamorphic overgrowths between at ca. 2750–2800 Ma (Table 1).

6. Conclusions

Our zircon U–Pb data provided, for the first time, a more detailed evolution of the Palaeo- to Neoproterozoic TTG crust in the Southern São Francisco Craton. The main periods of TTG production – the Santa Barbara, Rio das Velhas I and Rio das Velhas II events – represent a significant part of the protracted tectonomagmatic history of the Craton spanning from 3220 to 2770 Ma. Based on the spatial and age distribution of the TTG rocks we suggest that the Santa Barbara TTG rocks represent the only relic of the Palaeoarchaeoan crust of the Southern São Francisco Craton. This crust grew into a large segment of TTG crust during two main events of subduction related magmatism in the Neoproterozoic. These stages of TTG magmatism led to development of a composite, polydeformed TTG crust riddled with mafic–ultramafic greenstone belt terrains. The two main magmatic events (Rio das Velhas I and II events) span over a period of 30–40 Ma each, and are marked by voluminous emplacement of TTG magmas. The additions of juvenile and reworked TTG crust preceded the stabilization of the Southern São Francisco Craton by at least 70 Ma. The timing and duration of the latest TTG event (RV II) coincided with the felsic volcanism and deposition of turbiditic wackes of the main greenstone belt sequence. This same event was shortly followed by emplacement voluminous potassic granitoid magmas that led to construction of massive sheets of granitoids ranging in age from 2750 to 2700 Ma.

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Appendix A. U–Pb methodology

Zircons were extracted at the Departamento de Geologia (DEGEO), Universidade Federal de Ouro Preto. The technique makes use of conventional jaw crusher, milling, manual panning and heavy liquids separation. The zircons were hand-picked under a binocular microscope and mounted on 25 mm epoxy mounts. The mounts were polished and imaged under SEM-cathodoluminescence to accentuate internal growth zoning. For SHRIMP analysis, the mount was coated by an ultrathin pure gold coating to provide surface conductivity.

A.1. SHRIMP

The U, Th and Pb isotopic data from samples MD4, MD6, MD7A, MD7B, MD9, and MD12 were collected on the Sensitive High Mass Resolution Ion Microprobe (SHRIMP RG) at the Research School of Earth Sciences at the Australian National University, Australia. The current of the O₂-beam during the analytical sessions was set at least 2 nA, resulting in a sensitivity of 15–30 cps/nA/ppm Pb. Analyses on unknowns were interspersed with analyses of Temora standard, for which an age of 416.75 ± 0.24 Ma was adopted (Black et al., 2003). Calibration for U content was done through the SL13 zircon standard, which has a reported U content of 238 ppm (Williams and Claesson, 1987). Measured compositions were corrected for common lead using measured non-radiogenic ²⁰⁴Pb. Analyses that displayed high counts on ²⁰⁴Pb, were abandoned, so that applied corrections are minimal and insensitive to the chosen isotopic composition of common Pb. In all analyses, the component

of common Pb related to surface contamination was minimized through the meticulous cleaning procedure prior to loading and rastering the primary beam over the analyzed area for up to 2 min prior to analysis. Common Pb counts were therefore observed to be constant and low. An average crustal Pb isotopic composition following the model of Stacey and Kramers (1975) was used in the common Pb correction, appropriate to the age of the zircon. Data processing was done using the excel add-ins Squid and Isoplot (Ludwig, 2001a,b, 2003). All decay constants are those recommended by Steiger and Jäger (1977), but for calculation of the ages, the uncertainties on these constants are not applied.

A.2. LA-ICP-MS

The laser ablation-ICP-MS method (LA-ICPMS) has been developed to yield reliable U–Pb ages on zircon and monazite on a routine basis at the Department of Geology, Universidade Federal de Ouro Preto, Brazil. The analyses were performed using an Agilent 7700 Q-ICP-MS and a 213 nm New Wave laser. Operating conditions were optimized to provide maximum sensitivity for the high masses (^{207}Pb and ^{238}U) while inhibiting oxide formation ($\text{ThO}^+/\text{Th}^+ < 1.0\%$). The standard and unknown zircons were ablated in small volume (tear-drop shape) sample cell, with an insert that holds one 25-mm-diameter sample mount and a 7-mm-diameter standard mount. Acquisitions consisted of a 20 s measurement of the gas blank, followed by 40 s measurement of U, Th and Pb signals during ablation, and 30 s washout (e.g., Lana et al., 2010; Buick et al., 2011). Samples, standards and sample holders were acid-washed before being analyzed to remove possible surface Pb contamination. Laser ablations were performed at 40 μm spot size, $\sim 6\text{--}8\text{ J}/\text{cm}^2$ fluence and 10 Hz repetition rate. Ablations occurred in a He carrier gas, and the resulting aerosol was mixed with Ar prior to introduction into the ICP-MS via 4 mm Tygontubing (pre-cleaned with 1% ultra-pure nitric acid). Integration times were 15 ms for ^{206}Pb ; 40 ms for ^{207}Pb and 10 ms for ^{208}Pb ; $^{204}\text{Pb} + \text{Hg}$; ^{232}Th , ^{238}U .

The relevant isotopic ratios ($^{207}\text{Pb}/^{206}\text{Pb}$, $^{208}\text{Pb}/^{206}\text{Pb}$, $^{208}\text{Pb}/^{232}\text{Th}$, $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$, where ^{235}U was calculated from ^{238}U counts via the natural abundance ratio $^{235}\text{U} = ^{238}\text{U}/137.88$) have been calculated using the data reduction software Glitter (Van Achterbergh et al., 2001). Individual isotopic ratios were displayed in time-resolved mode. For our laser system, isotopic ratios generated during the first 5 s of each analysis were discarded. The integration window for the remainder of each analysis was chosen to exclude signal segments that were related to zones of Pb loss (e.g., fractures), high common Pb (as recognized by $^{204}\text{Pb} + \text{Hg}$ counts markedly higher than the high background caused by ^{204}Hg contamination) or Pb inheritance. Instrumental drift was corrected against the zircon standard using linear interpolative fits. Calibrations were based on six or more analyses of the standard (6–8 analyses of unknowns bracketed between 2 and 3 analyses of standards). ^{204}Pb -based common Pb corrections were not applied.

Two secondary standards were used during runs: Plesovice zircon ($337 \pm 1\text{ Ma}$; Sláma et al., 2008) and M125 zircon ($524 \pm 1\text{ Ma}$; Klotzli et al., 2009). Sixty-two analyses of Plesovice zircon std gave a Concordia age of $338 \pm 1\text{ Ma}$ (mean $^{207}\text{Pb}/^{206}\text{U}$ age = 337 ± 8 ; mean $^{206}\text{Pb}/^{238}\text{U}$ age = 338 ± 1 ; mean $^{207}\text{Pb}/^{235}\text{U}$ age = $338 \pm 1\text{ Ma}$). Fifty-two analyses of the M125 zircon std gave a Concordia age of $526 \pm 1\text{ Ma}$ (mean $^{207}\text{Pb}/^{206}\text{U}$ age = 525 ± 7 ; mean $^{206}\text{Pb}/^{238}\text{U}$ age = 526 ± 1 ; mean $^{207}\text{Pb}/^{235}\text{U}$ age = $526 \pm 1\text{ Ma}$). See supplementary data for detailed information about the individual analyses and “within run” ages obtained for these zircon standards. In order to constraint the reproducibility of the instrument for Archaean zircons we tested zircon grains from an Archaean tonalite (Kaap Valley Tonalite) which record a TIMS age of $3227 \pm 1\text{ Ma}$ (Kamo and Davis, 1994). Zircons from this sample were analyzed at the

end of two sections (Day 3 and Day 6). The analyses yielded concordant and subconcordant points as expected for this rock (e.g., Armstrong et al., 1990; Kamo and Davis, 1994; Schoene et al., 2008). The obtained Pb loss discordia for all 42 points (Day 3 + Day 6) gave an upper intercept age of $3227 \pm 3\text{ Ma}$ (MSDW = 0.99) and a lower intercept age of $447 \pm 150\text{ Ma}$.

Electronic supplement

Compiled tables of SHRIMP and LA-ICP-MS analyses. The excel file includes data for individual samples and three secondary standards.

Appendix B. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.precamres.2013.03.008>.

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