ARTICLE

New evidence of Neoarchean crustal growth in southern São Francisco Craton: the Carmópolis de Minas Layered Suite, Minas Gerais, Brazil

Novas evidências de crescimento crustal neoarqueano no Cráton São Francisco meridional: a Suite Acamadada Carmópolis de Minas, Minas Gerais, Brasil

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ABSTRACT: The Carmópolis de Minas Layered Suite is situated in the Campo Belo Metamorphic Complex domain, Minas Gerais, SE Brazil, which, together with other metamorphic complexes in the surroundings of the Quadrilátero Ferrífero, composes the Archean sialic crust of the southern part of the São Francisco Craton. This suite encompasses a remaining segment of a magmatic arc, which is deformed and metamorphosed to upper amphibolite-granulite facies. It shows layered and massive strata, constituted by rock types with lithogeochemical signature equivalent to low-K₂O tholeiitic series. Both tholeiitic and calc-alkaline magmatism phases were identified. Amphibolite and metarhyolite samples were used for zircon U-Pb dating using MC-LA-ICP-MS. The amphibolite zircons yielded ²³²Th/²³⁸U ratios ≈ 0.17 – 0.83 and a Concordia age of 2,752 ± 18 Ma. This interval yields an approximation to minimum age of the calc-alkaline phase. The metarhyolite zircons yielded ²³²Th/²³⁸U ratios ≈ 0.25 – 0.66 and ages of 2,713 ± 9.9 and 2,710 ± 31 Ma. This variation was interpreted as the minimum age interval of the calc-alkaline phase. One of the metarhyolite samples yielded two inherited zircon populations. These populations were dated at 3,374 ± 30 and 2,859 ± 23 Ma, suggesting the contribution of older crusts in the genesis of the suite. The results showed that the genesis of this suite represents an episode of juvenile arc crust formation during the Rio das Velhas Tectonothermal Event (2,780 Ma). This syn- to late-orogenic episode involved arc development, tholeiitic to calc-alkaline magmatism, metamorphism, and crustal recycling.

KEYWORDS: magmatic arc; U-Pb geochronology; calc-alkaline; tholeiitic; Archean.

RESUMO: A Suite Acamadada Carmópolis de Minas está situada no domínio do Complexo Metamórfico Campo Belo, Minas Gerais, SE-Brasil, que, junto a outros complexos metamórficos nos arredores do Quadrilátero Ferrífero, compõem a crosta sílica arqueana da parte meridional do Cráton São Francisco. Essa suite compreende um segmento remanescente de arco magmático, deformado e metamorfizado em fácies anfibolito-superior a granulito. Exibe estratos acamadados e maciços, constituídos por litotipos com assinatura litogeoquímica equivalente a uma série tholeiítica de baixo-K₂O. Uma fase de magmatismo tholeiítico e outra de magmatismo cálcio-alcálico foram identificadas. Uma amostra de anfibolito e duas de metarriolito foram utilizadas para datação U-Pb em zircões usando MC-LA-ICP-MS. O anfibolito apresentou zircões com razões ²³²Th/²³⁸U ≈ 0,17 – 0,83 e idade concórdia de 2.752 ± 18 Ma. Esse resultado foi interpretado como idade mínima da fase tholeiítica. As amostras de metarriolito apresentaram zircões com razões ²³²Th/²³⁸U ≈ 0,25 – 0,66 e foram datadas em 2.713 ± 9,9 e 2.710 ± 31 Ma. Esse intervalo fornece uma aproximação para a idade mínima da fase cálcio-alcálica. Uma das amostras de metarriolito apresentou duas populações de zircões herdados. Essas populações foram datadas em 3.374 ± 30 e 2.859 ± 23 Ma, sugerindo a contribuição de crostas mais antigas na gênese da suite. Os resultados demonstram que a gênese dessa suite representa um episódio de formação de crosta juvenil durante o Evento Tectonothermal Rio das Velhas (2.780 Ma). Esse episódio sin a tardi-orogênico envolveu desenvolvimento de arco, magmatismo tholeiítico a cálcio-alcálico, metamorfismo e reciclagem crustal.

PALAVRAS-CHAVE: arco magmático; geocronologia U-Pb; cálcio-alcálico; tholeiítico; Arqueano.

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INTRODUCTION

The Archean tectonic evolution of the southern portion of the São Francisco Craton (SFC) was marked by episodes of formation, thickening, and consumption of crust, as proposed by Carneiro (1992), Machado & Carneiro (1992), Machado *et al.* (1992, 1996), Noce *et al.* (1998), Silva *et al.* (2000), Teixeira (1985), and Teixeira *et al.* (2000), among others. Among this collection of papers, those of Teixeira *et al.* (1996, 1998) stand out, because they point to a polyphase history with three periods of intense tectono-magmatic activity between the Paleo- and Neoproterozoic Eras. According to these authors, the first period incorporates ages older than $\approx 3.1 - 2.9$ Ga and contributes to the set of oldest U-Pb ages of the South American Platform. The ages in this range represent a fruitful period of crustal formation and thickening (e.g. Teixeira *et al.* 1996, 1998, Carneiro *et al.* 1998; Hartmann *et al.* 2006). U-Pb ages with this order of magnitude were obtained in zircons from the gneisses of Campo Belo Metamorphic Complex (CBMC; Teixeira *et al.* 1998), the Belo Horizonte Metamorphic Complex (CMBH; Teixeira *et al.* 1996), the mafic-ultramafic volcanic sequence of the Piumhi greenstone belt (Machado & Schrank 1989), and the metasedimentary rocks of the Rio das Velhas Supergroup (SGRV; Machado *et al.* 1996; Noce *et al.* 2005; Hartmann *et al.* 2006). This period is also recorded in Sm-Nd TDM model ages, and Pb/Pb and Rb-Sr isochron ages (Carneiro 1992; Machado & Carneiro 1992; Machado *et al.* 1992; Teixeira *et al.* 1996, 1998), obtained in the metamorphic complexes that surround the Quadrilátero Ferrífero mining district. The second event occurred between $\approx 2.9 - 2.8$ Ga. Several studies in zircons from the migmatites neosome of the CBMC (Teixeira *et al.* 1998) and BHMC (Noce 1995; Noce *et al.* 1998) record an episode of high-grade metamorphism and migmatization between 2860 and 2839 Ma. In addition, processes of oceanic crust formation during this period are suggested by Sm-Nd isochron age of 2863 ± 65 Ma, obtained in komatiitic rocks from the Morro do Ferro greenstone belt (Pimentel & Ferreira Filho 2002). There is no mention in the literature of records on the 2860 and 2839 Ma event in the Bonfim Metamorphic Complex. This fact indicates that the tectonic evolution of this unit was distinct from the other metamorphic complexes in this region. However, the CMB records evidence of an event of magmatism and crustal reworking between ≈ 2780 and 2700 Ma (e.g. Carneiro 1992; Machado & Carneiro 1992). This event was defined by Carneiro (1992) as the Rio das Velhas Tectono-thermal Event (RVTE) and comprises the third period of tectonic activity described by Teixeira *et al.* (1996, 1998), also referred to as Rio das Velhas Orogeny. RVTE involved reworking of older TTG gneisses during the

evolution of a continental margin, generating metamorphism (Carneiro 1992) and producing andesitic to calc-alkaline magmatism (Carneiro 1992; Machado *et al.* 1992, 1996; Noce *et al.* 2005). The apex of this event was marked by a collisional stage between 2752 and 2700 Ma (e.g. Carneiro 1992; Noce *et al.* 1998), which included the Nova Lima Group sedimentation (Hartmann *et al.* 2006), and, at the final stages of stabilization of the orogen, an extensional event, responsible for the emplacement of mafic-ultramafic bodies in the crust (Pinese 1997; Carneiro *et al.* 2004) and a syn- to late-orogenic granitogenesis (Carneiro 1992; Noce 1995; Teixeira *et al.* 1996; Romano 1989).

Recent work by Romano *et al.* (2013) and Lana *et al.* (2013), corroborating the previous papers, proposed three main tectono-magmatic events of TTG crust formation. The authors named these events as Santa Bárbara (3220 – 3200 Ma), Rio das Velhas I (RV I; 2930 – 2900 Ma), and Rio das Velhas II (RV II; 2800 – 2770 Ma). After the RV II Event, the coalescence of the crustal segments that currently represent the metamorphic complexes in the vicinity of the Quadrilátero Ferrífero was recorded, where an extensive 2760 – 2700 Ma potassic magmatic event took place, marking the Archean cratonic core stabilization (e.g. Lana *et al.* 2013).

The isotopic records of these events are also identified at the Campo Belo Metamorphic Complex domain. The current tectonic models (e.g. Teixeira *et al.* 1998; Carneiro *et al.* 1998; Campos & Carneiro 2008) indicate that the crustal segment represented by CMCB collided with the N/NE sialic blocks, over the probable Neoproterozoic continental margin, corresponding to SW limit of the Quadrilátero Ferrífero mining district (Carneiro 1992; Machado & Carneiro 1992; Campos & Carneiro 2008). In contrast, either there is no information about the style of margin in the block opposite (CMCB) or available information is more generalist, addressing only the collisional orogen as a whole.

In this sense, within the Campo Belo Metamorphic Complex and close to the inferred limit with the Bonfim Metamorphic Complex crops out the Carmópolis de Minas Layered Suite (CMLS – e.g. Goulart & Carneiro 2013). Previous work by Carneiro *et al.* (2007) originally correlated the CMLS rocks with the Neoproterozoic Ribeirão dos Motas Layered Sequence (RMLS), which crops out at the SW studied area. This unit was interpreted by Carvalho Júnior (2001) as a stratiform layered intrusion, correlated to the mafic-ultramafic volcanic rocks of the Rio das Velhas Supergroup. Whole-rock Sm-Nd isotope constraints (Carneiro *et al.* 1997, 2004) yielded an isochron age of *ca.* 2.79 Ga for the Ribeirão dos Motas Layered Sequence, supporting this interpretation.

Nevertheless, later works (e.g. Goulart & Carneiro 2013; in press) observed evidence of a tardy calc-alkaline magmatic phase in the Carmópolis de Minas Layered Suite, not observed

in the Ribeirão dos Motas Layered Suite. These evidences consist of the emplacement of intermediate to acidic rocks, posterior to the tholeiitic magmatic phase. Given the new geological constraints, Goulart *et al.* (2013, unpublished) and Goulart & Carneiro (2013, in press) characterized the SACM as Neoproterozoic juvenile magmatic arc-related suite, correlated to the late RV II. The present work shows the preliminary results of U-Pb (LA-ICP-MS) geochronological dating in zircons from rocks of the Carmópolis de Minas Layered Suite, which discusses: 1) ages of the phases of tholeiitic and calc-alkaline magmatism; and 2) possible implications of this unit in the crustal evolution of the Southern São Francisco Craton.

LOCATION AND GEOLOGIC CONTEXT OF CARMÓPOLIS DE MINAS LAYERED SUITE

Carmópolis de Minas Layered Suite comprises a crustal segment of the Campo Belo Metamorphic Complex, located southwest of the Quadrilátero Ferrífero (QF), in the Carmópolis de Minas municipality (State of Minas Gerais, Figs. 1 and 2). This suite is positioned in a sinformal structure approximately 30 km long (Carmópolis de Minas Synclinal – Fig. 2). To the north, the structure axis trends NE-SW and inflects NW-SE to the south.

Contacts between the Carmópolis de Minas Layered Suite and the CBMC TTG gneisses are inferred. Along the unit, granitoids and three mafic dyke systems (two NW-SE and one NE-SW direction), designated as Lençóis I / II and Timboré (e.g. Carneiro *et al.* 2007) suites, intrude into this stratigraphic sequence. Remnants of detrital and chemical sedimentary units crop out subordinately and in small volume. These rocks consist of metachert, gondite, magnetite layers, and quartzite, which occasionally occur interspersed with amphibolite lenses.

The suite is composed of layered and massive, plutonic or sub-volcanic, mafic-ultramafic to felsic lithotypes, metamorphosed at amphibolite to granulite facies conditions (Figs. 3A to C). The typical outcrops of the CMLS show NE-SW-vertical to sub-vertical layering. In the syncline closing, the magmatic layering shows expressive deformation, exhibiting well-defined NE-SW-oriented M-fold axes (Fig. 3B). Geochemical and isotopic constraints (Goulart *et al.* 2013, unpublished; Goulart & Carneiro 2013, in press) indicate that low Mg number ($Mg\# < 57.87$, except metaultramafic cumulates), low K_2O contents (0.1 – 1.45 wt.%), and positive to slightly negative $\epsilon Nd(t)$ values (+13.14 to -0.25) are ubiquitous features of these rocks. According to the cited authors, the predominant low $Mg\#$ values in

association with vestiges of metasedimentary rocks indicate that the SACM protolith may have been derived from more evolved magmas, which in turn were fractionated from primary magmas, to then be housed at shallower depths in the crust. The low- K_2O rocks, as opposed to high- K_2O and TTG suites currently known in the sialic substrate of Southern CSF (e. g. Alkmin & Noce 2006; Campos & Carneiro 2008; Romano *et al.* 2013, Lana *et al.* 2013), indicate the SACM to be an Archean metamorphic equivalent of modern arc-related tholeiitic suites of the boninite-basalt-andesite-rhyolite type, suggesting that their protoliths were originated in a juvenile oceanic arc setting (see Gill 1981; Leat *et al.* 2003 Tamura *et al.* 2009).

The composition of the lithological assemblage is in agreement with the expected average proportions between tholeiitic and calc-alkaline rocks from juvenile magmatic arc-related suites (e.g. Gill 1981). Tholeiitic rocks are volumetrically predominant and represent several metamorphic lithotypes as arc-related amphibolite-metaultramafic cumulates and metamorphosed arc-related basic to intermediate rocks.

The metamaifites correspond to several varieties of amphibolite and leucoamphibolite. Garnet-amphibolite was described and occurs in small amounts. These rocks are composed of plagioclase, hornblende, pyroxene, Fe-Ti-oxides, garnet, and quartz. Metasomatized rocks contain actinolite, Na-plagioclase, biotite, epidote, scapolite, quartz, and carbonate. The meta-metaultramafic rocks are orthopyroxenite, hornblende, plagioclase-metapyroxenite, meta-olivine-websterite, and meta-harzburgite. Garnet-bearing amphibolite and garnet-bearing websterite have been described, but they occur in small amounts. The lithotypes are composed of orthopyroxene, clinopyroxene, hornblende, olivine, garnet, spinel, Fe-Ti-oxides, and sulfides. The secondary paragenesis is formed by serpentine, talc, tremolite/Mg-hornblende, and chlorite in smaller quantities. Metadunite and metalherzolite are unusual and present original mineralogy intensely replaced by secondary paragenesis. These rocks keep relict primary textures such as euhedral twinned clinopyroxene crystals showing rim recrystallization (mantled texture), euhedral tabular plagioclase crystals with recrystallized cores (ghost crystals), and several relict cumulate textures constituted by plagioclase, clinopyroxene, orthopyroxene, and olivine in lesser importance. The calc-alkaline rocks are less abundant and consist of metamorphosed rhyodacitic/rhyolitic rocks. These lithotypes occur as felsic injections, parallel to sub-parallel to the metaultramafic-amphibolitic bedding. Granitoids crop out in some portions of the unit, but the relationship of these with the CMLS is not known. These rocks are formed by Na-plagioclase, K-feldspar, and quartz. Mafic minerals are biotite, pyroxene, and/or hornblende and Fe-Ti-oxides but occur in small amounts.

Figure 1. Simplified geologic map of southern São Francisco Craton showing the location of the study area and part of the SW limit of the Quadrilátero Ferrífero. The Carmópolis de Minas Layered Suite boundaries are still represented as in Carneiro *et al.* (2007). In the upper left corner the location of the study area is shown in relation to the Southern São Francisco Craton (dark gray area). Sources: Leite *et al.* (2004), Carneiro *et al.* (2007).

Figure 2. Geologic map of Carmópolis de Minas Layered Suite.

Figure 3. Carmópolis de Minas Layered Suite typical structures. (A) Magmatic layering constituted by leucoamphibolite and amphibolite. (B) “M”-folded magmatic layering constituted by leucoamphibolite and amphibolite, with stratification formed by the accumulation of poikilitic hornblende crystals. (C) Magmatic layering in meta-websterite. (D) and (E) Amphibolite enclave in metarhyolite. These structures are associated with the presence of poikilitic hornblende (Hbl). (F) Thin section showing poikilitic hornblende crystals (Hbl) hosting plagioclase (Pl) and magnetite (Mag). Observe the euhedral to subhedral habit of the crystals (PPL, enlargement 5X). (G) and (H) Outcrop showing the sampled metarhyolite and amphibolite. The acidic injections are parallel to sub-parallel to the amphibolite strata.

The Nd-Sr isotope data that Goulart & Carneiro (2013, in press) obtained point to two magmatic sources for the SACM rocks. Positive $\epsilon_{\text{Nd}(t)}$ values ($> +0.41$) point out that the tholeiitic rocks are mantle-derived, whereas the calc-alkaline rocks, presenting slightly negative $\epsilon_{\text{Nd}(t)}$ values (-0.25), show that they may have been generated in a sin- to late-orogenic phase by sub-arc crust anatexis.

Several field evidences confirm the two magmatic phases during SACM formation:

- Mafic enclaves, microgranular and/or orbicular aggregates, and poikilitic euhedral crystals of hornblende, ortho- and clinopyroxene (Figs. 3D to F), hosting countless Fe-Ti-oxides and phenocrystal of plagioclase, are observed in the contact between amphibolite layering and felsic injections. These structures suggest assimilation of sub-arc mafic crust by felsic magmas.
- Amphibolite enclaves and lenses showing low-grade metamorphic paragenesis with Na-plagioclase, epidote, actinolite, quartz, and minor biotite also occur at the felsic injections contact. According to Morgan & London (1987), the contact between acidic melts and mafic rocks may cause metasomatism and low-grade paragenesis formation. This point of view implies that the tholeiitic and calc-alkaline magmatic phase cannot be contemporaneous, but suggests that the calc-alkaline magmatism may have involved several pulses, where not all have yet been identified.
- In the stratified domains, poikilitic crystals of pyroxene and hornblende were also observed. According to several authors (e.g. Storey *et al.* 1989; Seaman *et al.* 1995; Lindberg & Eklund 1988), similar textures can be generated by the contact reaction of melts with distinct rheological characteristics. Regarding CMLS, these textures suggest that tholeiitic and calc-alkaline magmatic phases could have coexisted, interacted, and generated hybrid magmas.

MATERIALS AND METHODS

Sample preparation (crushing, comminution, concentration, and separation of magnetic minerals) was performed in LOPAG – Laboratory for Sample Preparation for Geochemistry and Geochronology, Geology Department of the Ouro Preto Federal University. The non-magnetic fractions were analyzed by LA-MC-ICP-MS (Laser Ablation) at the Geochronology Laboratory of the Geosciences Institute of Brasília University. Zircon crystals were separated by means of methyl iodide and selected manually by means of a stereoscope. The selected crystals were mounted in an araldite circular section 2.5 cm in diameter and then

polished. The BSE (*backscattering electron probe*) images of zircon grains were obtained using a Leica MZ 125 optical microscope and a Jeol JSM 5800 scanning electron microscope (Fig. 4). The isotopic ratios were obtained from the MC-ICP-MS (Neptune) equipment coupled to a microprobe (New Wave UP 213). Specific data on the configuration of the Faraday collectors, correction of mass bias, standards, external correction and of laser conditions, corrections of common Pb, calculation of ratios, and error estimation are detailed in Stacey & Kramers (1975), Jackson *et al.* (2004), Kawashita & Chemale Jr. (2006), and Chemale *et al.* (2008, 2009). The ages were calculated using the Isoplot 3.0 program (Ludwig 2000). The analysis results are provided in Tab. 1.

RESULTS

Two metarhyolite samples (MR1 and MR2) and one amphibolite sample (AE19) were analyzed. These samples were obtained from the same outcrop, located in the northernmost part of CMLS, at the left bank of the Paiol River, which corresponds to the closing of the Carmópolis de Minas Synclinal (UTM 540888/7733485; Figs. 2, 3G, and 3H). This place was chosen for the large lithotype diversity, with peculiar structures, such as abundant poikilitic hornblende crystals and mafic enclaves observed in metarhyolite. The selected grains showing low metamictization degree and sizes compatible with the laser spot diameter were analyzed. Despite the fact that the zircons had shown low contrast in the BSE imaging, the analyses were directed preferentially to the crystal cores, because the sizes of these domains are more compatible with the laser spot. Morphology and isotopic characteristics of zircon grains are presented in Figs. 4 and 5. Geochronological results are presented in Tab. 1 and Fig. 5.

Sample AE19

This sample is fine to medium grained and composed of hornblende, plagioclase, and quartz. Accessory minerals are titanite, zircon, apatite, and Ti-magnetite. This sample constitutes zircons D1, D2, D3, D11, D13, and D16. The grains present short and elongated prismatic shapes, occasionally with sub-rounded rims, as a function of metamorphic overgrowth. Internal domains are homogeneous with some fracturing.

Samples and standards were corrected after Pb and Hg blanks; $^{207}\text{Pb}/^{206}\text{Pb}$ and $^{206}\text{Pb}/^{238}\text{U}$ ratios were corrected after common Pb; common Pb assuming as concordant age $^{206}\text{Pb}/^{238}\text{U} * ^{207}\text{Pb}/^{235}\text{U}$; $^{235}\text{U} = 1/137.88 * \text{U}_{\text{total}}$; Standard: GJ-1 (Jackson *et al.* 2004); $^{232}\text{Th}/^{238}\text{U} = ^{232}\text{Th}/^{238}\text{U} * 0.992743$. Errors were calculated with 1 sigma (% for isotopic ratios, absolute ages). 7. Discordance % = $100 * (1 - ^{206}\text{Pb}/^{238}\text{U}_t / ^{207}\text{Pb}/^{206}\text{Pb})$.

Despite the weak contrast of the images, it was possible to distinguish a blurred, oscillatory fine zoning in some crystals. Some zircons present metamorphic overgrowth separated from the internal domains by fractures with dissolution-resorption structures and inclusions of silicate or phosphate crystals. Some grains exhibit peripheral domains more enriched in inclusions. The analyses revealed moderate to high $^{232}\text{Th}/^{238}\text{U}$ ratios (0.17 – 0.83; Tab. 1). The obtained results are concordant to strongly discordant (2 – 65% discordance) and consist of a large interval of $^{206}\text{Pb}/^{207}\text{Pb}$ ages with range from 2749 ± 22 Ma to 2448 ± 22 . The analytical points defined a Pb-loss line that intercepts the Concordia in the upper part of the diagram at 2744 ± 11 Ma and the lower part at 252 ± 12 Ma (MSWD = 0.38), the latter with

no apparent geologic meaning. These discordant results are probably correlated with the presence of internal fractures in the analyzed grains. Nevertheless, the grouping of analysis defined by zircon grains D3, D11, and D16 yielded an apparent Concordia age of 2752 ± 18 Ma (MSWD = 1.6; Fig. 5).

Sample MR1

Sample MR1 is composed of plagioclase, K-feldspar, quartz, and subordinate biotite and orthopyroxene. Titanite and zircon are accessory minerals. The analyzed zircons were labeled with prefixes H and I. The grains are predominantly prismatic, short, subhedral, and/or equidimensional, occasionally sub-rounded and double-terminated. Internal domains are ample and homogeneous. Occasionally the subtle contrasts

Figure 4. Backscattering electron probe images of some zircons of this study. The circles represent the position of the laser spots.

in BSE images suggest the presence of blurred oscillatory zoning. The development of fractures is insignificant. In general, grains present peripheral domains with homogeneous texture, in some cases (zircon H25) with inexpressive concentric fractures delimiting the internal domains. Occasionally they are associated with dissolution structures, suggesting fluid percolation. Some grains present mineral inclusions. Results yielded moderate to high $^{232}\text{Th}/^{238}\text{U}$ ratios in the 0.21 – 0.66 interval. Analysis from zircons H9, H15, H25, H28, and I18 presented concordant analytical points (discordance < 1%). These results yielded a weighted mean $^{206}\text{Pb}/^{207}\text{Pb}$ age of 2718 ± 15 Ma and an apparent Concordia age of 2713 ± 9.9 Ma (MSWD = 1.6; Fig. 5).

Sample MR2

The essential paragenesis of this sample is plagioclase, quartz, and K-feldspar. The mafic mineral is biotite and the accessory minerals are Ti-magnetite, titanite, apatite, and zircon.

The zircons of this sample define three populations with well-defined $^{206}\text{Pb}/^{207}\text{Pb}$ ages. The first population is represented by zircons E6, E8, E11, E21, and E28. The crystals are prismatic, elongated, with sub-rounded rims, and internal domains with homogeneous texture or blurred

oscillatory zoning. Mineral and fluid inclusions, fracturing, and botryoidal structures are present in all grains. It is possible to distinguish with some difficulty pervasive transgressive recrystallization in weakly contrasting BSE images. These structures indicate that these zircons were partially recrystallized during medium- to high-grade metamorphism (e.g. Vavra *et al.* 1999; Connelly 2000; Corfu *et al.* 2003).

The zircon analysis yielded high $^{232}\text{Th}/^{238}\text{U}$ ratios ($\approx 0.42 - 0.57$). Grains E21 and E28 showed Th and U enrichment relative to Pb, when compared to E6, E8, and E11, resulting in slightly lower $^{232}\text{Th}/^{238}\text{U}$ ratios (0.26 and 0.32). Zircons E6, E8, E11, E21, and E28 presented concordant to discordant results (< 1 – 45% disc.) and $^{206}\text{Pb}/^{207}\text{Pb}$ ages with range in ages from $\approx 2717 \pm 47$ to 2183 ± 97 Ma. Discordant results probably reflect the presence of fractures in the zircons. Particularly, the analyses of zircons E21 and E28 resulted in apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages, inconsistent with the other samples of this group (2183 ± 97 and 2210 ± 31 Ma), but aligned with these in a radiogenic Pb-loss line that intercepts the Concordia at 2710 ± 31 Ma and 773 ± 64 Ma (MSWD = 1.06). Zircons E08 and E11 (discordance < 1%) yielded an apparent Concordia age of 2713 ± 15 Ma (MSWD = 0.42). The other zircon populations yielded well-defined $^{207}\text{Pb}/^{206}\text{Pb}$ ages that are distinct

Table 1. LA-MC-ICPMS analytical results

	Isotopic ratios								Ages (Ma)							Geochemistry				
	Zircon/spot	²⁰⁷ Pb/ ²³⁵ U	±	²⁰⁶ Pb/ ²³⁸ U	±	Rho 1	²⁰⁷ Pb/ ²⁰⁶ Pb	±	²⁰⁶ Pb/ ²³⁸ U	±	²⁰⁷ Pb/ ²³⁵ U	±	²⁰⁷ Pb/ ²⁰⁶ Pb	±	% Disc.	f206	²³² Th/ ²³⁸ U	Th (ppm)	U (ppm)	Pb (ppm)
AE1	D03	14.1006	2.84	0.5384	2.45	0.86	0.1900	1.43	2777	68	2756	78	2742	39	-1	0.0013	0.53	14	27	20
	D11	14.1099	1.33	0.5363	1.06	0.80	0.1908	0.81	2768	29	2757	37	2749	22	-1	0.0007	0.54	29	54	43
	D16	14.2281	2.23	0.5430	1.97	0.88	0.1900	1.05	2796	55	2765	62	2742	29	-2	0.0008	0.42	17	40	28
	D01	5.7651	3.46	0.2453	0.61	0.18	0.1705	3.41	1414	9	1941	67	2562	87	45	0.0056	0.83	196	239	86
	D02	8.4533	1.36	0.3334	1.13	0.83	0.1839	0.76	1855	21	2281	31	2688	20	31	0.0016	0.58	129	224	91
	D13	3.1016	1.18	0.1412	0.83	0.70	0.1593	0.84	852	7	1433	17	2448	21	65	0.0016	0.17	28	160	34
MR1	H09	13.453	2.87	0.520	2.45	0.85	0.188	1.49	2700	66	2712	78	2721	41	1	0.0010	0.66	25	38	19
	H15	13.323	2.08	0.518	1.36	0.65	0.187	1.58	2689	36	2703	56	2713	43	1	0.0017	0.61	19	31	15
	H25	13.597	2.50	0.527	2.09	0.84	0.187	1.37	2730	57	2722	68	2716	37	0	0.0005	0.55	39	71	35
	H28	13.416	1.88	0.522	1.57	0.84	0.186	1.03	2709	43	2709	51	2710	28	0	0.0003	0.53	45	85	38
	I18	13.687	2.69	0.526	2.14	0.80	0.189	1.63	2723	58	2728	73	2732	44	0	0.0004	0.65	46	71	33
MR2	E01	15.2065	1.22	0.4483	1.02	0.83	0.2460	0.68	2387	24	2828	35	3159	22	24	0.0002	0.17	39	234	139
	E27	26.0331	2.24	0.6662	2.01	0.90	0.2834	0.99	3291	66	3348	75	3382	33	3	0.0007	1.04	51	49	43
	E04	13.2351	1.34	0.4663	0.52	0.39	0.2059	1.24	2467	13	2697	36	2873	36	14	0.0014	0.79	75	96	51
	E17	8.5267	16.45	0.3044	14.62	0.89	0.2031	7.53	1713	250	2289	376	2852	21	40	0.0022	0.31	81	265	105
	E24	15.9777	1.14	0.5685	0.80	0.71	0.2038	0.80	2902	23	2875	33	2857	23	-2	0.0002	0.47	58	126	94
	E06	12.8810	2.56	0.5035	2.27	0.88	0.1855	1.19	2629	60	2671	68	2703	32	3	0.0004	0.42	26	62	41
	E08	13.6823	4.43	0.5304	4.08	0.92	0.1871	1.72	2743	112	2728	121	2717	47	-1	0.0012	0.51	8	16	11
	E11	13.4722	1.92	0.5249	1.61	0.84	0.1862	1.04	2720	44	2713	52	2709	28	0	0.0004	0.57	34	59	41
	E21	3.8727	5.32	0.2057	2.94	0.55	0.1365	4.43	1206	35	1608	86	2183	97	45	0.0011	0.26	122	470	128
E28	4.5974	2.18	0.2405	1.66	0.76	0.1386	1.41	1390	23	1749	38	2210	31	37	0.0003	0.32	159	505	106	

from those of the first population and that characterize them as inherited zircons. One of the populations is represented by zircons E04, E17, and E24. These crystals are stubby or prismatic with rounded terminations. BSE imaging revealed ample homogeneous internal domains surrounded by faded

overgrowths or occasional fractures (zircon E17). Weakly contrasting BSE images suggest the presence of transgressive recrystallizations. All the crystals presented late fractures with fluid percolation and mineral inclusions. The analyses showed high and variable discordance (between 2 and 40%; see Tab. 1), moderate to high $^{232}\text{Th}/^{238}\text{U}$ ratios ($\approx 0.31 - 0.79$), and apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages ranging between 2873 ± 36 and 2852 ± 21 Ma. This heterogeneity isotopic is apparently correlated with the presence of the fractures in the grains. The analytical points defined a Pb-loss cord with reasonably linear data array that intercepts the upper Concordia at 2859 ± 23 Ma (MSWD = 0.21) and lower Concordia at a meaningless geological age.

The third population is represented by zircons E01 and E27, with high $^{232}\text{Th}/^{238}\text{U}$ ratios. These zircons are ovoid to prismatic with rounded terminations, ample homogeneous domains, and blurred overgrowth. The zircon E01 yielded an extremely discordant analysis (24% discordance), which resulted in an apparent $^{207}\text{Pb}/^{206}\text{Pb}$ age of 3159 ± 24 Ma. Grain E27 yielded a sub-concordant result (3% discordance) and apparent $^{207}\text{Pb}/^{206}\text{Pb}$ age of $\approx 3382 \pm 33$ Ma, enabling the calculation of an isolated Concordia age of 3374 ± 30 Ma (MSWD = 2.9; Fig. 5).

DISCUSSION AND CONCLUSIONS

Although the BSE images do not allow for a clear view of the internal features of the zircon grains, the external morphology in association with $^{232}\text{Th}/^{238}\text{U}$ ratios can lead to some interpretations. The BSE imaging of zircon grains, as previously presented, revealed stubby (short prismatic) to prismatic habits (preferentially), with sub-rounded overgrowths and possible internal euhedral zoning. This morphology is consistent with zircons that underwent metamorphism in the upper-amphibolite to granulite facies conditions (see Vavra *et al.* 1999, Corfu *et al.* 2003, Hoskin & Schaltegger 2003). Several studies have interpreted higher $^{232}\text{Th}/^{238}\text{U}$ ratios in high-grade metamorphic zircons from felsic (e.g. Schaltegger *et al.* 1999; Hoskin & Black 2000) and mafic protolith (e.g. Vavra *et al.* 1999; Liati & Gebauer 1999; Rubatto *et al.* 1999) as a magmatic signature. Although there is no consensus on the interpretations of this feature, the $^{232}\text{Th}/^{238}\text{U}$ ratios tend to be higher for granulite facies zircons than for eclogite and amphibolite facies zircons (Vavra *et al.* 1999). Work by Rubatto (2002) showed that zircons from metamorphic eclogite have chemical compositions similar to igneous zircons; however, they have lower $^{232}\text{Th}/^{238}\text{U}$ ratios (< 0.1). The low $^{232}\text{Th}/^{238}\text{U}$ ratios may indicate a complete recrystallization of zircon and consequently reset of the isotopic systems (Hoskin & Schaltegger 2003). In this sense,

Figure 5. Wetherill Concordia diagrams for Carmópolis de Minas Layered Suite rocks.

studies on eclogite and mafic-ultramafic granulite (e.g. Liati & Gebauer 1999) have considered high $^{232}\text{Th}/^{238}\text{U}$ ratios from zircons with little or no preserved magmatic domains, as a pre-metamorphic heritage, and correlated ages are interpreted as the minimum age for crystallization of the protolith. This is the case of the U-Pb zircon dating from CMLS rocks.

The obtained ages between ≈ 3374 and 2710 Ma are recurrent in the Southern CSF (e.g. Teixeira *et al.* 1998; Noce *et al.* 2005; Hartman *et al.* 2006). In accordance with the studies of Teixeira (1996, 1998), Hartmann *et al.* (2006), and Lana *et al.* (2013), this age range records four magmatic events that occurred between the Paleo- and Neoproterozoic at the South São Francisco Craton.

Analyses of the amphibolite AE19 yielded a discordant upper intercept age of 2744 ± 11 Ma (MSWD = 1.5 – Fig. 5), which we interpret as a reasonable approximation to the age of the tholeiitic magmatic phase in the Carmópolis de Minas Layered Suite. However, because of restrictions regarding the areas not clearly preserved in the magmatic zircons sampled, we interpret the apparent Concordia age of 2752 ± 18 Ma as being the most likely crystallization age of the amphibolite protolith and the minimum age of tholeiitic magmatism of the CMLS. This interpretation is also supported by the predominant low Mg# (< 57.87) of this suite, indicating that the protoliths of the studied tholeiitic rocks were not crystallized from primary magmas, but from evolved magmas that were previously fractionated into the crust (Goulart *et al.* 2013 in preparation). The presented results point that the CMLS tholeiitic magmatic phase represents a period of emersion of oceanic arcs (Fig. 6A) during ETRV, which contributed to the formation of the Campo Belo Metamorphic Complex. According to Hartmann *et al.* (2006), the age of ≈ 2.75 Ga represents the Rio das Velhas Orogeny apex ($\approx 2759 - 2751$ Ma) in the southern São Francisco Craton.

The sample MR1 yielded a weighted mean $^{206}\text{Pb}/^{207}\text{Pb}$ age of 2718 ± 19 Ma. This result overlaps within error with the upper intercept age of 2710 ± 31 Ma (MSWD = 1.06) that was obtained in sample MR2 and constrains a likely age range for the development of the calc-alkaline magmatism recorded in the CMLS. Some field correlations that we presented in this work suggest the possibility of the fact that the calcium-alkaline magmatic phase might have occurred in several pulses. Therefore, we interpret the Concordia ages of ≈ 2713 Ma, which the samples MR1 and MR2 yielded, as the crystallization age of the metarhyolite protolith.

The ages of the samples MR1 and MR2 show that the CMLS calc-alkaline magmatic phase is slightly younger than the felsic magmatism of the Rio das Velhas Supergroup (≈ 2746 Ma) in the Quadrilátero Ferrífero domain

(Machado *et al.* 1992; Noce *et al.* 2005; Hartmann *et al.* 2006). However, the magmatic protolith ages of the metamorphosed acidic rocks are contemporaneous to several granitoids, commonly described in metamorphic complexes present in the outskirts of QF (Romano 1989; Carneiro 1992; Noce 1995; Romano *et al.* 2013) that now are associated with the Neoproterozoic potassic magmatic event defined by Romano *et al.* (2013) and Lana *et al.* (2013). Other granitoids mark the development of continental margin, at the SW limit of the QF, in the region currently represented by the Bonfim Metamorphic Complex (e.g. Carneiro 1992; Machado & Carneiro 1992; Campos & Carneiro 2008; Lana *et al.* 2013). In contrast, the spatial and temporal correlations between the SACM and these rocks suggest that to the southwest, the convergence margin of the segment currently represented by Campo Belo Metamorphic Complex may have been characterized by the development of oceanic arcs parallel to the continental edge, defining one accretionary edge (Fig. 6C). Inside the continental block and in response to the evolution of a convergent margin, the development of an extensional environment supports the intrusion of the Ribeirão dos Motos Layered Sequence (Fig. 6C), whose whole-rock isochron age of *ca.* 2790 Ma (Carneiro *et al.* 2004) overlaps within error with the 2752 ± 18 Ma age obtained for the amphibolite AE19.

At the moment, the difference that we observe between the ages of the amphibolite AE19 and metarhyolite MR1 and MR2 rules out the possibility of magmatic hybridization as an explanation to the structures observed in the contact between the tholeiitic and calc-alkaline phases; on the other hand, it strengthens the thesis of assimilation and metasomatism of the preexisting amphibolite crust by acidic melts. However, the presence of reliquiar compositional banding with the accumulation of poikilitic hornblende/orthopyroxene or microgranular mafic aggregates indicates that physical-chemical instability occurred in the contact between magmas with distinct rheological characteristics (see Lindberg & Eklund 1988). This observation still suggests that possibly other phases of calc-alkaline magmatism, not yet identified, could have coexisted with the tholeiitic magmatism along the CMLS evolution.

Tectonic models correlate the calc-alkaline magmatism genesis with the anatexis of the mafic sub-arc crust (e.g. Stern 2010), where the crustal emplacement of intermediate to felsic magmas records the beginning of the intermediate maturity stages of arc evolution, well defined by the formation of a felsic middle crust (Fig. 6B). The mafic lower crust was formed during infant and juvenile stages of the subduction and arc-related magmatism by the gradual replacement of the preexisting mafic-ultramafic oceanic crust. Presumably, the formation age of the initial mafic

arc crust is constrained by the age of the CMLS tholeiitic magmatic phase and therefore must be equal to or older than 2752 Ma (Fig. 6B). Development of juvenile arc-related magmatism would have involved the consumption and recycling of preexisting oceanic crusts and assimilation of crust-derived components.

Although the amphibolite AE19 has not presented direct evidence of crust-derived component assimilation, the sample MR2 records the presence of inherited zircons, with U-Pb ages ranging between ≈ 3374 and 2859 Ma. These zircons represent a crustal inheritance that was passed from the

lower arc crust to acidic melts during anatexis. Ages with this magnitude record two tectonic events that occurred between Paleo- and Mesoarchean, involving the development of continental nuclei and probable juvenile crust formation (see Machado & Schrank 1989; Pimentel & Ferreira Filho 2002; Hartmann *et al.* 2006; Lana *et al.* 2013). These events correspond to the Santa Barbara and Rio das Velhas I Events, according to that which was proposed by Lana *et al.* (2013), and reaffirm the formation of primitive (oceanic and continental) crustal nuclei at that period.

Figure 6. Schematic model for the evolution of the Carmópolis de Minas Layered Suite arc magmatism (based on Stern 2010). (A) Juvenile arc. Tholeiitic magmatism (amphibolite, mafic, and ultramafic cumulates). (B) Late to mature arc. Crustal thickening and beginning of calc-alkaline magmatism by sub-arc crust anatexis. (C) Tectonic model showing the genesis of the SACM. Observe correlation with Ribeirão dos Motas Layered Sequence.

Unpublished work by Goulart & Carneiro (2013, submitted), which supports the proposition of this model, was based on Nd-Sr isotope data from a representative part of the lithological framework that composes the Carmópolis de Minas Layered Suite. The authors report a significant isotopic data set that includes several positive to slightly negative $\epsilon_{\text{Nd}(t)}$ parameters, variable $\epsilon_{\text{Sr}(t)}$ parameters, a pseudo-isochron age for CMLS of 2736 ± 300 Ma with $\epsilon_{\text{Nd}(i)} = +0.4$, and six Sm-Nd T_{DM} model ages ranging from ≈ 3266 to 2860 Ma. From these results we can highlight the following:

- The pseudo-isochron age is consistent with the ages that we have presented in this paper, whereas the slightly positive value of $\epsilon_{\text{Nd}(i)}$ reflects the affinity mantle of the primitive protolith of the CMLS.
- The Sm-Nd T_{DM} model age range constrains, with a best approximation, the age of the magma sources and characterizes an isotopic inheritance from protolith that has been involved in the arc-magmatism or in sub-arc crust formation.
- Whole-rock analysis carried out in amphibolite, similar to sample AE19, yielded positive $\epsilon_{\text{Nd}(2713)}$ and $\epsilon_{\text{Sr}(2713)}$ parameter values, with an Sm-Nd T_{DM} model age of ≈ 2985 Ma, indicating that the tholeiitic primordial magmas were originated in depleted mantle sources and later, during emplacement in the crust, they assimilated older crustal components.
- The single metarhyolite sample (MR1) yielded a Sm-Nd TDM model age of ≈ 2860 Ma, older than the suite, although newer than Sm-Nd TDM model ages of the other samples. Thus, the genesis of the protolith of this rock can be linked to sub-arc crust anatexis, a fact corroborated by the slightly negative $\epsilon_{\text{Nd}(2713)}$ values (-0.25) and positive $\epsilon_{\text{Sr}(2713)}$ values (+12), suggesting

a protolith correlated to juvenile crustal reservoir, with short crustal residence time. The Sm-Nd TDM model age of 2860 Ma replicates within error the upper intercept age that was obtained in the ≈ 2859 Ma inherited zircons (E04, E17, and E24) of sample MR2, confirming the probable age of one of the crusts involved in the sub-arc crust formation.

Thus, the development of the Carmópolis de Minas Layered Suite occurred in a restricted range time (2752 – 2710 Ma), during the last 40 Ma of the Rio das Velhas Orogeny. In this period, the crustal segments that currently compose the Campo Belo Metamorphic Complex consisted of isolated young crustal nuclei that were agglutinated between Rio das Velhas Orogeny and potassic magmatism after this. At the end of the Neoproterozoic events, the isolated continental nuclei, including the younger protocontinental segments and the last magmatic arcs (e.g. CMLS), were amalgamated, starting the architecture and stabilization of the Archean platform that preceded the Proterozoic events and presently represents the sialic substrate of this portion of the São Francisco Craton.

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