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In situ LA-ICPMS U-Pb dating of detrital zircons from the Cercadinho Formation, Minas Supergroup

Datação U-Pb in situ por LA-ICPMS em zircões detríticos da Formação Cercadinho, Supergrupo Minas

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Abstract

In this paper, new geochronological data obtained for the detrital rocks of the Cercadinho Formation, basal unit of the Piracicaba Group, Minas Supergroup, are presented. U-Pb Laser Ablation Induced Coupled Mass Spectrometer (LA-ICPMS) analysis in detrital zircon from quartzite samples provided a new maximum depositional age for the Cercadinho Formation. The youngest zircon population, among the dated samples, provided an average age of 2680 ± 24 Ma. These rocks have an expressive contribution of Meso- to Neoarchean zircons, with ages between 2812 ± 19 and 2909 ± 19 Ma, and older populations between 3212 ± 18 and 3272 ± 16 Ma, which occur mainly in the core of younger zircon grains. Comparing the U-Pb ages obtained in this work with previously published geochronological data for the basal units of the Minas Supergroup (Moeda Formation) an aging of the source for the detrital rocks of Cercadinho Formation can be observed, with a major contribution of zircons from TTG rocks crystallized between the Meso- and Neoarchean.

Keywords: Cercadinho Formation; Detrital zircons populations; Laser Ablation Induced Coupled Mass Spectrometer; U-Pb dating; Maximum depositional age.

Resumo

Nesse trabalho são apresentados novos dados geocronológicos obtidos para rochas detríticas da Formação Cercadinho, unidade basal do Grupo Piracicaba, Supergrupo Minas. Análises U-Pb por *Laser Ablation Induced Coupled Mass Spectrometer* (LA-ICPMS) em zircões detríticos provenientes de amostras de quartzito permitiram obter uma nova idade máxima para a deposição da Formação Cercadinho, sendo que a população mais jovem entre as amostras datadas forneceu uma idade média de 2680 ± 24 Ma. Essas rochas possuem uma expressiva contribuição de zircões Meso- e Neoarqueanos, com idades entre 2812 ± 19 and 2909 ± 19 Ma, e populações mais antigas entre 3212 ± 18 e 3272 ± 16, que ocorrem principalmente no núcleo de zircões mais jovens. Comparando-se esses resultados com idades anteriormente obtidas por outros autores para unidades basais do Supergrupo Minas (Formação Moeda), percebe-se um envelhecimento da área fonte para rochas de nível estratigráfico superior, com uma maior contribuição de zircões provenientes de TTGs cristalizados entre o Meso- e o Neoarqueano.

Palavras-chave: Formação Cercadinho; Populações de zircões detríticos; *Laser Ablation Induced Coupled Mass Spectrometer* (Ablação por Laser em Espectrometria de Massa com Plasma Indutivamente Acoplado); Datação U-Pb; Idade máxima de sedimentação.

INTRODUCTION

Geochronological analysis of heavy minerals, and especially detrital zircons in clastic rocks, represents an important tool for the study of the source of sediments and the depositional history of these rocks (Košler et al., 2002). Because of their high resistance, detrital zircons 'survive' through multiple sedimentary cycles (Thomas, 2011). In the Quadrilátero Ferrífero (QF) region of Minas Gerais State, Brazil (Figure 1), the main period of crustal growth took place between 3.2 to 2.8 Ga (Machado and Carneiro, 1992; Teixeira et al., 1996; Lana et al., 2013). Reworking of the old crust, with widespread migmatization in cratonic basement, intrusion of granitic bodies and felsic volcanism followed between 2.86 – 2.6 Ga (Machado et al., 1992; Teixeira et al., 1996; Noce et al., 1998; Romano et al., 2013), resulting in the accretion of juvenile and crustal magmas into the upper crust and at the same time causing widespread isotopic disturbance in host rocks. Younger ages documented for the QF region indicate a newer episode of magmatism and metamorphism around 2.1 Ga (Machado et al., 1992; Machado et al., 1996; Rosière et al., 2012).

The QF is in part delineated by metasedimentary platformal Minas Supergroup, which represents a thick supracrustal sequence of Paleoproterozoic age. Its period of deposition lacks well defined magmatic and metamorphic events, and all existing geochronological data are from detrital zircon U-Pb ages (Figure 2).

The Minas Supergroup is subdivided into the basal Caraça, Itabira, Piracicaba, through the top Sabará Groups (Dorr, 1969) (Figure 2). In the case of the Piracicaba Group, the only available data are from its basal unit, the Cercadinho Formation (Machado et al., 1996).

In order to obtain reliable data concerning the variety of sources of the detrital sediments, a high number of zircon crystals is required (80 – 100 grains, Košler et al., 2002), so that the provenance analysis can be better evaluated (Fedo et al., 2003). This can be attained with the use of fast age-dating equipment, such as the LA-ICPMS (Laser Ablation Induced Coupled Mass Spectrometer). This method allows for the dating of individual crystals and different zones in the same crystal, which permits the identification of specific source rocks (Fedo et al., 2003) and to obtain ages of different growth zones in each zircon crystal.

The present work introduces new zircon U-Pb ages obtained by the LA-ICPMS technique for the Cercadinho Formation, helping to fill a gap in the geochronological record of the Minas Supergroup. Since, in some locations of the QF, the Cercadinho Formation is in direct contact with the giant banded iron formation-hosted high-grade iron deposits, the age obtained for its deposition further helps delimitate the age of deposition of the Cauê Formation.

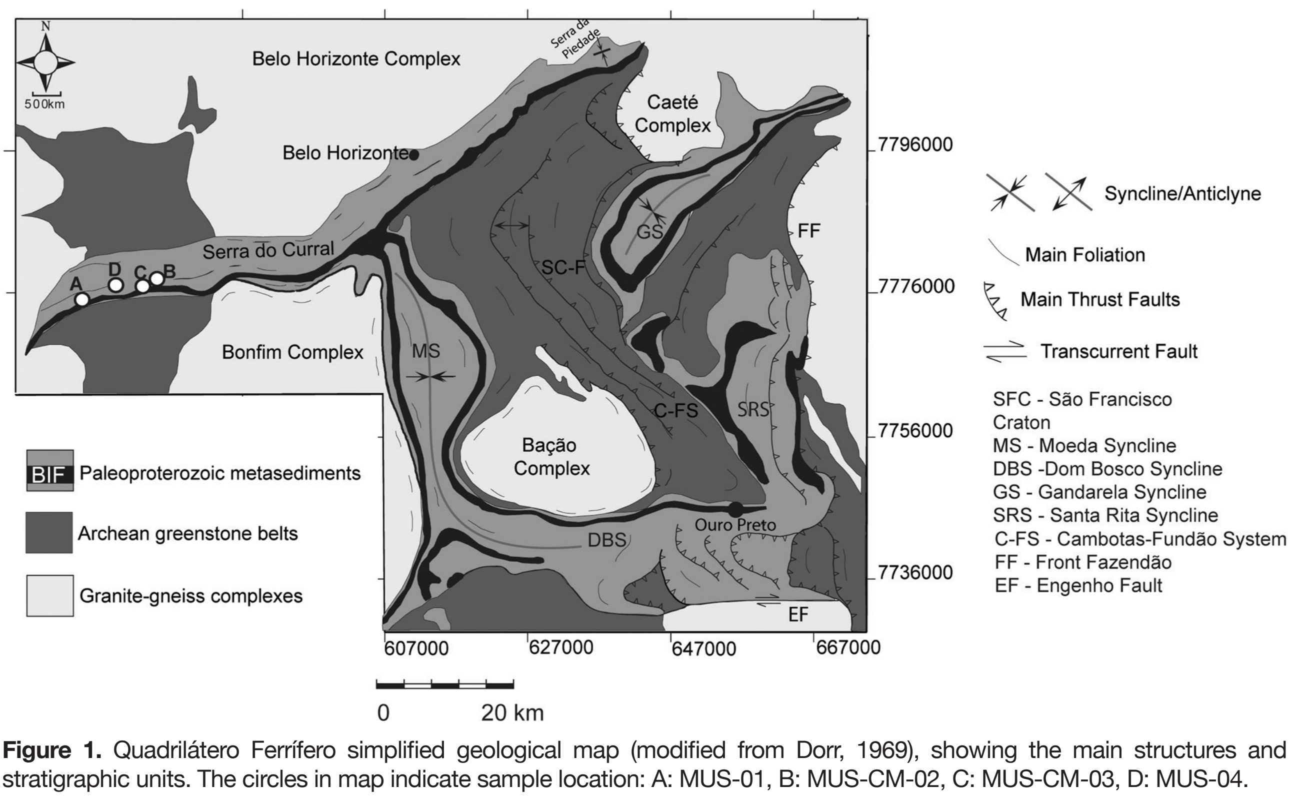


Figure 1. Quadrilátero Ferrífero simplified geological map (modified from Dorr, 1969), showing the main structures and stratigraphic units. The circles in map indicate sample location: A: MUS-01, B: MUS-CM-02, C: MUS-CM-03, D: MUS-04.

REGIONAL GEOLOGICAL CONTEXT

The Quadrilátero Ferrífero (QF) region is located in the southern portion of the São Francisco Craton (Almeida, 1977) (Figure 1). It comprises an Archean granite-gneiss basement, the Archean Rio das Velhas Supergroup greenstone belt sequence, and the Paleoproterozoic metasedimentary Minas Supergroup (Dorr, 1969) (Figure 2). The region is characterized by a complex structural arrangement, with Archean basement domes surrounded by large synclines where the Minas Supergroup rocks dominate (Dorr, 1969; Chemale et al., 1994; Alkmim and Marshak, 1998).

The proposed Proterozoic tectonic evolution for the region suggests three main deformational phases (Alkmim and Marshak, 1998). The first episode generated fold and thrust belts with an NE-SW trend, verging to NW, during the Rhyacian Event (2.1 – 2.0 Ga). The second phase is related to the Paleoproterozoic orogenic collapse, caused by a regional extensional tectonic, resulting in the uplift of the Archean granite-gneiss domes and formation

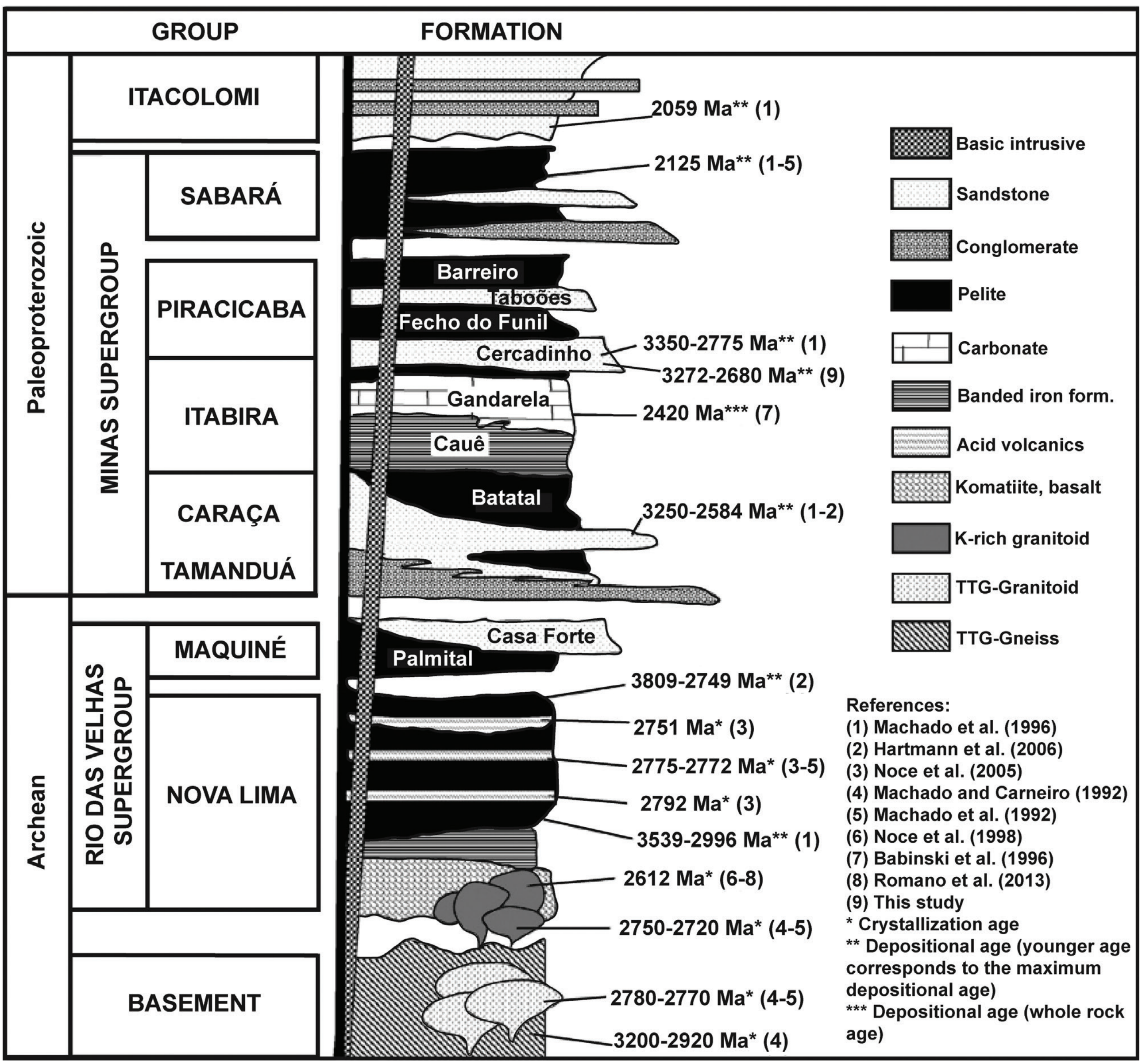


Figure 2. Stratigraphic column of Quadrilátero Ferrífero. In the right side of the figure, the geochronological data obtained for the different stratigraphic units and the references of these data. Modified from Romano et al. (2013).

of the regional synclines (the dome-and-keel structure of Marshak and Alkmim, 1989). The third event is related to the Neoproterozoic Brasiliano orogeny (0.7 – 0.45 Ga), and was responsible for the formation of fold and thrust belts verging to the west (Alkmim and Marshak, 1998).

The regional metamorphic temperatures vary from 300 to 600ºC and estimated pressures ranges from 3 to 5 kbar (Pires, 1995). Thermal metamorphism of low to intermediate temperatures is also described, and it is related to the uplift of the basement domes during orogenic collapse with tectonic extension (Marshak and Alkmim, 1989).

The Caraça, Itabira, Piracicaba and Sabará groups encompass the subdivision of the Minas Supergroup Paleoproterozoic metasedimentary rocks (Dorr, 1969) (Figure 2). The basal Caraça Group includes the Moeda and Batatal Formations, and corresponds to a clastic, alluvial to deltaic or shallow marine sequence, formed by conglomerate, quartzite and phyllite. The Itabira Group represents a period of stable platform, with the deposition of chemical-clastic sediments. The Cauê Formation hosts the great volume of iron formations and iron ore bodies in the region, which are of great economic importance (Rosière et al., 2008), and the Gandarela Formation is composed of carbonate units (Babinsky et al., 1995) (Figure 2).

The Piracicaba Group is formed by the Cercadinho, Fêcho do Funil, Taboões and the top Barreiro formations. The Sabará Group was previously considered to be part of the Piracicaba Group (Simmons, 1968), but Renger et al. (1994) later proposed that the Sabará rocks should be elevated to the status of a group. The Cercadinho Formation is composed mainly of ferruginous quartzite and conglomerates at its base, and also ferruginous phyllite and dolomitic phyllite (Simmons, 1968). Hematite is described in both the conglomerate matrix and in the quartzite. The Fêcho do Funil Formation is composed of phyllite, siltstone and dolomite (Simmons, 1968). The Taboões Formation is composed predominantly of quartzite, with argillaceous, silty and dolomitic layers in its base, in the gradational contact with the underlying unit (Simmons, 1968). The highly pure quartzite has trace amounts of sericite, specularite and other opaque minerals (Simmons, 1968). On the top of the Piracicaba Group, the Barreiro Formation consists of carbonaceous phyllites interbbeded with dark purplish-reddish and brown phyllites.

The Sabará Group unconformably overlies the Piracicaba Group. The deposition of this group is considered to be related to the Rhyacian Event (Machado et al., 1996), consisting of a flysch sequence formed by metagraywacke, carbonaceous phyllite, metadiamictites, metaconglomerates, and felsic to intermediate metavolcanic rocks (Dorr, 1969).

The Itacolomi Group (Dorr, 1969) is the youngest unit in Quadrilátero Ferrífero, resting unconformably on the Minas Supergroup. It is interpreted as a molassic sequence composed of quartzite, metarkose and metaconglomerate, some of them containing clasts of iron formation.

PREVIOUS GEOCHRONOLOGY OF THE QUADRILÁTERO FERRÍFERO

In the QF region, there are a great deal of data for the TTG (tonalite-trondhjemite-granodiorite) complexes and associated granitic intrusions (Machado et al., 1992; Machado and Carneiro, 1992; Noce, 1995; Teixeira et al., 1996; Noce et al., 1998; Noce et al., 2000; Seixas et al., 2012; Romano et al., 2013; Lana et al., 2013). The oldest period of crustal generation in the QF occurred between 3.2 – 2.8 Ga (Machado and Carneiro, 1992). Lana et al. (2013) subdivide this period in three different events of TTG magmatism: the Santa Bárbara Event (3.22 – 3.20 Ga), the Rio das Velhas Event I (2.93 – 2.90 Ga) and the Rio das Velhas Event II (2.80 – 2.77 Ga).

Between 2.86 and 2.6 Ga, the basement was affected by tectonic-metamorphic events with migmatization and voluminous potassic granitic intrusions (Noce et al., 1998; Romano et al., 2013). Machado et al. (1992) obtained ages of 2.78 and 2.72 Ga for the emplacement of granitoids. Romano et al. (2013) indicated the period of 2.75 to 2.60 Ga for the intrusion of potassic granitoids, with the period 2.75 to 2.7 Ga being the most representative. A younger age of 2.35 Ga was found by Seixas et al. (2012) (U-Pb ID-TIMS in zircons from the Lagoa Dourada TTG suite), which was considered to be a time of continental crust production during the end of the Siderian.

The ages obtained for volcanic felsic rocks of the Rio das Velhas Supergroup (2.78 and 2.7 Ga, Machado et al., 1992) indicate that the greenstone belt volcanism was contemporaneous to the granitoid emplacement. Lobato et al. (2007) obtained an age of 2.67 Ga on hydrothermal monazite associated with gold mineralization in the Rio das Velhas Supergroup, indicating that the hydrothermal gold mineralization occurred during the latest stages of the greenstone belt evolution.

The geochronological record of the Minas Supergroup establishes the deposition of its units to be between 2600 and 2125 Ma (Figure 2). Using the zircon Pb-Pb dating method, Machado et al. (1996) dated detrital zircons from the Moeda Formation quartzite, obtaining ages between 3.26 and 2.61 Ga, and suggested that deposition started at 2.6 Ga. Hartman et al. (2006) obtained an U-Pb SHRIMP age of 2.58 Ga on detrital zircons from the same Moeda Formation quartzite.

The whole rock Pb-Pb dating in a weakly deformed stromatolitic limestone from the Gandarela Formation (Babinski et al., 1995) yielded an age of 2.42 Ga, which corresponds to the upper depositional limit of the Cauê iron formations. Zircons from a metavolcanic layer within the Cauê iron formation provided an U-Pb ICP-MS age of 2.65 Ga (Cabral et al., 2012), implying an Archean age for the deposition of the iron formations, therefore older than the basal unit of the Minas Supergroup. Geocronological studies on monazite in hematite-martite hydrothermal veins, in the western portion of the Curral Range, indicate an U-Pb SHRIMP age of 2.03 Ga for the iron mineralization (Rosière et al., 2012).

Machado et al. (1996) obtained LA-ICPMS Pb-Pb ages on detrital zircons from a sample of quartz arenite, lower unit of the Piracicaba Group, Cercadinho Formation, and obtained an older population of zircons of 3.35 Ga and a younger population of 2.78 Ga, with a mode at 2.8 – 2.9 Ga. Babinski et al. (1995) obtained a whole rock Pb-Pb age of 2.1 Ga for deformed dolomitic lenses in the Fêcho do Funil Formation (Piracicaba Group), but this age was interpreted to be related to the metamorphism associated to the Rhyacian Event in the QF region. The age of this metamorphic event is supported by the geochronological data obtained for the upper stratigraphic units.

Zircons from metagraywackes from the Sabará Group were dated by the U-Pb method (Machado et al., 1992; Machado et al., 1996), providing ages of 2.16, 2.13 and 2.12 Ga. This set of ages indicates that the end of the deposition of the Minas Supergroup occurred around 2125 Ma. Quartzites from the Itacolomi Group were dated by Machado et al. (1996) using the zircon Pb-Pb age method, and produced an age of 2.06 Ga. According to Machado et al. (1996). the ages documented for the Sabará and Itacolomi Groups indicate that their sedimentation was related to a foreland basin associated with the Rhyacian Event.

THE CERCADINHO FORMATION

For the present work, samples from the basal unit of the Piracicaba Group, the Cercadinho Formation, were collected in the western part of Serra do Curral (Figure 1). This region was chosen because the rock sections of the Piracicaba Group are thicker and better exposed (Simmons, 1968), and because western Serra do Curral is less deformed (Rosière et al., 2001).

The samples were collected in four different points of the ridge, at the base of the Cercadinho Formation, near the contact with the Cauê Formation. One of the samples (MUS-02) was taken exactly at the contact between these two formations (Figure 3B). The rocks consist of quartzite (Figure 3A) and conglomeratic quartzites, which are poorly sorted, varying from fine sand to pebble, containing lithic fragments (quartzites, Figure 3B and 3C) and muscovite. All samples contain iron oxides (probably martite), which may be both disseminated or associated with quartz veins. The sample directly in contact with the Cauê Formation (Figure 3B) has a considerable contribution of iron oxide in its matrix.

METHODS

The samples were prepared in the Laboratory for Geochronology and Geochemistry (LOPAG), Geology Department of Universidade Federal de Ouro Preto, Brazil. About 20 kg of each of the four samples were processed for zircon extraction making use of conventional jaw crusher, milling, manual selecting, heavy liquids and magnetic separation. The zircons were hand-picked under a binocular microscope and mounted on 25 mm epoxy mounts. The final process consisted in the polish of their surfaces.

In order to observe the morphological characteristics and identify the zonation patterns in the zircon crystals and to have a guide for the geochronologic analysis, optical microscope, backscattered electron (BSE) and cathodoluminescence (CL) images of individual crystals were obtained for this work. The backscattered imaging (Figure 4) was performed in the Center of Microscopy of Universidade Federal de Minas Gerais, Belo Horizonte, MG, Brazil (http://www.microscopia.ufmg.br), and was obtained on a scanning electron microscope (SEM) FEG Quanta 200 FEI. The cathodoluminescence images (Figure 4) were obtained at the Laboratory of Electronic Microscopy of the Geoscience Institute of the Universidade de Campinas (IG/UNICAMP) on a SEM LEO 430i, with a ChromaCL cathodoluminescence detector attached.

The LA-ICPMS analysis for U-Pb geochronology of detrital zircons was conducted in the Laboratory of Geochronology of Universidade Federal de Ouro Preto, Minas Gerais. The equipment is an Agilent 7700 Q-ICP-MS and a 213 nm New Wave laser. The operating conditions were optimized to provide maximum sensitivity for the high masses (^{207}Pb and ^{238}U) while inhibiting oxide formation (ThO+/Th+<1.0%). The standard and unknown zircons were ablated in small volume (tear-drop shape) sample cells, 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 measurements of U, Th and Pb signals during ablation, and a 30 s washout. 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, ~6-8 J/cm^2 fluence and 10 Hz repetition rate. Ablations occurred in a He carrier gas, and the resulting aerosol was

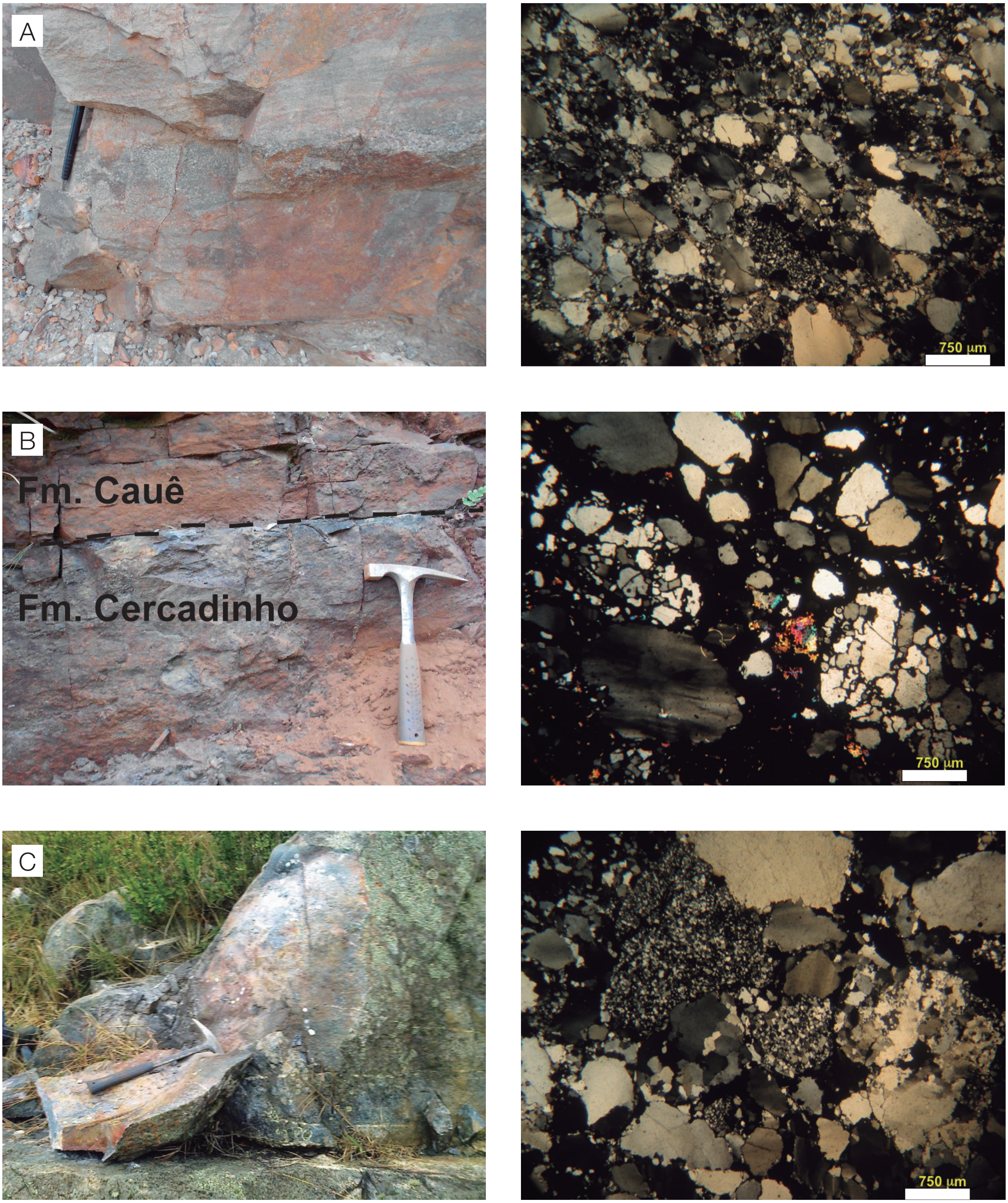


Figure 3. Outcrop pictures from the sampled locations and corresponding photomicrographies. (A) Sample of quartzite, with iron oxides in its matrix. (B and C) Poorly sorted conglomeratic quartzite, with iron oxides in the matrix. The sample in B was collect right in the contact with Cauê Formation. A: M-US-01; B: M-US-CM-02; C: M-US-CM-03.

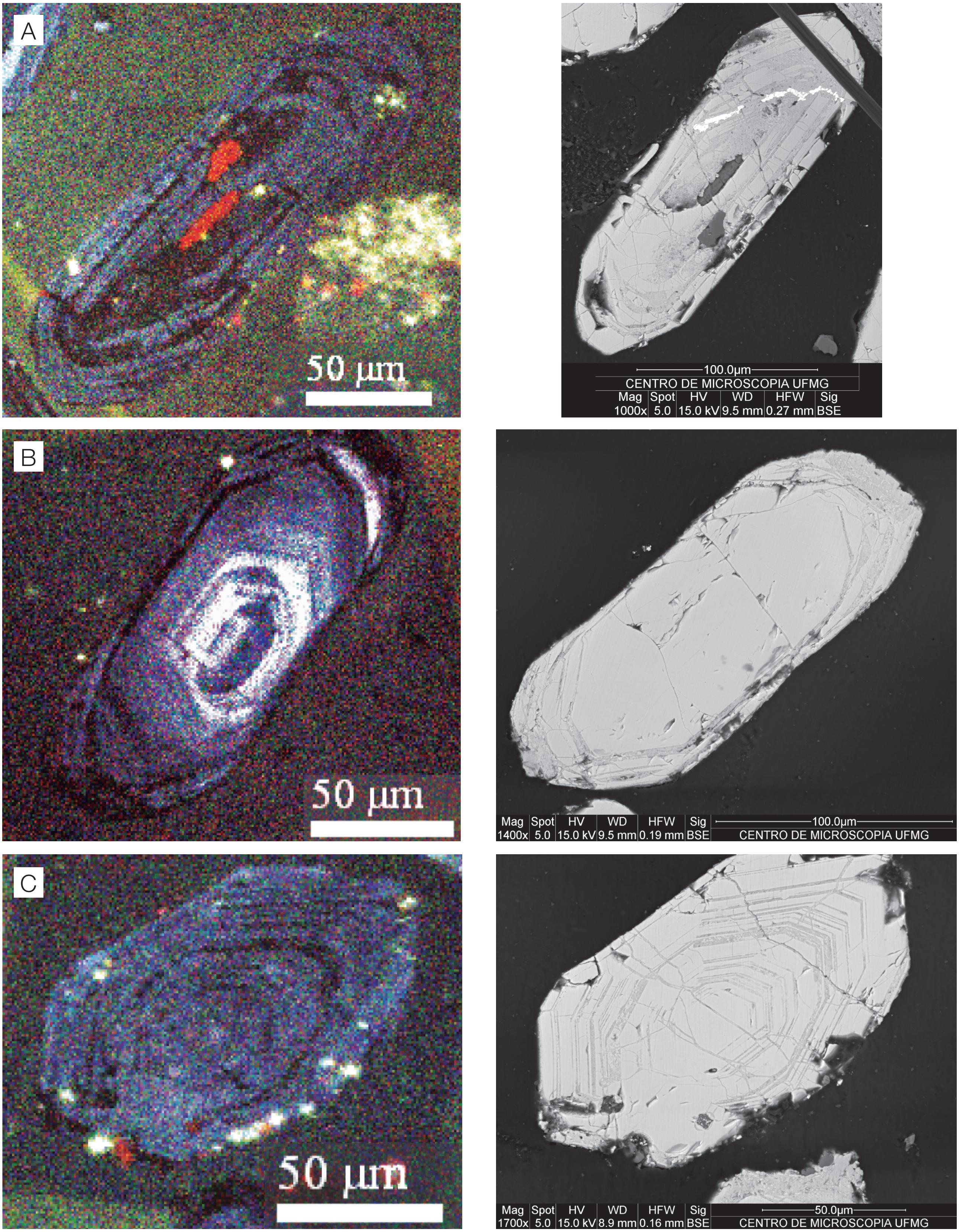


Figure 4. Cathodoluminescence (left column) and corresponding backscattered images (right column) of some of the analyzed zircons. The grains are highly fractured, and show internal zoning and inclusions.

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}Pb+Hg; ^{232}Th, ^{238}U.

The relevant isotopic ratios ($^{207}Pb/^{206}Pb$, $^{208}Pb/^{206}Pb$, $^{208}Pb/^{232}Th$, $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$, where ^{235}U was calculated from ^{238}U counts via the natural abundance ratio $^{235}U = {}^{238}U/137.88$) have been calculated using the data reduction software Glitter (Van Achterbergh et al., 2001). Individual isotopic ratios were displayed in time-resolved mode. For this laser system, isotopic ratios generated during the first 5s of each analysis were discarded. The integration window for the remainder of each analysis was chosen so as to maximize concordance and to exclude signal segments that were related to zones of Pb loss (e.g. fractures), high common Pb (as recognized by ^{204}Pb+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 - 3 analyses of standards). Common ^{204}Pb was measured and compared against primary and secondary standards. No common lead correction was necessary given the low ^{204}Pb content relative to primary standard GJ-1.

Two secondary standards were used during runs: Plesovice zircon (337 ± 1 Ma; Sláma et al., 2008) and M125 zircon (624 ± 1 Ma). Sixty-two analyses of Plesovice zircons gave a Concordia age of 338 ± 1 Ma (mean $^{207}Pb/^{206}U$ age = 337 ± 7; mean $^{206}Pb/^{238}U$ age = 338 ± 1; mean $^{207}Pb/^{235}U$ age = 338 ± 1 Ma). Fifty-two analyses of the M125 zircon gave a Concordia age of 526 ± 1 Ma (mean $^{207}Pb/^{206}U$ age = 525 ± 7; mean $^{206}Pb/^{238}U$ age = 526 ± 1; mean $^{207}Pb/^{235}U$ age 526 ± 1 Ma). The LA-ICPMS data were reduced using the ISO-PLOT program (Ludwig, 1999) with ages calculated and plotted on concordia diagrams using the IsoplotEx 2.46 program (Ludwig, 1999).

RESULTS

The zircon grains found in all the samples are brown, translucent to opaque. They are stubby, in general with few elongated grains. The grains can be rounded to subrounded, but most of them show preserved prismatic shape (Figure 4), indicating less transport and a proximal source. The BSE and CL images show that the grains are characterized by oscillatory zoning (Figure 4), with some having older cores (Figures 6A, 6C and 6F). Inclusions are also observed (Figure 4A). The CL images show that some zircons have a higher luminescence in the core (Figure 4B). Because of their detrital nature, the zircon grains are highly fractured (Figure 4).

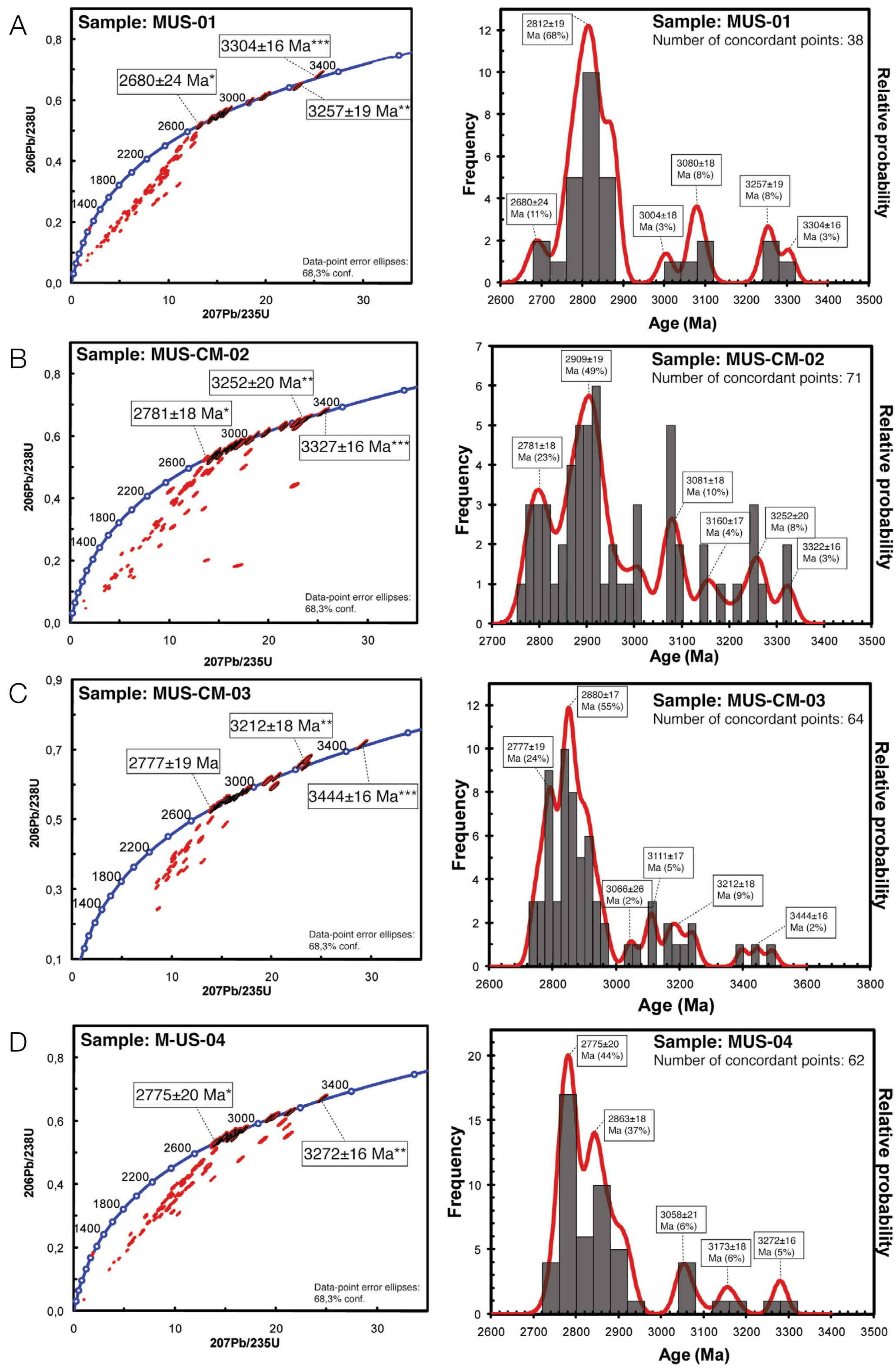
The results obtained through the LA-ICPMS analysis are shown as concordia diagrams and frequency histograms (Figure 5). The concordia diagrams show a considerable number of concordant ages. Table 1 shows the number of zircons, analytical points, concordant points, the ages of the youngest and oldest zircon populations, and age peaks (average age value of the most significant zircon population) for each sample. During the analyses, the most fractured zircon grains were avoided, as well as those that displayed inclusions and internal flaws. Some grains had more than one analytical spot, in order to verify the different ages between the core and the grain margin (Figure 6).

In general, the oldest zircon ages are Paleoarchean, placed between 3212 ± 18 and 3444 ± 16 Ma (Table 1, Figures 6A and 6B). The oldest ages correspond, in most cases, to the core of the zircon grains (Figures 6B and 6C). The youngest zircon population ages vary from 2680 ± 24 to 2781 ± 18 Ma (Neoarchean) (Table 1, Figure 6G). These ages are commonly registered in the overgrowth zones of older grains (Figure 6F). The peak of all ages is between 2812 ± 19 and 2909 ± 19 Ma (Figures 6B to 6F), indicating a major contribution of zircons from the Meso- to the Neoarchean.

The histogram of sample MUS-01 has six peaks of frequency (Figure 5A) and four zircon populations were identified. The oldest zircon population is formed by Paleoarchean zircons (3257 ± 19), and the oldest zircon is 3304 ± 16 Ma. There are two populations of Mesoarchean zircons (3080 ± 18 and 2812 ± 19 Ma), with the last being the most significant zircon population of this sample. The youngest zircon population of this sample (and the youngest one among all the samples) has an average age of 2680 ± 24 Ma, and it is formed by Neoarchean zircons.

The frequency age histogram of sample MUS-CM-02 shows six peaks and five zircon populations (Figure 5B). The oldest zircon population is formed by Paleoarchean zircons (3252 ± 20 Ma), and the oldest dated zircon is 3327 ± 16 Ma in age. Three zircon populations are from the Mesoarchean (3160 ± 17, 3081 ± 18 and 2909 ± 19 Ma), the younger one being the most representative zircon population of the sample. The youngest zircon population (2781 ± 18 Ma) is close to the limit between Meso- and Neoarchean.

Sample MUS-CM-03 also has six peaks in its frequency histogram (Figure 5C) and four zircon populations. The oldest zircon population is of Paleoarchean age (3212 ± 18 Ma), and the oldest zircon is 3444 ± 17 Ma, being the oldest zircon population among the samples (Figure 6A). The sample has two Mesoarchean zircon populations (3111 ± 17 and 2880 ± 17 Ma), the latter being the most representative one. The youngest zircon population is 2777 ± 19 Ma in age, and it is formed by Neoarchean zircons.



*Youngest zircon population, **Oldest zircon population, ***Oldest zircon.

Figure 5. Concordia diagrams and frequency histograms (probability curve shown) of zircon ages obtained for the four samples. In the concordia diagrams, the youngest and oldest populations are indicated. In the frequency histograms, the zircon populations' ages are indicated in each peak of frequency. Supplementary data: Appendix 1; Appendix 2; Appendix 3; Appendix 4.

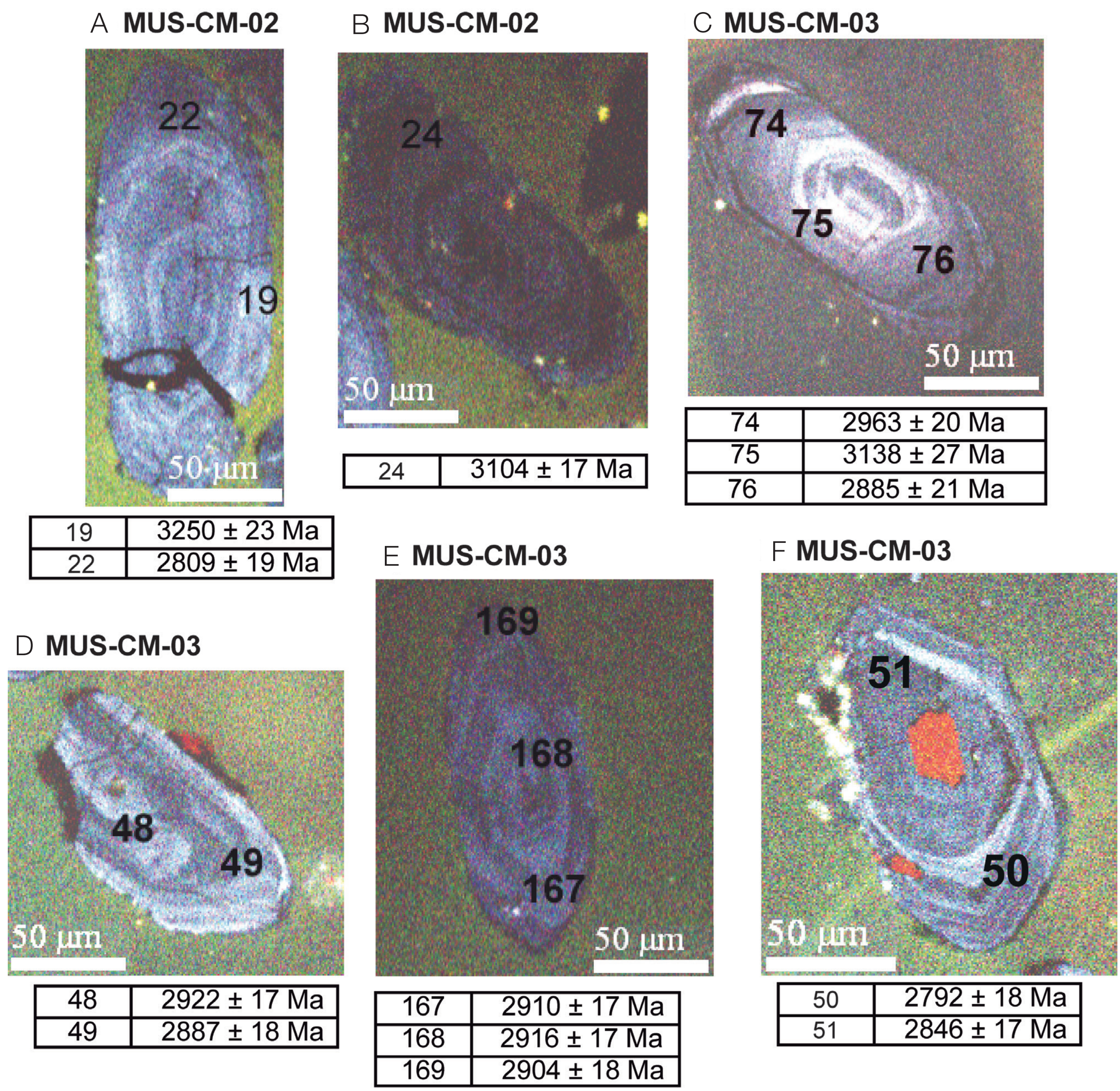


Figure 6. Examples of zircon crystals indicating where the analytical spots were located. The table below each image indicates the ages obtained for each one of these spots ($Pb^{207}/Pb^{206} \pm 1\sigma$). (A) Paleoarchean zircon (core and overgrowth). (B) Paleoarchean core with Meso- to Neoarchean overgrowth. (C to E) Mesoarchean zircon core with younger overgrowths. (F) Mesoarchean zircon core with Neoarchean overgrowth. (G) Neoarchean zircon.

The histogram of sample MUS-04 has five peaks of frequency and five zircon populations. The oldest zircon population is of Paleoarchean age (3272 ± 16 Ma), and the oldest zircon is 3343 ± 18 Ma. There are three populations of Mesoarchean age (3173 ± 18, 3058 ± 21 and 2863 ± 18 Ma). The Neoarchean zircon population of 2775 ± 20 Ma is the youngest one in the sample, and is also the most representative one.

DISCUSSION

The geochronological data obtained for this study indicate a maximum depositional age of about 2680 ± 24 Ma (youngest zircon population) for the onset of deposition of the detrital Piracicaba Group sequence (Table 1).

The detrital, basal Moeda conglomerate and quartzite, yielded maximum ages of deposition of 2606 ± 47 Ma and

2584 ± 10 Ma (Machado et al. (1996) and Hartman et al. (2006), respectively). The youngest zircon population obtained for the Cercadinho Formation in the present study, 2680 ± 24 Ma (Table 1), is about 74 million years older than those of the Moeda Formation. The peak ages are between 2812 ± 19 and 2909 ± 19 Ma (Table 1), and the oldest populations are between 3212 ± 18 and 3272 ± 16 Ma (Table 1). Comparing these results with the previous geochronological data for the Minas Supergroup sequence (Table 2), the aging of the source rocks for the youngest Piracicaba Group stratigraphic unit of the Minas Basin is clear.

These geochronological data justify some considerations concerning the rock sources for the Cercadinho Formation. The older zircon populations, with ages between 3252 and 3272 Ma may correspond to the older period of TTG magmatism. These ages are even older than those reported by Machado and Carneiro (1992) (3.2 – 2.8 Ga). Comparing the results with the work of Lana et al. (2013) (Table 3), the zircon population of 3212 ± 18 Ma (Figure 5, Table 3) must have crystallized during the Santa Bárbara TTG magmatic event (3220 – 3200 Ma). Part of these grains experienced overgrowth during subsequent events, resulting in younger ages on their rims. Comparing the results with those of Lana et al. (2013), it can be concluded that the significant Mesoarchean populations, with ages between 2812 and 2909 Ma, suggest that the major contribution for the sediments of the Cercadinho Formation are sourced in the TTG rocks formed during the Rio das Velhas magmatic events (2930 – 2900 to 2770 Ma) (Table 3).

Table 1. Geochronological data obtained for the dated samples.

Sample	MUS-01	MUS-CM-02	MUS-CM-03	MUS-04
Number of zircons	119	205	149	423
Number of Analytic Points	104	122	110	108
Concordant Points	38	71	64	62
Youngest Zircon Population (Ma)*	2680 ± 24	2781 ± 18	2777 ± 19	2775 ± 20
Oldest Zircon Population (Ma)*	3257 ± 19	3252 ± 20	3212 ± 18	3272 ± 16
Peak of Ages (Ma)**	2812 ± 19	2909 ± 19	2880 ± 17	2775 ± 20
Peak of Ages Percentage (%)***	68	49	55	44

*Average of Pb^{207}/Pb^{206} ± 1σ ages;
**Average value of the most significant zircon population;
***Percentage of concordant points in the most expressive zircon population.

Table 2. U-Pb and Pb-Pb depositional ages obtained for rocks from different stratigraphic units of Minas Supergroup and overlying units in different publications.

<table>
<tr><th colspan="2">Stratigraphic unit</th><th colspan="2">Geochronological data and dated rocks</th></tr>
<tr><td colspan="2">Itacolomi Group</td><td colspan="2">2059 ± 58 Ma
(Pb-Pb dating on detrital zircons from quartzites, Machado et al., 1996)</td></tr>
<tr><td colspan="2">Sabará Group</td><td colspan="2">2125 ± 4 Ma
(U-Pb dating on detrital zircons from metagraywackes, Machado et al., 1996)</td></tr>
<tr><td rowspan="3">MINAS SUPERGROUP</td><td>Cercadinho Formation</td><td>2775 ± 9 Ma
(Pb-Pb dating on detrital zircons from quartz arenite, Machado et al., 1996)</td><td>2680 ± 24Ma[A]
2775 ± 20Ma[D]
2777 ± 19 Ma[C]
2781 ± 18Ma[B]
(U-Pb dating on detrital zircons from quartzite and conglomeratic quartzite)</td></tr>
<tr><td>Gandarela Formation</td><td colspan="2">2420 ± 19 Ma
(Whole rock Pb-Pb dating in stromatolitic limestone, Babinski et al., 1995)</td></tr>
<tr><td>Moeda Formation</td><td>2606 ± 47 Ma
(Pb-Pb dating on detrital zircons from quartzite, Machado et al., 1996)</td><td>2584 ± 10 Ma
(U-Pb dating on detrital zircons from quartzite, Hartman et al., 2006)</td></tr>
</table>

The results obtained in this work are indicated: [A]MUS-01; [B]MUS-CM-02; [C]MUS-CM-03; [D]MUS-04; Detrital zircons ages indicate maximum depositional age, and the whole rock age indicate depositional age.

Table 3. Comparison between the ages of different zircon populations obtained in this study and the magmatic events registered in the Quadrilátero Ferrífero.

Zircon Populations	Younger Zircon Populations (Ma)	Mesoarchean ages (Ma)	Zircon Population (Ma) in the SB event interval	Older Zircon Populations (Ma)
Cercadinho Formation (This study)	2680 ± 24[A] 2775 ± 20[D] 2777 ± 19[C] 2781 ± 18[B]	2812 ± 19[A] 2863 ± 18[D] 2880 ± 17[C] 2909 ± 19[B]	3212 ± 18[C]	3272 ± 16[D] 3257 ± 19[A] 3252 ± 20[B]
Santa Bárbara TTG Magmatic Event (Lana et al., 2013)			3220 – 3200	
Rio das Velhas Magmatic Event (Lana et al., 2013)	2930 – 2900 to 2770			
Intrusive Potassic Granitoids (Romano et al., 2013)	2750 – 2700			
Felsic Volcanism (Rio das Velhas Sg.) (Machado et al., 1992)	2776 – 2772			

[A]MUS-01, [B]MUS-CM-02, [C]MUS-CM-03, [D]MUS-04.

Younger zircon populations between 2680 ± 24 and 2781 ± 18 Ma for the Cercadinho Formation are within the range of ages of the younger Archean magmatism recorded in the QF area (Machado et al., 1992; Romano et al., 2013) (Table 3), which generated intrusive potassic granitoids (2750 – 2700 Ma, Romano et al., 2013). Another possible source for these younger zircons are felsic volcanic rocks from the Rio das Velhas Supergroup, which yielded ages of 2776+23/-10 Ma and 2772 ± 2 Ma (Machado et al., 1992).

Finally, the results obtained in this work indicate a maximum age of deposition for the Cercadinho Formation in ca. 95 Ma, younger than previously verified by Machado et al. (1996) (2775 ± 9 Ma). The peak of ages between 2800 and 2900 Ma in Machado et al. (1996) coincides with those obtained in this work, and the older zircon ages of 3353 ± 276 Ma fall in the interval of 3212 ± 18 to 3444 ± 11 Ma obtained in this study.

CONCLUSIONS

The geochronological analysis of detrital zircons from the Cercadinho Formation has indicated that:

- All zircon grains analyzed are inherited from Archean sources;
- Although the Piracicaba Group is stratigraphically above the Caraça and Itabira Groups, the present data indicate a maximum age of deposition of the base of the Piracicaba Group at 2680 ± 24 Ma, 95 Ma younger than previous data obtained by Machado et al. (1996) by Pb-Pb in detrital zircons (2775 ± 9 Ma).
- The Cercadinho Formation rocks have a considerable contribution of Paleoarchean zircons, frequently in the core of younger zircons, and were generated in earlier TTG magmatic events;
- The major contribution of zircons for these rocks are from TTG rocks generated between the Mesoarchean to its limit with the Neoarchean (2.9 – 2.8 Ga), indicating an aging for the source rocks of the upper stratigraphic units, as the younger Rio das Velhas magmatic unit sources were exhumed;
- Due to the older ages obtained for the upper units, the age of the Cercadinho Formation does not provide a conclusive understanding regarding the stratigraphic stacking of the Minas Supergroup, neither does it add information about the depositional age of the Cauê banded iron formations.

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