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DETRITAL ZIRCON U-Pb GEOCHRONOLOGY OF THE MARICÁ GROUP: SOURCES AREAS AND MAXIMUM DEPOSITIONAL AGE

GEOCRONOLOGIA U-Pb DE ZIRCÃO DETRITÍCO DO GRUPO MARICÁ: ÁREAS FONTES E IDADE MÁXIMA DE DEPOSIÇÃO

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RESUMO - O Grupo Maricá é a unidade basal da Bacia do Camaquã e é composto principalmente por depósitos fluviais e marinhos rasos. Estudos de proveniência do Grupo Maricá são fundamentais para o entendimento das fases iniciais dessa bacia. Este trabalho objetiva apresentar novos dados de proveniência de LA-ICP-MS U-Pb para o reconhecimento das áreas fontes e determinação da idade máxima de deposição do Grupo Maricá. Este trabalho inclui reconhecimento de campo, análises petrográficas e a datação U-Pb de um arenito e dois clastos, da Formação Arroio América, a unidade mais jovem do Grupo Maricá. A Formação Arroio América registra depósitos de um sistema fluvial entrelaçado e é composta por arenitos, arenitos conglomeráticos e conglomerados. O clasto granítico foi datado em 2166 ± 9.3 Ma. Dados de proveniência de uma amostra de arenito e de um clasto de arenito exibem intervalos de idades e padrões de distribuição semelhantes. São ambos derivados de fontes mistas (599 - 3025 Ma), com grande contribuição de fontes siderianas (2422 Ma), ediacaranas (621 Ma) e estaterianas (1749 Ma). Contribuições menores riacianas (2212-2040 Ma) e arqueanas (2823-2503) também estão presentes. A falta de zircões tonianos em conjunto com o clasto granítico paleoproterozóico indicam que não há contribuição do embasamento do Grupo Maricá (Terreno São Gabriel). As fontes ediacaranas estão relacionadas aos granitos ediacaranos da região de Bagé como a suíte Santo Afonso. A idade máxima de deposição do arenito é de 599,8 ± 11,5 Ma e do clasto de arenito de 619,4 ± 11 Ma. A semelhança de idades máximas e áreas fontes indicam que porções dessa bacia e provavelmente do próprio Grupo Maricá serviram como fonte de sedimentos, indicando um contexto dinâmico com deposição, soterramento, soerguimento e retrabalhamento em um curto espaço de tempo.
Palavras-chave. Grupo Maricá. Formação Arroio América. Proveniência U-Pb. Zircão Detrítico. Idade Máxima de Deposição.

ABSTRACT - The Maricá Group is the basal unit of the Camaquã Basin and comprises mainly fluvial deposits and shallow marine beds. Provenance studies of the Maricá Group are crucial to understanding the initial development of this basin. This paper aims to present new LA-ICP-MS U-Pb provenance data for the evaluation of the source areas and the maximum depositional age of the Maricá Group. This work includes fieldwork recognition, petrographic analysis, and U-Pb dating of one sandstone and two clasts' samples, from the Arroio América Formation, the youngest unit from Maricá Group. The Arroio América Formation was deposited on a braided fluvial system and is composed of sandstones, conglomeratic sandstones, and conglomerates rocks. The granitic clast yields a Concordia age at 2166 ± 9.3 Ma. The sandstone and the sandstone clast display a similar zircon age range and pattern. They are derived from mixed sources (599 – 3025 Ma) with a major contribution of Syderian (2422 Ma), Ediacaran (621 Ma), and Statherian (1749 Ma) sources. Minor contributions from Ryacian (2212-2040 Ma) and Archean (2823-2503) are also present. The lack of Tonian zircon ages together the Paleoproterozoic granitic clast (2.1 Ga) reveals that there are no contributions from the basement of the Maricá Group (São Gabriel Terrane). The Ediacaran sources are related to Ediacaran granites from Bagé Region as the Santo Afonso Suite. The maximum depositional age of the sandstone was constrained at 599.8 ± 11.5 Ma and the sandstone clast at 619.4 ± 11 Ma. The similarity between the sandstone and the clast ages shows that portions of this basin and probably the Maricá Group itself served as a source of sediments, indicating a dynamic setting with deposition, burial, uplift, and rework in a short time.
Keywords. Maricá Group. Arroio América Formation. U-Pb Provenance. Detrital Zircon. Maximum Depositional Age.

INTRODUCTION

The NE-SW-elongated Camaquã Basin comprises a volcano-plutonic-sedimentary succession and records distinct tectonic processes from Precambrian to early Cambrian in southernmost Brazil. The Maricá Group represents an important marker of the first stages of the basin's evolution. Furthermore, recent studies reported the first occurrence of acritarchs associated with Late Ediacaran Leiosphere Palynoflora (LELP) (Lehn et al., 2019), which highlights the relevance of the origin and evolution of the Maricá Group in the Precambrian tectonic frame.

The Maricá Group is affected by deformation and successive volcanic episodes which obliterate its stratigraphy and lead to uncertainties about the stratigraphic itself and the tectonic context. The tectonic setting of the Maricá Group is still a matter of debate, some authors argued that it is related to late to post-collisional stages of the Brasiliano Orogenic Cycle (Chemale Jr., 2000; Paim et al., 2000, 2014; Hartmann et al., 2008) and some correlated with an anorogenic setting, within-plate evolution (Pelosi & Fragoso-Cesar, 2003).

Despite previous sedimentary studies (Paim, 1995; Pelosi & Fragoso-Cesar, 2003; Borba et al., 2004; Pelosi, 2005) only a few provenances and isotopic data are available (Borba et al., 2006, 2008; Almeida et al., 2012). The Maricá Group comprises the Passo da Promessa, São Rafael and Arroio América formations (Pelosi & Fragoso-Cesar, 2003). The Passo da Promessa Formation is characterized as the basal formation of the Maricá Group. Its maximum depositional age was constrained by a volcanic clast dated at 630.2 ± 3.4 Ma by Borba et al. (2008). The maximum depositional age of the São Rafael was determined at 601 ± 13 Ma by detrital zircon provenance from a sandstone (Almeida et al., 2012). Conversely, provenance studies were not carried out in the Arroio América hitherto. Therefore, the purpose of this paper is to provide new LA-ICP-MS U-Pb provenance data for the Maricá Group to determine the source areas and the maximum depositional age.

REGIONAL GEOLOGY

The Precambrian framework in southern Brazil is made up of a reworked border of the Rio de La Plata Craton and the Dom Feliciano Belt. These units comprise a mosaic of distinct terranes limited by regional shear zones, named Sul-Rio-Grandense Shield (SRGS). According to the tectonic stratigraphic division, the SRGS is constituted by four units, the Taquarembó, Tijucas, São Gabriel terranes, and Pelotas Batholith (Chemale Jr., 2000; Hartmann et al., 2007) as shown in figure 1. The complete age data of each unit is available in Supplementary file 1.

The Taquarembó Terrane comprises relics of the Rio de La Plata Craton, granitic intrusions and sedimentary cover. The cratonic fragments are recorded in the Santa Maria Chico Granulitic Complex (Hartmann et al., 2007; Girelli et al., 2018), that is intruded by Neoproterozoic granites of the São Sebastião Supersuite, Bagé Supersuite and Saibro Suite (Camozzato et al., 2016). The sedimentary cover is composed of Camaquã and Paraná basins sediments. The Santa Maria Chico Granulitic Complex is mainly composed of sillimanite gneiss, calc-silicate gneiss, mafic and acid granulite, mafic and ultramafic rocks related to the island to continental arc episodes between 2.4 and 2.2 Ga. The collisional stage is marked by metamorphic overprint at 2.0 Ga (Hartmann et al., 2008, Girelli et al., 2018). In the Santa Maria Chico Granulitic Complex also occurs a granite with Statherian age of 1824 ± 5.3 Ma (Girelli et al., 2018).

The São Sebastião Supersuite comprises the Santa Rita Granite (646 ± 52 Ma; Naumann, 1984), the Santo Antônio monzogranites (640 ± 52 Ma; Barros & Nardi, 1994), the granitic rocks of the Vautier Suite (597 ± 6 Ma; Laux et al., 2017) and Cerro Preto Suite (590.8 ± 3.6 Ma; 588.6 ±1.5 Ma; Camozzato et al., 2018). The Bagé Supersuite includes the Santo Afonso Suite (624.8 ± 7.1 Ma; Camozzato et al., 2018), whereas the post-collisional granites are attributed to the Saibro Suite of 530-560 Ma age (Soliani Júnior, 1986; Gastal & Lafon, 1998; Gastal et al., 2005).

Located in the northwesternmost of the Ibaré fault system, the Batovi Complex is made of arkose and calciferous metasandstone with subordinate marble, banded iron formations, and metabasalts associated with volcanic proximal source area. The maximum depositional age of the paleo-basin is suggested at ca. 1.7 Ga (Laux et al., 2010).

The São Gabriel Terrane crops out in the western portion of the Dom Feliciano Belt and records evidence of an ocean opening at ca. 920 Ma (Arena et al., 2016; Hartmann et al., 2019) and closing at ca. 790 Ma (Arena et al., 2016; Cerva-Alves et al., 2020).

In the São Gabriel Terrane, magmatic arc events are associated to TTG (tonalite-trondhjemite-granodiorite) Cambaí Complex (680 – 794 Ma) and supracrustal sequences (Cambaizinho, Passo Feio, and Passo do Salso formations; Remus et al., 2000; Lena et al., 2014; Lopes et al., 2015; Vedana et al., 2018) are related to Vacacaí Group, both intruded by post-collisional granites (Saalmann et al., 2011; Hartmann et al., 2011; Cerva-Alves et al., 2020).

The Camaquã Basin cover mostly the São Gabriel Terrane and is bounded by the Porongos Complex to the east (Figure 1).

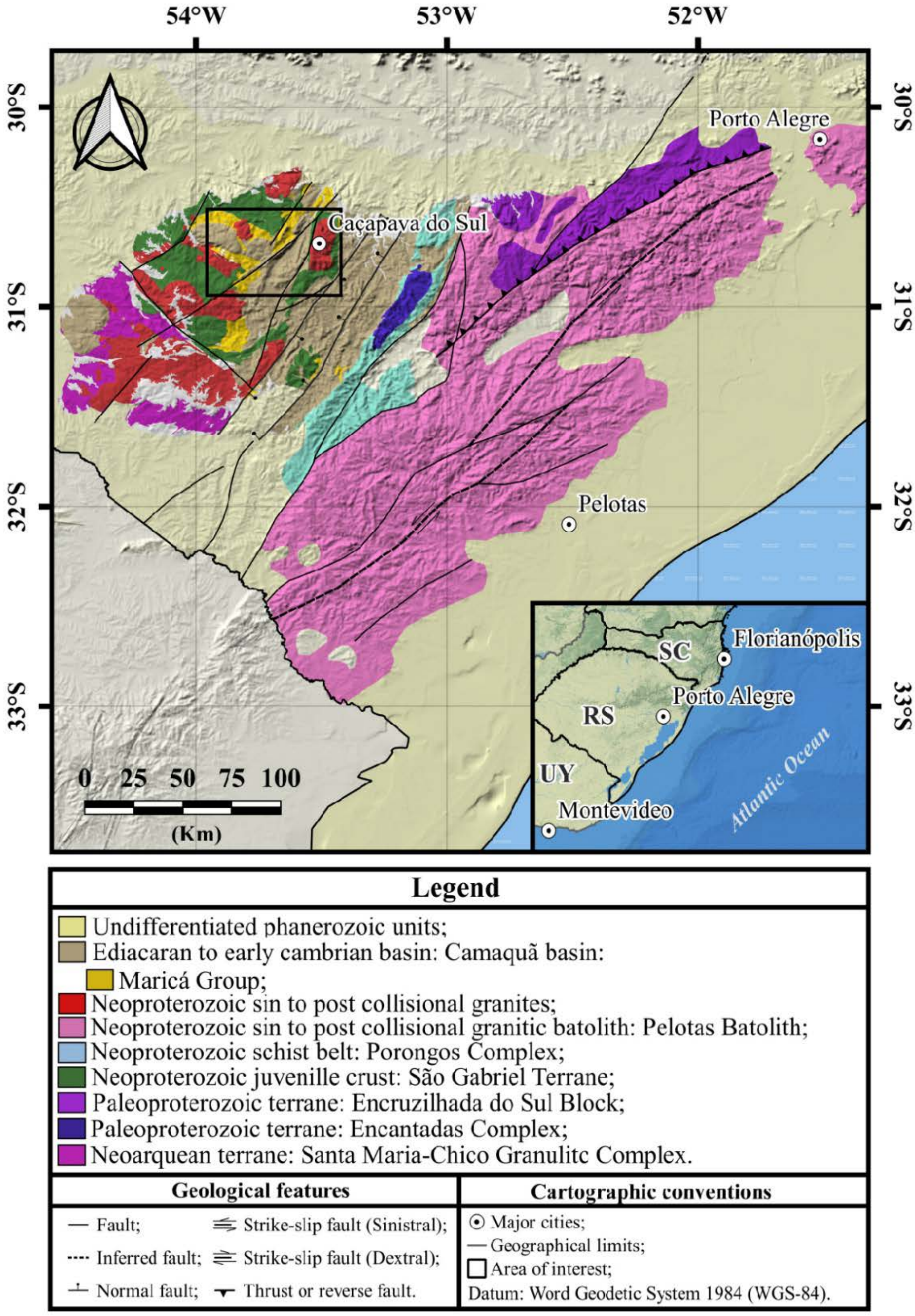

Figure 1 - Geological map of the Sul-Rio-Grandense shield with the main units of the Dom Feliciano Belt.

This basin is covered by Phanerozoic rocks to the north and the south. From base to top, this basin comprises volcano-plutonic-sedimentary successions that are divided into the Maricá, Bom Jardim, Santa Bárbara, and Guaritas groups (Figure 2a; Paim et al., 2014). The Maricá Group is the focus of this work and is described in detail in the 2.1 section.

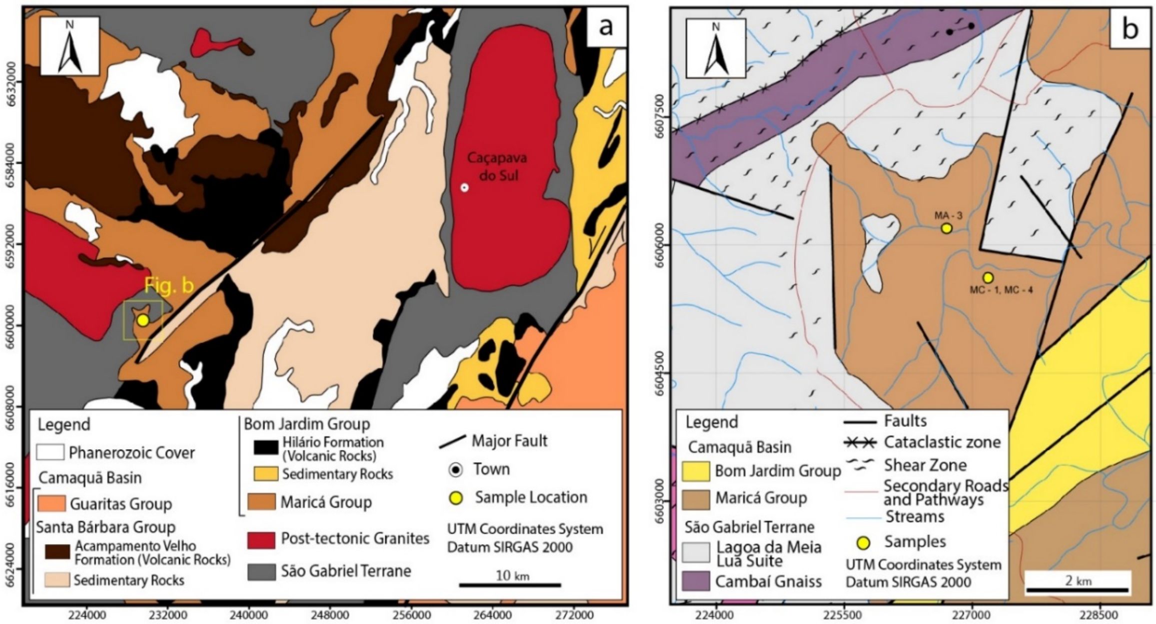

Figure 2 – a) Simplified geological map of the main areas of occurrence of the Maricá Group (Modified from Bicca, 2013). b) Local map showing the sample location in yellow (Modified from Bitencourt et al., 2013).

The Bom Jardim Group comprises a volcano-sedimentary sequence, divided into three formations from bottom to top, the Cerro Angélica, Hilário and Picada das Graças formations (Janikian et al., 2008).

The Santa Bárbara Group is a volcano-sedimentary sequence that includes the Acampamento Velho Formation and three sedimentary successions (Ribeiro & Fantinel, 1978; Borba & Mizusaki, 2003). The youngest group is the Guaritas Group that is divided into Pedra Pintada and Varzinha formations and the Rodeio Velho Member (Paim et al., 2000).

The Tijucas Terrane is made up of Paleoproterozoic basement, Neoproterozoic supracrustal successions, and granitic intrusions that crop out throughout the Porongos Complex and Encruzilhada Block (Chemale Jr., 2000; Saalmann et al., 2011; Takehara & Laux, 2019). The Encantadas complex, characterized as the Paleoproterozoic basement of the Porongos Complex, is constituted by TTG gneiss, mylonitic syenogranites and monzogranites, interspersed with amphibolitic lenses. These rocks associations were formed during the evolution of a Paleoproterozoic magmatic arc between 2.3 and 2.0 Ga (Hartmann et al., 2000, 2003; Chemale Jr., 2000; Saalmann et al., 2011; Camozzato et al., 2013a, b, 2017) and subjected to at least three metamorphic episodes. The older metamorphic overprint is established at ca. 2.0 Ga (Hartmann et al., 2000). The Neoproterozoic episodes were dated at 702 ± 21 Ma (Hartmann et al., 2003) and between 631 and 679 Ma (Hartmann et al., 2000; Camozzato et al., 2013a, b).

In the southwestern region, the Encantadas Complex is tectonically interleaved with Cerro da Vigia Complex (Camozzato & Philipp, 2012), formed of tonalite, granodiorite, amphibolite, and meta hornblendite (2.0 Ga; Camozzato et al., 2013a, b), which is intruded by Seival metagranite (1.7 Ga; Camozzato et al., 2013a, b).

In the Cerro da Vigia Complex, the Tupi Silveira amphibolite is dated at 1.5 Ga (Camozzato et al., 2013a, b) and is considered evidence of an intracontinental rift event of Calimiano age (Camozzato et al., 2013a, b).

The supracrustal succession of the Porongos Complex is composed mostly of schists, phyllites, quartzites, marbles, and metavolcanic rocks, interleaved with ultramafic rocks and sin-tectonic granites (e.g., Jost & Bitencourt, 1980).

The origin and number of Porongos paleobasins remain a matter of debate; however, based on provenance data, the complex can be divided at least into two basins (Pertille et al., 2015a, b; Gruber et al., 2016; Höfig et al., 2018; Battisti et al., 2018). The older basin is associated with thick quartzite sequence (Santana Formation or Porongos I) and present source ages varying from 3.3 to 0.9 Ga (Hartmann et al., 2004; Gruber et al., 2011; Pertille et al., 2015a, b, 2017; Höfig et al., 2018).

The metavolcanic rock (mostly dacite and rhyodacite) were considered contemporaneous to sedimentation in a rift/passive margin environment, setting the maximum depositional age at 780 Ma (e.g., Saalmann et al., 2011; Hofig et al., 2018) or as magmatic arc sequence correlated with Várzea do Capivarita Complex (e.g., Gruber et al., 2016; Martil et al., 2016; Battisti et al., 2018).

The younger basin, particularly preserved in the northern Capané region, displays age sources between 2.5 and 0.58 Ga (Pertille et al., 2017; Höfig et al., 2018).

MATERIALS AND METHODS

The study area was selected based on a previous geological map (Bitencourt et al., 2013), which mapped the Arroio América sheet (SH.22.Y-A-IV-1) and also indicated the best outcrop expositions of the Maricá Group (Figure 2).

One sandstone sample and two cobbles of conglomeratic sandstone were collected from the Arroio América Formation of the Maricá Group (Figure 2b). The main composition and diagenetic features of the collected samples were described in one thin section of each sample using optical microscopy (Folk, 1979).

Samples collected for provenance studies were crushed and milled using a jaw crusher. Zircons were separated by conventional procedures (heavy liquids), concentrated by hand panning and handpicking. For each sample was collected about 200 random zircons, which were mounted in a circular (2.5 cm diameter) epoxy grain mounts and polished until the internal portions of zircon grains were revealed.

Images of zircons were obtained using backscattered and cathodoluminescence methods to the best recognition of their internal features, as inherited core, fractures, recrystallization, and metamitic zones.

The zircons grains were carefully studied using backscattered electron methods at Superscan SSX-550 SEM-EDX, Shimadzu Japan at Nanotecnologia Novonano, Federal University of Pelotas.

U-Pb data were acquired using the LA-SF-ICP-MS in the Isotopic Geochemistry Laboratory in the Federal University of Ouro Preto (UFOP). Cathodoluminescence (CL) images were obtained in a Scanning Electron Microscope (SEM) JEOL 6510. U-Pb analyses were obtained using an Element 2 Thermo Finnigan coupled with a Photon-Machines 193 nm laser system.

Data were acquired using peak jumping mode with background measurement for 20 seconds, zircon ablation for 20 seconds, and a spot size of 30 micrometers. Data reduction was done in GLITTER Software.

The common lead correction was applied using a Ms Excel spreadsheet program (Gerdes and Zeh, 2006) based on Stacey and Kramers (1975) Pb composition model. Isoplot (Ludwin, 2003) was used, and the errors were presented in 2σ. The results table was built according to Horstwood et al. (2016).

Isoplot R online (Vermesche, 2018) was used to generate Concordia diagrams, histograms, kernel density estimates (KDE), and cumulative density functions. All plots only use analyses that were within 100 ± 10% of concordance. All calculated ages are reported at the 95% confidence level.

DetritalPy, a module for Python language, (Sharman et al., 2018) was used to calculate the maximum depositional age following the recommendations and discussions of Sharman & Malkowski (2020).

O calculate the maximum depositional age of the samples we use the method of the youngest statistical population (YSP) and the youngest single cluster overlapping at 2σ by Sharman et al. (2018) with the Dickinson and Gehrels (2009) recommendations, using at least three analyses in the youngest cluster (YC2σ[3+]).

The youngest cluster is defined as the youngest group of analyses that have overlapping uncertainties.

And the YC2σ is defined as the weighted mean and the associated 2σ uncertainty of this cluster. To avoid maximum depositional ages too young or too old that the true depositional age, which still is unknown and matter of debate, we selected three methods to calculated, two more conservative (YSP and YC2σ[3+]) and the youngest single grain age (YSG), the most common and used in the literature.

RESULTS

Fieldwork

In the studied area, based on small and discontinuous outcrops, a composite sedimentary log of 210 m was raised. The sedimentary log displays the main facies and the stratigraphic level relative to each sample collected (Figure 3a).

Two main facies were recognized, denominated as trough-cross bedded sandstones (St) and massive sandstones (Sm). The St facies is predominant, and the Sm facies is restricted to the base of the log (Figure 3a).

The Sm facies is made up of well-sorted, very fine- to fine-grained massive sandstones. Beds are up to 2 m thick, tabular with few meters of lateral extension.

The massive structure of the Sm facies suggests frictional freezing of concentrated density and the tabular geometry indicates unconfined flows.

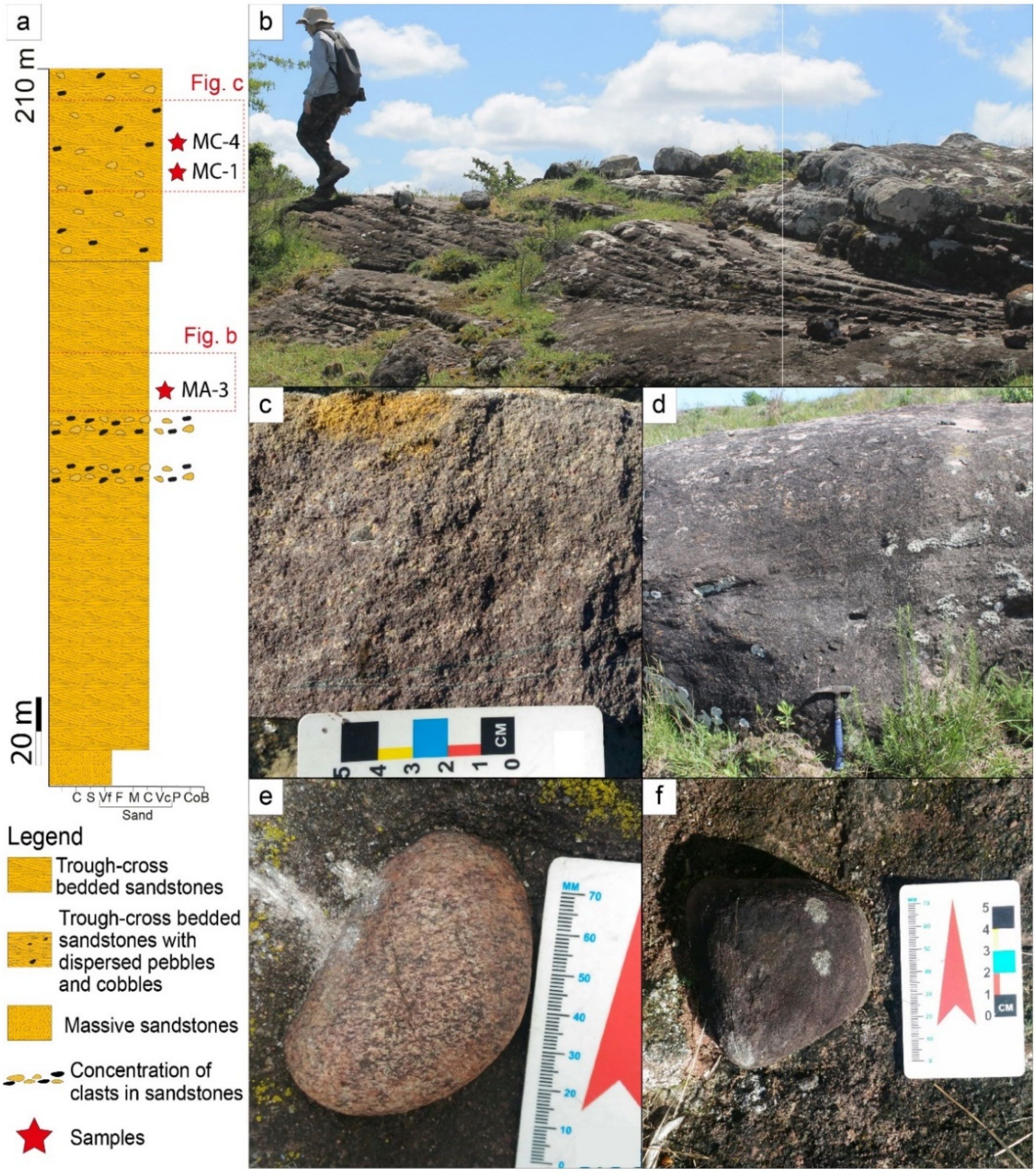

Figure 3 - a) Composite sedimentary log of the outcrops studied in this work including the main facies and the stratigraphic level relative to each sample. b) St facies - trough-cross bedded sandstones. c) Subarkose sandstone (MA–3 sample). d) Trough-cross bedded sandstones with well-rounded clasts dispersed along crossbedding. e) cobble of syenogranite (MC-1 sample). f) cobble of brown-colored sandstone (MC-4 Sample).

The Sm facies deposits are followed by the St facies composed of medium- to very-coarse grained sandstones (sample MA-03; Figure 3c). These sandstones are brown-colored and frequently present reddish levels of a millimeter to centimeter size, which concentrate oxidized opaque minerals (Figure 3c).

The grains are subangular to angular with moderate sphericity and pour to moderated sorted. Beds are lenticular, have decimeters to meter thick, and display well-marked, medium- to small-scale trough-cross bedding (Figure 3a and d).

Eventually, conglomeratic lenses may occur at the base of some bed sets as well as isolated well-rounded clasts dispersed along cross-bedding (Figure 3d).

Gravel-size materials up to 10 cm in size are made up of granite, gneiss, volcanic rock, quartzite, sandstone, and schist. The sedimentary processes involved in these facies formation are unidirectional currents at lower flow regimes associated with the migration of subaqueous 3D dunes.

The presence of isolated pebbles suggests larger macroforms or bars associated with unidirectional, moderately selective subaqueous flows. Conglomerate lenses suggest a gravel core formed during peak flood conditions nucleating and giving rise to the macro forms.

The MC-1 sample (Figure 3e) have 7 cm wide and corresponds to a rounded reddish cobble of syenogranite. In the hand sample, the cobble is composed of K-feldspar (45%), quartz (30%), plagioclase (20%), and biotite (5%). Quartz crystals are oriented and stretched defining a mylonitic texture.

The MC-4 corresponds to a well-rounded cobble of 6 cm wide of brown-colored sandstone (Figure 3f). In the hand sample, the rock is mostly composed of quartz with structure with lamination marked by the alternation of centimetric layers of medium-coarse and fine-grained minerals.

Petrography

The MA-3 sample is coarse- to very-coarse grained arkose sandstone (Folk, 1979; Figure 4a). The framework is formed mostly by quartz and feldspars and minor occurrences of lithic fragments, opaque minerals, and micas. The detrital grains are sub-angular to sub-rounded, poorly sorted and the grains exhibit long and concavo-convex contacts. The cement is constituted by calcite and clay minerals such as kaolinite and illite. Monocrystalline quartz dominates over polycrystalline quartz. The monocrystalline quartz commonly presents straight extinction and fractures filled by calcite. The feldspars are orthoclase and plagioclase, and a minor amount of microcline. Frequently the feldspars appear as grain ghosts and small remnants.

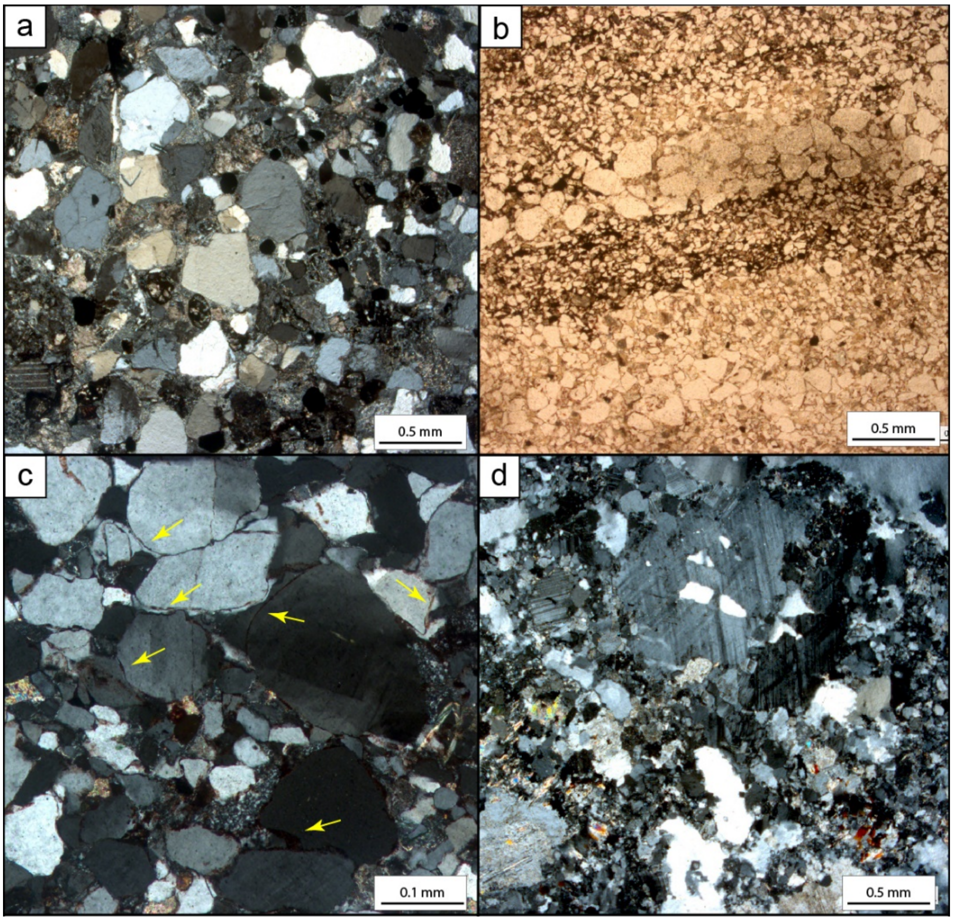

Figure 4 - Selected photomicrographs of textures and minerals of the samples studied. a) Coarse to very-coarse subarkose sandstone (MA-3 sample). b) Medium to fine-grained quartz arenite with graded bedding (MC-4 sample). c) Iron oxides coating the detrital quartz grains (yellow arrow) and quartz overgrowths (MC-4 sample). d) Cobble of syenogranite (MC-1 sample).

Most k-feldspar grains are intensely replaced by clay minerals and calcite. The plagioclase grains exhibit altered twins and are also frequently replaced by calcite. The mica grains are intensely compacted with pseudo-matrix formation. The lithic fragments are predominantly composed of granitic-gneissic rocks.

The MC-4 sample consists of medium- to fine-grained quartz arenite (Folk, 1979) with graded bedding (Figure 4b). The medium-grained portion shows rounded to sub-rounded grains while in the fine-grained portion the grains are sub-rounded to angular.

The quartz grains are predominantly monocrystalline, but polycrystalline grains also occur. Three types of cement are encountered: quartz, iron oxide, and minor amounts of clay minerals (Figure 4c). Iron oxides are dark red and occur coating the detrital quartz grains.

Quartz cement occurs as typical syntaxial overgrowths. The feldspar grains are subordinate and mostly occur in fine-grained laminas frequently replaced by calcite. Opaque minerals are angular with low sphericity, oxidized, and are concentrated in fine-grained laminas.

The MC-1 sample is a syenogranite composed of quartz, orthoclase, microcline, plagioclase, muscovite, and opaques (Figure 4d). The original texture is inequigranular with localized mylonitic bands composed of fine quartz crystals.

The quartz crystals vary between 0.1 and 1.5 mm, are subhedral-anhedral, and show undulating extinction. In foliated portions the fine quartz crystals are elongated and stretched, showing orientation and recrystallization. The feldspar crystals are anhedral with sizes between 0.2 and 1 mm. Microcline and orthoclase crystals are replaced by sericite. The muscovite crystals are subhedral and have sizes ranging from 0.1 to 0.5 mm. The opaque minerals have an average size of 0.1 mm and are oxidized. The oxides occur filling fractures and often filling the muscovite cleavage.

U-Pb Analysis

The MA-3 sample has zircon grains 50-250 μm long, mostly subhedral, with few anhedral and only 4 euhedral grains. The shape of the grains varies from angular to well-rounded. The rounded grains are the most frequent. Fractures and metamict portions are restricted in extent while magmatic zoning is common and present in different shapes of zircons grains (Figure 5a). Inclusions and xenocrysts cores also occur. A total of 64 concordant ages from 78 analyzed zircon grains yield an array of ages from 599 ± 11 to 2818 ± 32 Ma. The ages show mostly Paleoproterozoic sources, among the total, 49% are Siderian, 18% Rhyacian, 3% Orosian, and 8% Statherian (Figure 6c). In addition, minor contributions from Archean (2% Meso-Archean and 9% Neo-Archean) and Neoproterozoic (11%) were also observed. Neoproterozoic sources comprise 2% of Cryogenian and 9% of Ediacaran (Figure 6c). The main age peak on the cumulative curve is 2453 Ma, with minor peaks at 2212, 1757, 621 Ma (Figure 6a). The Neoproterozoic grains are Cryogenian (638 Ma) and Ediacaran (628-599 Ma).

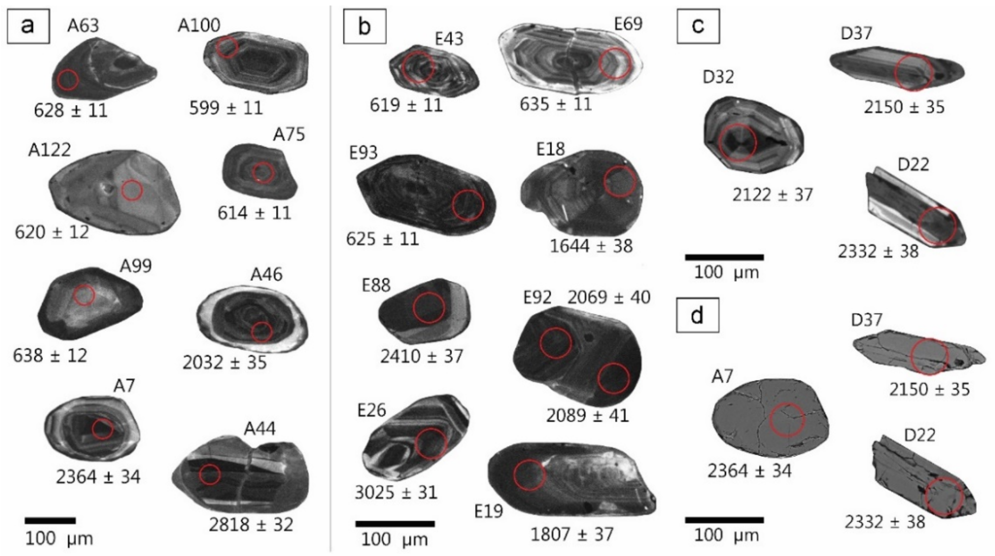

Figure 5 - Selected cathodoluminescence images (a, b, and c) of the analyzed zircon grains. a) Sandstone (MA - 3 sample). b) Cobble of sandstone (MC -4 sample). c) Cobble reddish of metasyenogranite (MC-1 sample). d) Selected backscattering images of the analyzed zircon grains. A7 zircon from MA-3 sample and D37 and D22 zircons from MC-1 sample. The analyzed spots of U-Pb LA-MC-ICP-MS are shown as red circles and ages in Ma.

The zircon grains of the MC-4 sample have 50-200 μm long, are mostly subhedral and anhedral, with few euhedral grains. They are mostly sub-angular and sub-rounded, but angular and rounded grains also occur.

Magmatic zoning and fractures are common, but metamict portions are restricted in extent (Figure 5b). Inclusions and xenocrysts cores also occur. A total of 31 concordant ages of 42 analyzed zircon grains display an array of ages from 619 ± 11 to 3025 ± 31 Ma. The data indicate mostly Paleoproterozoic sources, with Siderian (10%),

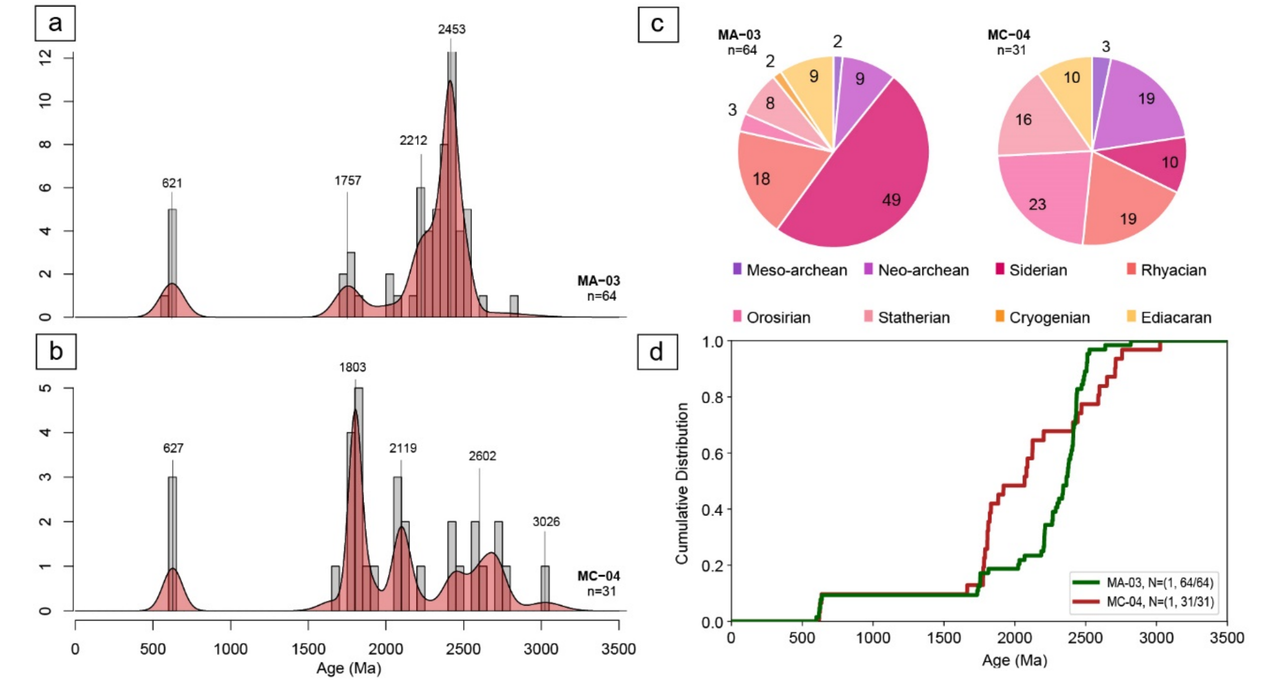

Figure 6 - a and b. Kernel density estimation curve in red and histograms in gray with the U-Pb dating results of detrital samples. a) Results from the MA-03 sample and b) results from the MC-04 sample. c) Pie chart showing the proportion of each zircon population separated by age. d) Diagram of the cumulative distribution function of the MC-4 and MA-3 samples.

Rhyacian (19%), Orosirian (23%), and Statherian (16%) contributions (Figure 6c). Furthermore, the data also indicated the presence of Archean (3% Meso-Archean and 19% Neo-Archean) and Neoproterozoic sources (10% Ediacaran; 635, 625, and 619 Ma) (Figure 6c). The main peak on the cumulative curve is 1803 Ma, with minor peaks at 3026, 2602, 2119, and 627 Ma (Figure 6b).

The cumulative distribution function from both samples shows a similar detrital zircon age pattern, with an approximately bimodal distribution pattern. A minor contribution of Cryogenian and Ediacaran, lack of Tonian and Mesoproterozoic, and the principal population of Paleoproterozoic grains (Figure 6d) characterize this bimodal pattern.

The zircon crystals of the MC-1 sample show 40-220 µm long and mostly are subhedral and euhedral (Figure 5c). All crystals have magmatic zoning, mostly are intensely fractured (Figure 5d, D37, and D22), but metamict portions are restricted in extent. Inclusions and xenocrysts cores also occur. A Concordia age at 2166 ± 9.3 Ma was calculated based on 8 of 16 analyzed zircons (Figure 7).

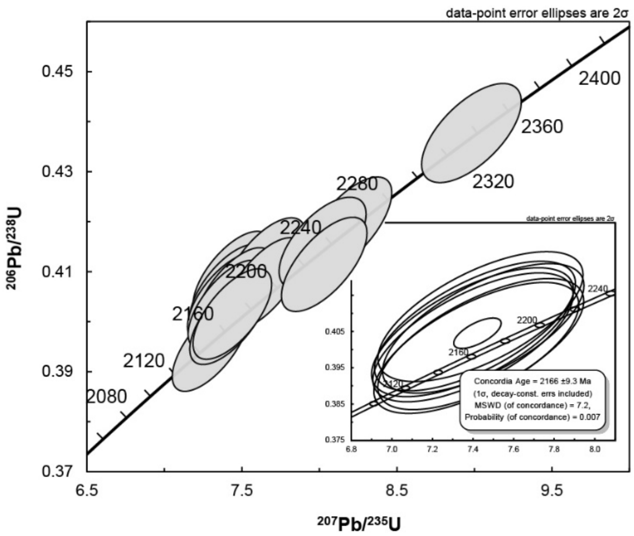

Figure 7 - Isotopic analyses of zircon crystals of sample MC-1 displayed in a Concordia diagram and age calculated.

The maximum depositional ages calculated for the MA-03 and MC-04 samples are present in figure 8. The YSP and YC2 conservative methods have similar results relative to the overlapping ages while the YSG methods present the youngest ages in both samples. The

MA-03 sample yields an age of 623.5 ± 5.9 Ma by the YSP method, while the YC2σ[3+] method yields an age of 612.2 ± 13.3 Ma and the youngest grain is 599.8 ± 11.5 Ma (Figure 8a).

The MC-04 sample yields an age of 622.6 ± 7.7 Ma by the YSP method, 626.7 ± 12.7 Ma by YC2σ[3+] and the youngest grain is 619.4 ± 11 Ma (Figure 8b).

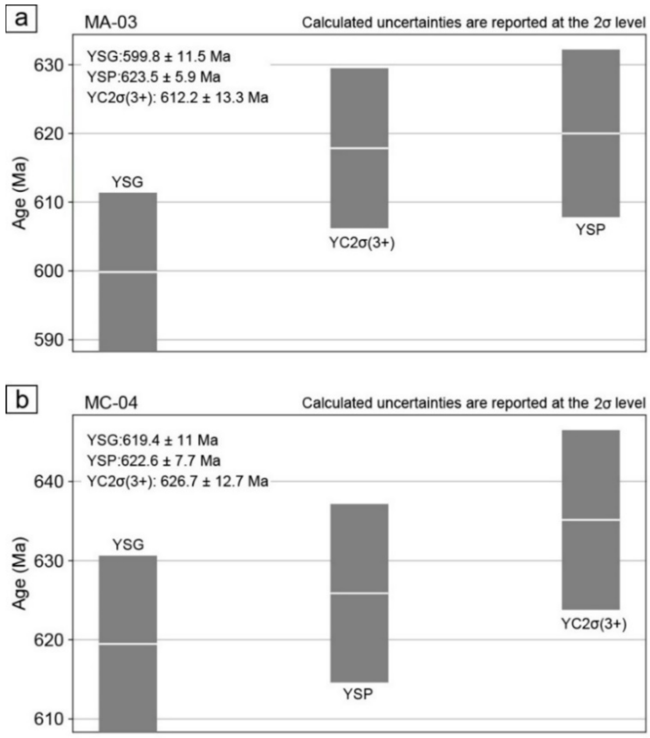

Figure 8 - Maximum depositional ages calculated by the method of the youngest statistical population (YSP), the youngest single cluster overlapping at 2σ with at least three analyses in the youngest cluster (YC2σ[3+]) and the youngest single grain age (YSG). a) MA-03 sample and b) MC-04 sample.

DISCUSSION

The description and interpretation of the sedimentary facies in this work was based on previous studies interpretations (Pelosi & Fragoso-Cesar, 2003; UFRGS, 2003; Borba et al., 2004; Bittencourt et al., 2013), due to the restricted and small studied area. Both St and Sm facies described in the present study are reported by Borba et al. (2004; 2006) and Pelosi and Fragoso-Cesar (2003) for the upper portion from Maricá Group (Arroio América Formation). Thus, these facies are interpreted as the record of downstream accreting macroforms, with the migration of subaqueous dunes in more confined or unconfined flows related to a braided fluvial system.

The petrographic analyses from the MA-3 sample show a poor sorting arkose composition with the predominance of quartz and feldspars grains, and minor quantities of lithic fragments, micas and opaque minerals. This main composition is also described for sandstones from Arroio América Formation (Pelosi, 2005). The diagenetic features identified suggest a meso diagenetic stage, as reported by Pelosi (2005). These features are the results of a strong mechanic and chemical compaction shown by the long and concavo-convex contacts of the framework grains and mica grains that are intensely compacted with pseudo-matrix formation. Moreover, the calcite and illite cement and the replacing of feldspar grains agree with more advanced diagenetic stages. These features were also identified by Borba et al. (2004) in the Arroio América Formation sandstones.

Petrographic analyses of cobbles and pebbles from the Maricá Group, only performed by Pelosi (2005), determined that the conglomeratic levels from sandstones of the Arroio América Formation are dominated by granitic foliated rocks. This lithology corresponds to the MC-1 sample. According to Pelosi and Fragoso-Cesar (2003), sandstones cobbles constitute 3% of the lithologies identified in the Arroio América Formation (Pelosi & Fragoso-Cesar, 2003). However, petrographic analyses were not performed. In the present work, the sandstone cobble consists of medium- to fine-grained quartz arenite (Folk, 1979), which shows a higher mineral and textural maturity than the described for the sandstone from the Maricá Group. In addition, this difference of sorting and mineral and textural maturity between the gravel and sand-sized fraction is a remarkable contrast also identified and highlighted by Borba et al. (2004). This difference is well shown here in the MC-4 and MA-03 samples.

Despite the petrographic differences pointed here, the sandstone sample (MA-03), and the sandstone cobble (MC-4) display similarities in the zircon ages range and the slightly distinct provenance patterns (Figure 6a and b). The sediments from both samples were derived from mixed sources (599 – 3025 Ma) with a major contribution of Syderian (2422 Ma) and Ediacaran (621 Ma) sources. Another significant source is Statherian (1749 Ma). Minor contributions from Ryacian (2212-2040 Ma) and Archean (2823-2503) are also present. The sources of the Archean peaks at 3.0 and 2.6 Ga are recognized in the China Complex (3.41 Ga, Hartmann et al., 2001), in the sedimentary Las Tetas Complex (3.26 and 2.76 Ga; Hartmann et al., 2001), and in the Cebollatí Complex (Oyhantçabal et al., 2021). The sandstone sample MA-3 main age peak at 2.4 Ga, may derive from the closer Santa Maria Chico Complex (Hartmann et al., 2008; Girelli et al., 2018). Ages of proximately 2.4 Ga are also observed in the detrital zircons of Porongos Complex quartzite and schist (Hartmann et al., 2004; Gruber et al., 2011, Pertille et al., 2015a; b; 2017; Hofig et al., 2018) and in the detrital zircon of schist and phyllite samples of Passo Feio Formation (Remus et al., 1999; Lopes et al., 2015) located in the São Gabriel terrane (Figure 1).

Rhyacian ages (2.2 -2.0 Ga) are present along the cratons, cratonic fragments, and recycled sedimentary cover of southern Brazil, Uruguay, and Argentina (e.g., Santos et al., 2003). Therefore, the main age peaks at 2.2 and 2.1 Ga could represent sediments derived from Encantadas and Arroio dos Ratos complexes (Chemale Jr., 2000; Saalmann et al., 2011; Camozzato et al., 2013a, b) and in the Santa Maria Chico Granulitic Complex (Girelli et al., 2018). These Rhyacian ages are also consistent with the Porongos Complex and Passo Feio Formation detrital zircons.

The sandstone sample MA-3 and the sandstone cobble sample MC-4 display significant age peaks at Statherian age (1.8-1.7 Ga). Possible Statherian sources are related to Vigia Dome and Batovi Complex (Laux et al., 2010; Camozzato et al., 2013a, b). The Statherian units of Vigia Dome are tectonically interleaved with the Porongos Complex metasedimentary sequence and Encantadas Complex orthogneiss (Camozzato et al., 2013a, b), which could justify the presence of the Rhyacian and Statherian detrital zircons in the Maricá provenance. In addition, Statherian ages were also identified in granite from Santa Maria Chico Complex with an age of 1.8 Ga (Girelli et al., 2018) and as detrital grains (1.7 – 1.8 Ga) in Passo Feio Formation (Lopes et al., 2015).

There are two mains possible sources of the identified Ediacaran ages (599-627 Ma). The granitic rocks of the Pelotas Batholith, in the eastern, and the Bagé Supersuite, in the southwestern in the Bagé region. Similar ages of the younger peak 624 and 621 Ma are identified in the Cordilheira Suite, Pinheiro Machado Complex and Viamão Suite (Frantz et al., 2003, Babinsk et al., 1997, Philipp et al., 2016a). Conversely, in the Bagé Supersuite, the Santo Afonso Suite was dated at 624.8 ± 7.1 Ma (Camozzato et al., 2016; 2018).

The younger sources can be related to Ediacaran granites that are spread along the Dom Feliciano Belt or Bagé region. However, NE and NNW paleocurrents are reported for the Arroio América Formation in the Lavras do Sul region (Pelosi, 2005), restricting the possible source areas and indicating the southern ones as the most likely.

The Concordia age of an igneous clast (MC-1 sample) reveal ages comparable to the Paleoproterozoic basement (2.1 Ga) and not with the Maricá Group basement (São Gabriel Terrane), in agreement with the lack of Tonian detrital zircons in both samples analyzed here. Pelosi and Fragoso-Cesar (2003) also report this aspect through petrographic studies performed in clasts. In addition, the Sm-Nd TDM model ages (2.37-1.76 Ga; Borba et al., 2006) of sedimentary samples from Maricá Group show a clear contrast with the Nd isotopic compositions of the juvenile basement, the São Gabriel Terrane, which yields typical TDM ages of around 1.0 Ga, indicating the predominance of Paleoproterozoic sources (Borba et al., 2006).

Both samples analyzed here, the sandstone and the clast, yielded similar maximum depositional ages, with the errors included. The MA-03 sample yielded ages between 623.5 ± 5.9 to 612.2 ± 13.3 Ma and the MC-04 sample yielded ages between 622.6 ± 7.7 to 626.7 ± 12.7 Ma. This indicates that portions of this basin and probably the Maricá Group itself served as a source of sediments. This suggests a dynamic setting with deposition, burial, uplift and rework in a short time. Although the use of the youngest grain as the maximum depositional age is considered by many works as a less robust method and less conservative, and that can provide too young ages (see Sharman & Malkowski, 2020 and references therein), the authors highlight that this method provides an age that most coincides to the true depositional age. Consequently, we consider the maximum depositional age for the Arroio América Formation at 599.8 ± 11.5 Ma (Figure 8a).

Thus, considering the ages of previous works of the Maricá Group, the maximum depositional ages of each formation are: Passo da Promessa Formation have 630.2 ± 3.4 Ma (Borba et al., 2008), the São Rafael Formation have 601 ± 13 Ma (Almeida et al., 2012) and the Arroio América Formation have 599.8 ± 11.5 Ma. Therefore, the Arroio América Formation is older than the intrusive andesites from the base of Bom Jardim Group (593 ± 6 Ma) (Remus et al., 1999), and younger than 599.8 ± 11.5 Ma.

CONCLUSIONS

In this contribution, we provide new data to the Arroio América Formation, Maricá Group, contributing to a better understanding of the complex geology of the Camaquã Basin and the Dom Feliciano Belt evolution. The following conclusions are drawn based on our integrated investigation:

1. The sediments from both samples, the sandstone, and the sandstone clast, were derived from mixed sources (599 – 3025 Ma) with a major contribution of Syderian (2422 Ma) and Ediacaran (621 Ma) sources. Another significant source is Statherian (1749 Ma). Minor contributions from Ryacian (2212-2040 Ma) and Archean (2823-2503) are also present.

2. The younger sources are probably related to Ediacaran granites from the Bagé Region, like the Bagé Supersuite in agreement with the NE and NNW paleocurrents of Arroio América Formation.

3. The lack of Tonian zircon ages together with the age of the granitic clast (MC- 1 sample with a Concordia age of 2.1 Ga) reveals that there are no contributions from the basement of the Maricá Group (São Gabriel Terrane), as also suggested by Borba et al. (2006), based on Sm-Nd TDM model ages and by Pelosi and Fragoso-César (2003) based on clast provenance.

4. The very close maximum depositional ages and similar zircon pattern from the sandstone and the clast shows that portions of this basin and probably the Maricá Group itself served as a source of sediments, indicating a dynamic setting with deposition, burial, uplift, and rework in a short time scale.

5. The maximum depositional age for the Arroio América Formation is constrained at 599.8 ± 11.5 Ma. Therefore, the Arroio América Formation is older than the intrusive andesites from the base of Bom Jardim Group (593 ± 6 Ma) (Remus et al., 1999), and younger than 599.8 ± 11.5 Ma.

6. Accordingly, the maximum depositional ages of each formation are: Passo da Promessa Formation have 630.2 ± 3.4 Ma (Borba et al., 2008), the São Rafael Formation have 601 ± 13 Ma (Almeida et al., 2012) and the Arroio América Formation have 599.8 ± 11.5 Ma.

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