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Regional high-grade metamorphic peak imprint in zircons from the mafic-ultramafic Jacurici Complex, São Francisco Craton, Brazil

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Abstract

The Cr-rich Jacurici Complex is located at the limit between the Serrinha Block and the Salvador-Curaçá Belt, Northeastern São Francisco Craton. In order to better understand the age span of magmatism and tectonism, we have studied a basement high-grade charnockite orthogneiss, a metanorite of the Complex and a crosscuting undeformed quartz-feldspar pegmatite. For the orthogneiss, SHRIMP U-Pb ages of zircon cores and overgrowth rims yielded, 2966 ± 9 Ma for crystallization and 2091 ± 10 Ma for metamorphism, respectively. Zircons from the metanorite show internal textures consistent with high grade metamorphism. The U-Pb LA-ICP-MS age determination provided a 2099 ± 6 Ma metamorphic age for the Jacurici Complex, indicating it was already emplaced during amalgamation around 2.1 Ga. Zircons from the undeformed quartz-feldspar pegmatite provided a LA-ICP-MS U-Pb age of 2083 ± 11Ma, marking the end of the N-S transcurrence. The magmatic Jacurici Complex age remains undefined, but is equal to, or older than, 2.1 Ga. Therefore, possible correlations with other mafic-ultramafic intrusions, such as the Cu-rich Caraíba Complex, should be reassessed. Our results indicate that the N-S transcurrence ended earlier in the Jacurici Complex region than in the northwestern area of the Salvador-Curaçá belt.

KEYWORDS: Jacurici Complex; São Francisco Craton; Serrinha Block; Salvador Curaça Belt; zircon U-Pb age.

INTRODUCTION

U-Pb ages in zircons can be modified by solid-state dissolution-precipitation and by fluid-driven processes related to metamorphic, hydrothermal or magmatic fluids (Hoskin and Black 2000, Corfu *et al.* 2003, Hoskin 2005, Grant *et al.* 2009, Rubatto 2017). Under regional metamorphism at different P-T conditions, zircon will partially to completely recrystallize or form overgrowth rims, possibly preserving multiple geological episodes in its growth patterns (Bauer *et al.* 2007, Fu *et al.* 2009, Rasmussen *et al.* 2011, Phillips *et al.* 2015, Li *et al.* 2019). Coupled cathodoluminescence imaging and in-situ U-Pb dating allows the identification of metamorphic events within the zircon complex internal textures and growth rims. Metamorphic events can frequently overwrite magmatic zircon ages, which can lead to incorrect interpretations, where metamorphic ages are falsely interpreted as crystallization ages (Hoskin and Black 2000, Corfu *et al.* 2003, Hoskin 2005, Rubatto 2017).

The Cr ore-bearing Jacurici mafic-ultramafic Complex (NE São Francisco Craton, Brazil) is intrusive along the western margin of the Mesoarchean-Paleoproterozoic Serrinha Block (Barbosa and Sabaté 2004, Oliveira *et al.* 2004a, 2010, Baldim and Oliveira 2016). Mafic-ultramafic rocks tend to be difficult to date using U-Pb techniques on zircons due to the mineral's scarcity in these associations. On the other hand, mafic-ultramafic rocks can host Ni, Cu, Cr and PGE mineralization, so constraining these systems temporally is essential in order to reconstruct the ore formation processes and relationships with the tectonic setting. The Jacurici Complex magmatism has been proposed to be synchronous with the Itiúba Syenite magmatism based on zircon U-Pb dating. The Jacurici Complex yielded 2085 ± 5Ma ages (Oliveira *et al.* 2004b) while the Itiúba Syenite has an age of 2084 ± 9 Ma (Oliveira *et al.* 2004a).

The area where the Jacurici Complex occurs is characterized by high-grade metamorphism, reaching up to granulite facies conditions, with local anatexis and migmatization (Barbosa

Supplementary data

Supplementary data associated with this article can be found in the online version: Suplementary materi al.

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and Sabaté 2003, 2004, Leite *et al.* 2009). The Jacurici Complex is partially affected by the high-grade metamorphism, ranging from upper amphibolite to granulite facies (Cunha *et al.* 2012, Dias *et al.* 2014, Marques *et al.* 2003), with large local magmatic orthopyroxene crystals recrystallized to smaller granoblastic grains (Marques *et al.* 2017). The Jacurici Complex is also affected by later metasomatic processes (Del Lama *et al.* 2001, Marques *et al.* 2017) and is crosscut by non-deformed quartz-feldspar pegmatites, interpreted as being related to the later stages of the Itiúba Syenite magmatism (Marques *et al.* 2017). The proposed age for crystallization of the Jacurici Complex as being similar to the age of the Itiúba Syenite (U-Pb zircon ages of 2084 ± 9 Ma — Oliveira *et al.* 2004b) is difficult to reconcile when considering the geological scenario.

In order to temporally constrain the Jacurici Complex emplacement age, geochronological analyses were conducted on zircons from a selected basement gneiss from the Serrinha Block (Santa Luz Complex), from a norite of the Jacurici Complex and a crosscutting-pegmatite. The constraint of the Jacurici Complex emplacement age allows for a more profound understanding of its magmatic evolution, sources and metallogenetic processes with implications for the exploration of other mafic-ultramafic intrusions found within the São Francisco Craton.

GEOLOGICAL BACKGROUND

The São Francisco Craton is composed of Archean to Paleoproterozoic rocks amalgamated during the Paleoproterozoic (Almeida 1968, 1977) (Fig. 1A), recently denominated the Rhyacian-Orosirian São Francisco-Congo orogen (Baldim and Oliveira 2021). In the northeastern part of the Craton, the Paleoproterozoic collision of the Serrinha, Gavião and Jequié microcontinents and the Salvador-Curaça belt (Barbosa and Sabaté 2004) forms a 600 km transpressive eroded mountain belt in NE Brazil (Peucat *et al.* 2011). The study area (Fig. 1B) is located at the contact between the Serrinha Block and the Salvador-Curaça belt, a region dominated by a N-S sinistral

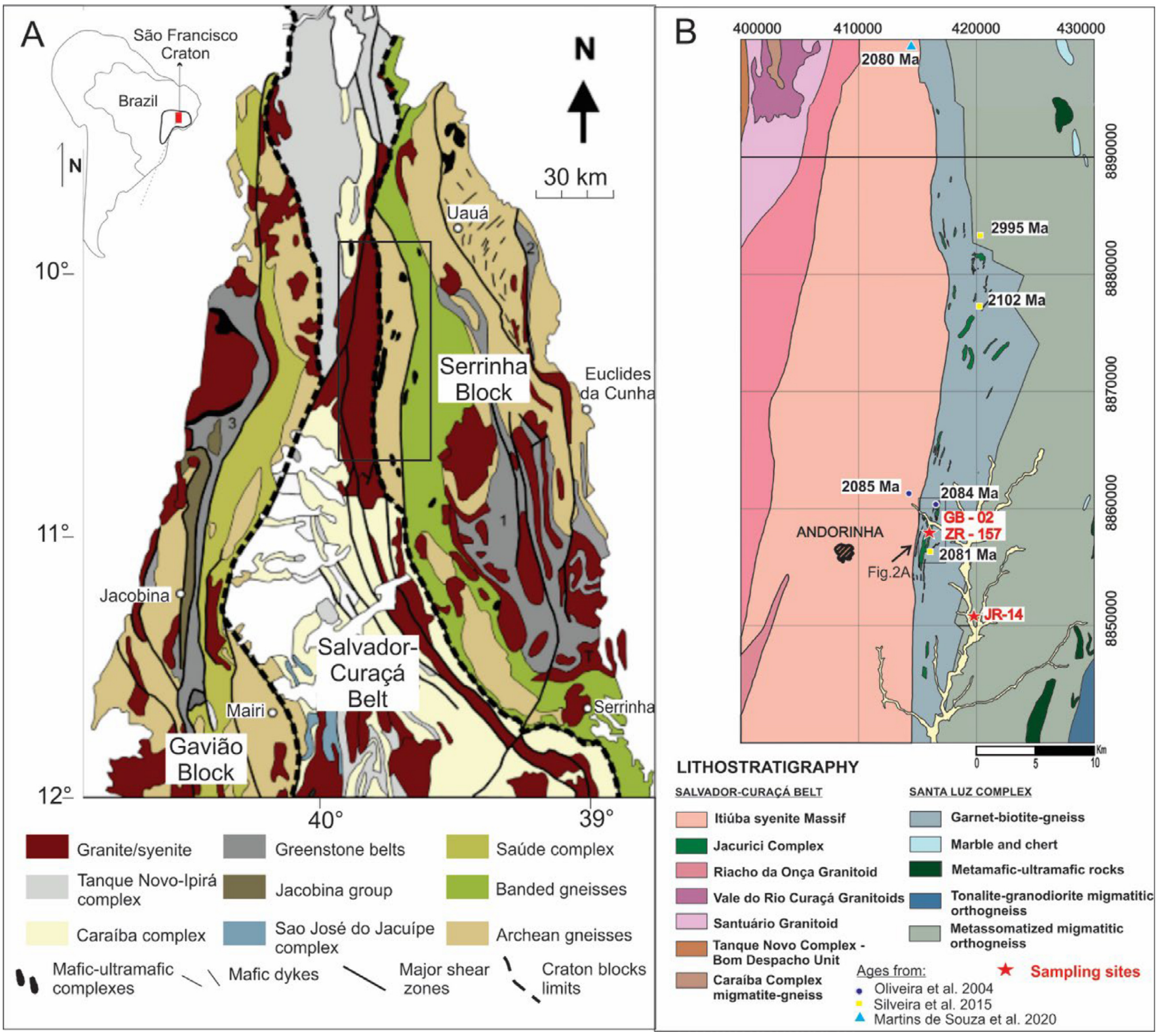


Figure 1. Location map of the study area in the northeastern part of the São Francisco Craton (NE Brazil) showing (A) main terrains, Gavião Block, Salvador-Curaçá belt and Serrinha Block (map from Oliveira *et al.* 2010), and highlighting the area (B) where the Jacurici Complex occurs (modified from (Costa 2014). Sampling sites are indicated, although two samples were taken from underground (see text and Fig. 2 for details).

shear fault (Fig. 1B) (Barbosa and Sabaté 2004, Oliveira *et al.* 2010) and Paleoproterozoic granitic intrusions, over an Archean basement composed of granulite, migmatites, and gneisses. The high-grade regional metamorphism that affected the basement rocks is considered to have occurred around 2.1 Ga (Barbosa *et al.* 2012, Cunha *et al.* 2012).

The Serrinha Block is one of the cratonic nucleii of the NE São Francisco Craton, composed of Mesoarchean to Paleoproterozoic rocks (Barbosa 1990, Oliveira *et al.* 2004a, 2010, Baldim and Oliveira 2021, Rios *et al.* 2008, 2009). The Serrinha block can be separated into 4 main tectonic terranes: (i) the Santa Luz and the Uauá gneiss-granulite complexes; (ii) the metamorphosed volcano-sedimentary rocks of the Rio Itapicuru and Rio Capim greenstone belts; (iii) a series of granitic and mafic intrusions; (iv) a metasedimentary sucession (Conceição *et al.* 2002, Costa *et al.* 2011, Baldim and Oliveira 2016, 2021, Oliveira *et al.* 2004a, 2010, Rios *et al.* 2008, 2009).

The northern portion of the Salvador-Curaçá Belt is represented by Neoarchean to Paleoproterozoic complexes, including the Caraíba Complex, and granitic intrusions (Fig. 1B). The orogenic belt comprises: (i) granodiorite to tonalite granulites; (ii) banded iron formations, aluminous- and -graphite gneiss, calc-silicatic rocks (Tanque Novo and Ipirá complex); (iii) mafic-ultramafic associations (São José do Jacuípe suite); (iv) syn-collisional granitic to later syenitic plutons (ca. Itiúba syenite, Capela do Alto Alegre monzonite, Bravo granite) (Oliveira *et al.* 2004a, 2010, Costa *et al.* 2011, Martins de Sousa *et al.* 2020).

The Salvador-Curaçá belt is mainly composed of high-grade metamorphic rocks (Baldim and Oliveira 2021 and references therein), reaching ultrahigh-temperature (UHT) conditions (7 to 8 kbar and 900 to 950°C) in the sapphirine-bearing gneiss from the Ipirá Complex (Leite *et al.* 2009 and references therein).

The mafic-ultramafic Jacurici Complex occurs parallel to the eastern border of the Itiúba Syenite, an enormous 150 km alkaline magmatism intruded during the Paleoproterozoic in the late stages of the tectonism. Those stages occurred during the transcurrency (Conceição *et al.* 1991, Barbosa and Sabaté 2002), in the limit between the western margin of the Serrinha Block and the Salvador-Curaça Belt (Fig. 1B). The Jacurici mafic-ultramafic Complex comprises a series of segments (up to 300 m in thickness), intruding a N-S belt up to 70 km-long (Marques and Ferreira Filho 2003, Marques *et al.* 2017, Friedrich *et al.* 2020). The stratigraphy observed in different segments is composed of a lower ultramafic zone, followed by a thin mafic zone. The ultramafic zone (up to 250 m in thickness) is formed by dunite, harzburgite, lherzolite and pyroxenites and hosts a thick chromitite layer (up to 8 m) (Marques and Ferreira Filho 2003, Teixeira *et al.* 2017). The mafic zone (up to 40 m in thickness) is composed of norite and gabbronorites. The proposed stratigraphy is described in 3 main segments, from south to north: Ipueira-Medrado, Monte Alegre Sul and Várzea do Macaco (Marques and Ferreira Filho 2003, Dias *et al.* 2014, Marques *et al.* 2017, Friedrich *et al.* 2020). Based on petrological studies, the Complex is interpreted as the remnants of a conduit system through which a large volume of magma flowed (Marques and Ferreira Filho 2003, Marques *et al.* 2003, 2017). The studies of Oliveira *et al.* (2004b) and Silveira *et al.* (2015) provided zircon U-Pb ages of 2085 ± 5 Ma (norite from the Medrado segment) and 2102 ± 5 Ma (metagabbronorite from a lateral intrusion in the Monte Alegre Sul area), respectively. The magmatism has been considered to be Paleoproterozoic, although some questions remain regarding the difficulty in reconciling the crystallization age and the metamorphic/deformational evolution registered in the Complex that reaches granulite facies conditions locally (Marques *et al.* 2017).

METHODOLOGY

U-Pb dating was performed on zircon crystals separated from samples ranging from 1 to 3 kg prepared for zircon dating. The samples were crushed, powdered, and sieved to fractions between 75–178 μm. Heavy mineral concentrates were obtained via panning and were subsequently purified using bromoform. Zircon grains were handpicked, set in an epoxy resin mount, and then polished. Backscattered-electron zircon images were obtained using a SEM JEOL JSM 5800, and the cathodoluminescence analyses were carried out in a FEI-QUANTA 250 scanning electron microscope, equipped with cathodoluminescence (CL) and secondary-electron detectors.

Zircon crystals from samples GB-02 and ZR-157 were analyzed using a Thermo Neptune Multi-Collector–Inductively Coupled Plasma-Mass Spectrometer coupled to a Nd-YAG laser (k = 213 nm) ablation system at the Universidade Federal do Rio Grande do Sul (UFRGS), Brazil. The analyses were performed on a single spot of 30 μm using the following laser parameters: repetition rate of 10 Hz and energy of 0.7 to 1.1 mJ/cm^2. Unknown analyses were bracketed by measurements of the international standard GJ-1 (Jackson *et al.* 2004), at every set of 4 zircon spots, and used to estimate the necessary corrections and internal instrumental fractionation. The raw data was corrected in a homemade Excel spreadsheet for background, instrumental mass-bias drift and common Pb (see Chemale Jr. *et al.* 2012). Zircons from sample JR-14 (Gneiss) were dated using a SHRIMP ion microprobe (SHRIMP IIe/MC) at the Center for Geochronological Research at the University of São Paulo (CPGeo-USP). The SHRIMP ion probe is operated under Williams (1998) procedures. The Temora standard (Black *et al.* 2003) was used for $^{206}Pb/^{238}U$ ratio calibration, and the common lead was corrected by measured ^{204}Pb. Sato *et al.* (2011) provides further detail on the SHRIMP methodology. Plots of the Concordia diagram and ages were calculated using Isoplot (Ludwig 2003).

Full dataset is available in the Supplementary material.

RESULTS

The Jacurici Complex is intrusive in a high grade Mesoarchean terrain represented at the study area by gneisses and migmatites of the Santa Luz Complex, according to the most recent geological mapping by the Geological Survey of Brazil (Fig. 1B; Costa 2014). The Jacurici Complex is composed mainly of ultramafic rocks that evolve toward the top to mafic rocks, and is metamorphosed, folded and disrupted in several segments along a N-S belt. It hosts a thick chromitite layer that is explored as an ore target along the belt. One of the main ore-bearing segments is the Ipueira, located in the southern portion where an underground mine is currently in operation. Our work was focused in this area, where we collected samples as illustrated in Figs. 1B and 2. At the Ipueira mining site (Fig. 2), we collected two samples: one from a norite of the Jacurici Mafic-ultramafic Complex (GB-02); and, one from a quartz-feldspar pegmatite that crosscuts the mafic-ultramafic rocks (ZR-157). The basement sample was collected from a large outcrop in an intermittent stream, named Riacho Barriguda (UTM coordinates 419884/8850571). The area is considered to belong to the Santa Luz Complex. The outcrop exposes a complex geology dominated by quartz-feldspar gneiss with local migmatization and injections of mafic rock (amphibolites). The amphibolites are folded and show pinch-and-swell structures (Fig. 3A). Sample JR-14 is the most representative of the outcrop and consists of a quartz-feldspar gneiss with low amounts of mafic minerals (Fig. 3B). The mineralogical composition has K-feldspar, quartz, plagioclase and orthopyroxene as its major constituents (Fig. 3C). The grain boundaries of these minerals are amoeboid to embayed. Minor biotite occurs, apparently replacing orthopyroxene, and shows no preferential orientation. Subordinate oxides, associated with orthopyroxene (Fig. 3C), and zircons, associated with felsic minerals, were also identified. The rock was classified as a charnockite orthogneiss.

The norite sampled from the drill-core I-765-90º (see Fig. 2B for location) and the interval were carefully selected to avoid contamination with later veins or veinlets (Fig. 3D). The norite is light gray and fine to medium-grained (Fig. 3E). The rock is composed mainly of orthopyroxene, plagioclase and amphibole with subordinate phlogopite showing a complex evolution. Original magmatic textures are still preserved

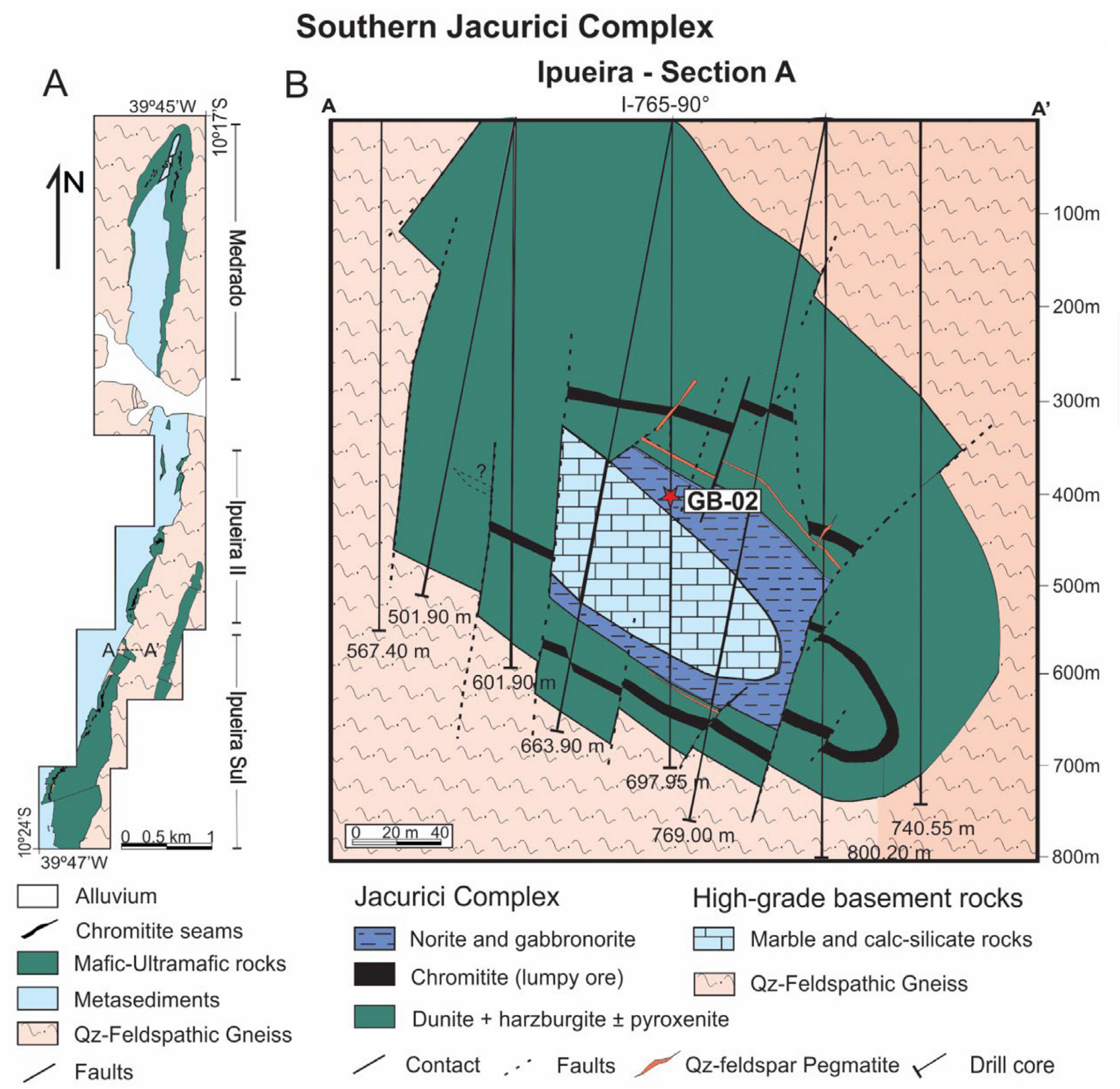
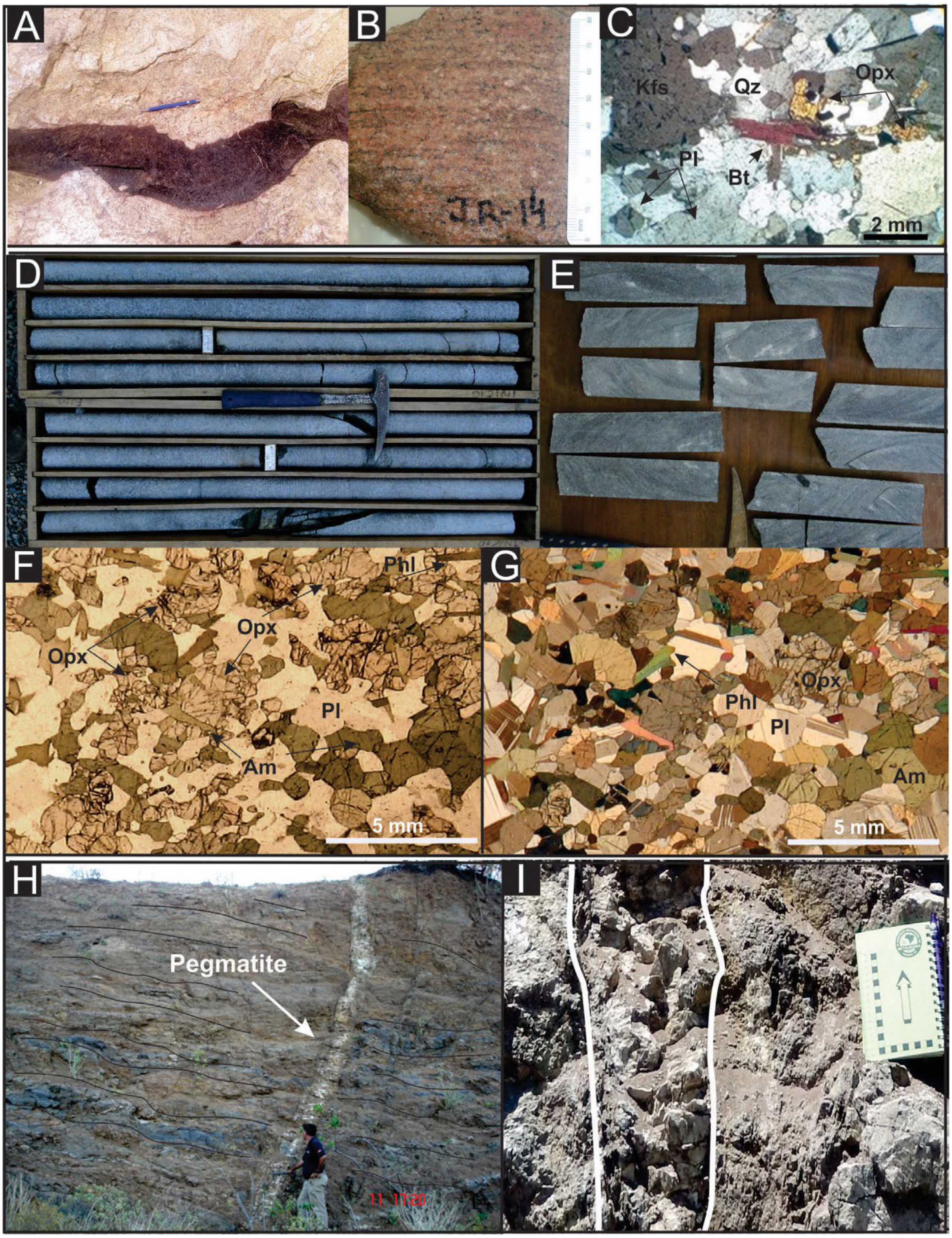


Figure 2. Simplified geological map from the (A) Ipueira-Medrado area and (B) schematic geological section of the Ipueira segment showing the location of sample GB-02 (modified from Marques *et al.* 2017), adapted from FERBASA Geology Division, internal report).



Kfs: potassic feldspar; Pl: plagioclase; Opx: orthopyroxene; Qz: quartz; Bt: biotite; Am: amphibole; Phl: phlogopite.

Figure 3. (A) Photograph of the sampled high-grade quartz-feldspar gneiss outcrop showing injections of mafic rock (amphibolites) with pinch-and-swell structures (Santa Luz Complex); (B) Photograph of the quartz-feldspar gneiss sample (JR-14); (C) Microphotograph (crossed nicols polarized light) showing orthopyroxene characterizing JR-14 as charnockite orthogneiss; (D and E) Photographs of sampled norite interval (GB-02) of the Jacurici Complex, drill core I-765-90º (FERBASA), Ipueira Mine; (F and G) Photomicrographs of the sample GB-02 (F simple and G crossed nicols polarized light) showing Complex petrological evolution for the norite (see text); (H and I) Leucocratic undeformed quartz and K-feldspar pegmatite crosscutting mafic-ultramafic rocks of the Jacurici Complex.

locally, showing amphibole to be intercumulus (Figs. 3F and 3G), although it is still uncertain as to the nature of the amphibole in these textures. Large orthopyroxene magmatic crystals (3 to 4 mm) show partial recrystallization with discrete margins recrystallized to smaller orthopyroxene grains in a granoblastic texture. The orthopyroxene is also partially recrystallized to amphibole (Figs. 3F and 3G), possibly during retrograde metamorphism. The plagioclase exhibits ubiquitous twinning but no evidence of concentric zonation. Some crystals show twins with tapering edges (Fig. 3G) suggesting deformation. The amphibole also shows local triple junctions with plagioclase, characterizing a granoblastic texture (Figs. 3F and 3G). Phlogopite occurs in minor proportions as a late metamorphic/metasomatic mineral replacing amphibole (Figs. 3F and 3G).

The Jacurici Complex area is intruded by several leucocratic granitoids. Some granitic intrusions take advantage of the contact between the mafic-ultramafic rocks and the basement during emplacement. These granitoids are usually sheared, presenting variable degrees of mylonitization. Some granitoids are undeformed showing that the granitogenesis occured syn- to post-transcurrence. Associated with this late stage, dozens of quartz-feldspar pegmatites crosscut the Jacurici Complex. They intrude along contacts between different layers within the stratiform intrusion (Fig. 2B), and also infill through faults and fractures (Figs. 2B and 3H) showing no deformation and sharp contacts with the mafic-ultramafic rocks (Fig. 3I). A representative sample was collected in an underground gallery, near the section exhibited in Figure 2B. No photograph is available, but Figures 3H and 3I show similar geological contexts. The pegmatite is leucocratic with abundant K-feldspar and quartz with minor white mica, and is undeformed. The grain sizes of K-feldspar and quartz are larger than 1 cm. No thin section was prepared.

Zircon and U-Pb geochronology

The zircon crystals from the charnockite orthogneiss sample (JR-14) are elongated (300 to 400 µm), mostly composed of 4:1 and 3:1 ratio (Fig. 4 — I, IV, VI, X), and subordinate 1:1 to 2:1 ratio. The zircons are euhedral with pyramidal terminations. The cathodoluminescence imaging (CL) reveals zircons with heterogeneous zoning, showing core and rim domains. The cores register oscillatory zoning (Fig. 4 — I, II, VI, IV), and engulfment features (Fig. 4 — I, III, VII). The CL show a dark-grey thicker rim, with oscillatory to weak polygonal zoning, and a bright thin unzoned outer rim (Fig. 4).

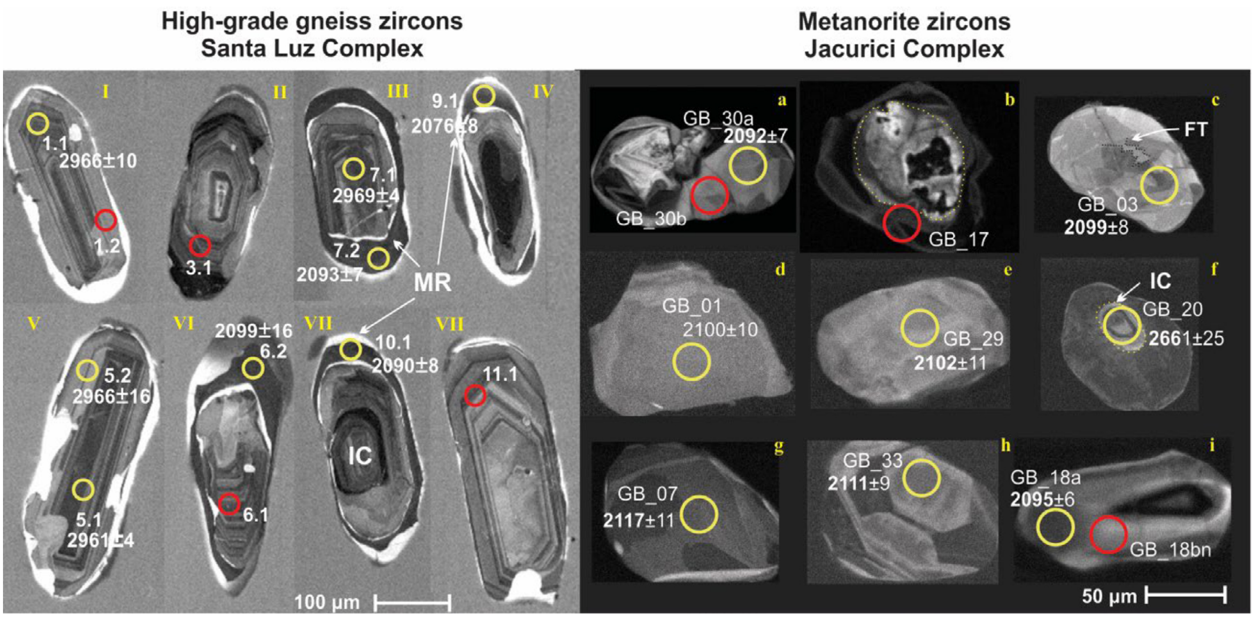
The norite zircon crystals (GB-02) are short (30 to 50 µm), with a 1:1 to 2:1 ratio. CL images shows zircons with a chaotic to metamictic core domain (Figs. 4A, 4B, 4C, 4F and 4I), with ghost oscillatory zoning and engulfment (Figs. 4A, 4B, 4C, 4F and 4I). Most of the zircons display no cores with weak to unzoned polygonal zoning throughout the crystals (Figs. 4D, 4E, 4G, 4H). Fir-tree patchy zoning (Fig. 4C) occurs in coreless zircons. The zircon rims are unzoned to weak polygonal/patchy zoning. Few inherited cores were identified.

The quartz-feldspar pegmatite zircons (ZR-157) are medium sized crystals (100 to 150 µm), with 2:1 ratio, slightly zoned, showing bipyramidal tendency with slightly rounded edges. Some crystals show fractures, and no inherited cores were identified.

All samples display discordant crystals and some degree of Pb-loss, the pegmatite in particular. Analyses with concordance from 98 to 102% were selected to produce Concordia ages for samples JR-14 and GB-02. However, for the pegmatite, the Concordia age was not possible due to the higher degree of Pb-loss. Therefore, for sample ZR-157, analyses with concordance lower than 103% and error lower than 3% for the $^{207}Pb/^{235}U$ ratio were considered for the upper intercept age calculation. Figure 5 presents the Concordia diagrams for the samples and the best ages for each group of analyses.

The 11 zircon crystals from the gneiss (JR-14) display ages from 3026 to 2066 Ma and Th/U ratios from 1.57 to 0.10 (average 0.50) (Fig. 6) from zircon rims and cores. Figures 5C and 5D plots the Concordia ages for zircon rims (C) and core (D), revealing a nuclei age of 2966 ± 9 Ma (MSWD = 0.06) and 2091 ± 10 (MSWD = 1.3).

The norite (GB-02) produced ages ranging from 2662 to 1700 Ma and Th/U ratios from 1.28 to 0.08 (mean 0.5)



MR: metamorphic rim; IC: inherited core; FT: fir-tree zoning. Circles show the position of spot analyses (yellow - concordant results; red- discordant results).
Figure 4. Zircons cathodoluminescence imaging from the norite of the Jacurici Complex and from the Santa Luz charnockite orthogneiss highlighting internal textures.

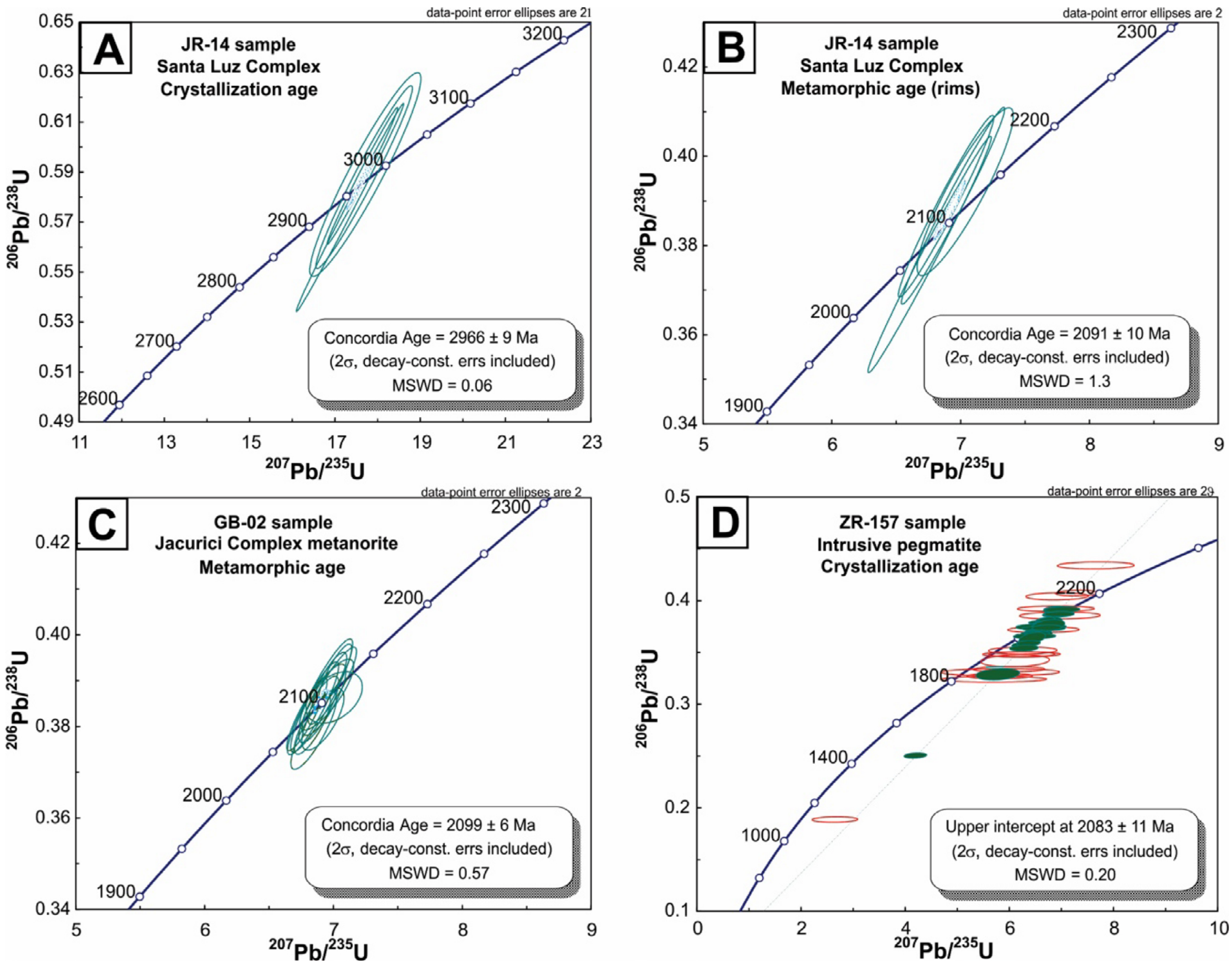


Figure 5. Zircon U-Pb Concordia ages of the Santa Luz Complex orthogneiss (JR-14), (A) crystallization and (B) metamorphism (rims) and (C) of the Jacurici Complex metanorite (GB-02), metamorphism. (D) Zircon U-Pb upper intercept crystallization age of the intrusive pegmatite (ZR-157); Errors and ellipses correspond to 2 sigma values. In D, red ellipses are analyses not considered in the age calculation.

(Fig. 6). The ages were produced from 39 spots in 32 zircon crystals. Eight concordant zircon crystals from GB-02 define an age of 2099 ± 6 Ma (MSWD = 0.57) (Fig. 5A).

The quartz-feldspar pegmatite (ZR-157) presents ages from 2179 to 1659 Ma and Th/U ratios from 1.19 to 0.28 (average 0.55) (Fig. 6) based on 50 spots in 29 zircon crystals. Thirty one out of fifty analyses yielded an upper intercept age of 2083 ± 11 Maand MSWD of 0.20 (Fig. 5B). The lower intercept age presents enormous error and is meaningless.

DISCUSSION

The Jacurici Complex magmatic age and tectonic setting are not well constrained. It is located in an area that marks the limit between two major terrains: the Serrinha Block to the East and the Salvador-Curaçá Belt to the West. There is a debate regarding whether or not the Complex is intrusive in the Serrinha Block (Kosin *et al.* 2003, Costa 2014) or in the Salvador-Curaçá Belt (Barbosa *et al.* 2012, Misi *et al.* 2012). We have sampled a charnockite orthogneiss located to the East of the Jacurici Complex (JR-14, Fig. 1B). The SHRIMP U-Pb determinations for zircons cores, with oscillatory zoning and relatively high Th/U ratio (Fig. 6), yielded 2966 ± 9 Ma ages (Fig. 5A) interpreted as the crystallization age for the gneiss protolith.

The Western part of the Serrinha Block is composed of calc-alkaline to TTG orthogneisses of the Mesoarchean Santa Luz Complex (3.2-2.9 Ga) (Rios *et al.* 2008, Oliveira *et al.* 2010). On the other hand, the Salvador-Curaçá Belt is an orogen constituted by an amalgamation of ancient terrains during the Rhyacian-Orosirian. The Salvador-Curaçá Belt preserves the remains of a reworked Neoarchean arc (Oliveira *et al.* 2010, Martins de Sousa *et al.* 2020), represented mainly by ca. 2.7-2.6 Ga orthogneisses from the Caraíba Complex (Silva *et al.* 1997, Oliveira *et al.* 2010) and associated metamorphosed supracrustal rocks.

The field and petrographic characteristics (Figs. 3A, 3B, and 3C) of the sampled charnockite orthogneiss (JR-14), as well as its age, are more compatible with the description and ages attributed to the Santa Luz Complex (Barbosa and Sabaté 2004, Oliveira *et al.* 2004a, Rios *et al.* 2009, Baldim and Oliveira 2021) suggesting that the terrain immediately east of the Jacurici Complex belongs to the Serrinha Block, at least.

Both the Santa Luz and the Caraíba Complexes were affected by high-grade metamorphism reaching up to granulite facies with local migmatization during the Rhyacian amalgamation

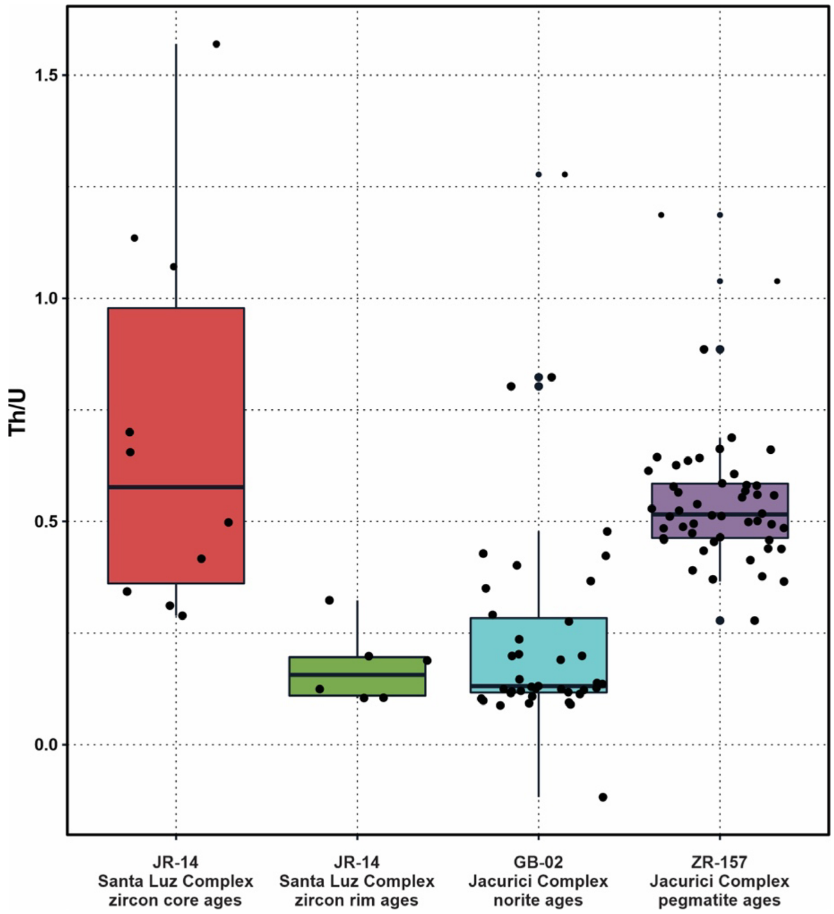


Figure 6. Th/U ratios from zircons from samples JR-14 (core and rim), GB-02 and ZR-157. Lower Th/U values suggest metamorphic origin and Th/U around 0.5 indicates igneous origin (Rubatto 2017, Yakymchuk *et al.* 2018).

of the Archean terrains (Kosin *et al.* 2003, Leite *et al.* 2009, Oliveira *et al.* 2010). Regarding metamorphism, the internal textures of the zircons of the charnockite orthogneiss (JR-14) demonstrate recrystallization under metamorphic fluids (Vavra *et al.* 1996, Rubatto and Hermann 2007, Rubatto *et al.* 2008, Grant *et al.* 2009) causing overgrowth of outer rims. The outer rims present low Th/U ratio (Fig. 6), also supporting its metamorphic nature, and provided a 2091 ± 10 Ma SHRIMP U-Pb age.

The ca 2.1 Ga age of the metamorphic outer zircon rim of the charnockite orthogneiss is interpreted as the metamorphic peak in the area near the Jacurici Complex considering that this rock is heavily affected by metamorphism, reaching migmatization levels. This age is compatible with the overall time-span of the metamorphic peak resulting from the amalgamation of the Serrinha Block eastward with the Salvador-Curaçá Belt, and is also coeval with the arc-continent-continent collision involving the Serrinha building blocks- including the Santa Luz Complex, the Rio Itapicuru Arc, the Uauá Complex, the Capim Arc- and the Congo Craton (Ntem-Chailu and Ogooué Complex) (Oliveira *et al.* 2010, Baldim and Oliveira 2021). The Serrinha Block shows intrusions synchronic to the 2.1 Ga metamorphic peak — such as the Fazenda Gavião granodiorite (Costa *et al.* 2011) and the Itareru tonalite (Conceição *et al.* 2002), located to the south of our studied area and interpreted as intruded during, or shortly after, arc-continent collision (Costa *et al.* 2011, Baldim and Oliveira 2021).

In the Salvador-Curaçá Belt, the metamorphism occurs from 2.1 Ga to 2.04 Ga, (Barbosa *et al.* 2008, Oliveira *et al.* 2004a, 2010, Silveira *et al.* 2015, Martins de Sousa *et al.* 2020), including both collision and post-collision stages. The belt comprises several blocks, such as the Caraíba Complex, the São José do Jacuípe Complex, the Salvador and Bravo granulites, and display zircons with metamorphic rims with a particular prevalence of ages between 2.08 to 2.06 Ga (Silva *et al.* 1997, Barbosa *et al.* 2008, Oliveira *et al.* 2010, Martins de Sousa *et al.* 2020). A series of granitoids intrudes the belt, and their age and associated deformation (e.g. foliated to isotropous granitoid) help to reconstruct the age-span of the syn-collision to syn-late-post transcurrance in areas to the west of the Jacurici Complex. The Cais Granite (2100 Ma and 2093 Ma, Martins de Sousa *et al.* 2020, the Itiúba Syenite, the Capela Granite (2084 Ma and 2078 Ma, Oliveira *et al.* (2010), and the Bravo Granite (2060 Ma, Barbosa *et al.* 2008) are, interpreted as syn-collisional, syn-transcurrent and late-transcurrent intrusions respectively, demonstrating the time-span of the processes (Oliveira *et al.* 2004a, Rios *et al.* 2007, Martins de Sousa *et al.* 2020). The minimum age for the beginning of the collision is considered to be between 2100 Ma and 2094 Ma while the transcurrence occurred from 2084 Ma to 2060 Ma (Martins de Sousa *et al.* 2020).

The Jacurici Complex crystallization age has long been considered to be 2085 ± 5 Ma (Oliveira *et al.* 2004a), synchronous to the Itiúba Syenite (2084 ± 9 Ma, Oliveira *et al.* 2004a). However, the Jacurici Complex is metamorphosed under high-grade conditions (Marques *et al.* 2017), posing some problems for the current interpretation. A lateral mafic intrusion interpreted as coeval and belonging to the Jacurici magmatism yielded a 2102 ± 5 Ma age (Silveira *et al.* 2015), interpreted as the crystallization time for the Complex. The U-Pb dating of zircons from the selected norite of the Jacurici Complex in the Ipueira Mine (GB-02, Fig. 2B) yielded an age of 2099 ± 6 Ma. However, our dated zircons revealed relevant metamorphic zoning patterns in CL imaging (Fig. 4). One specific feature, the fir-tree texture (Fig. 4), suggests temperatures ranging from 800 to 900°C and pressure from 1.0 to 2.0 GPa (Vavra *et al.* 1996, Grant *et al.* 2009, Rubatto 2017), which is compatible with granulite facies conditions. These agree with petrographic features previously reported in northern segments of the Complex, where large elongated magmatic orthopyroxene crystals are partially recrystallized into fine-grained granoblastic orthopyroxene (Marques *et al.* 2017, Friedrich *et al.* 2020). A similar texture, although not so well developed, was observed during this study in the norite sample. The high-grade metamorphic conditions that partially affected the Jacurici Complex are similar to what is reported for some of the host rocks, corroborating the conclusion that the terrain was affected by high-grade metamorphism. Pelitic metasediments that host the Complex were described as affected by the regional granulite metamorphism, with P-T conditions estimated to be 750-800°C and 7-8 Kb (Del Lama *et al.* 2001). The regional metamorphism from the W Serrinha Block tectonism and amalgamation (Oliveira *et al.* 2010, Baldim and Oliveira 2016) affected the Jacurici Complex, producing zircon internal textures such as fir-tree as well as low Th/U ratios (Fig. 6) typical of high-grade metamorphism (Hoskin and Black 2000, Corfu *et al.* 2003, Hoskin 2005, Rubatto *et al.* 2008, Grant *et al.* 2009, Rubatto 2017), and causing the U-Pb system reset. Therefore, we here interpret that the Jacurici Complex was already intruded when the peak of the regional metamorphism was achieved at around 2.1 Ga. It is important to mention that CL images were not available in the previous geochronological determinations (Oliveira *et al.* 2004a) of the Jacurici Complex, a fact that might have led to the misinterpretation of the meaning of the ages.

The Jacurici Complex was folded and disrupted, then later intruded by quartz-feldspar pegmatites that are undeformed (Marques *et al.* 2017). The norite described here also shows features suggestive of retrograde metamorphism, with orthopyroxene being replaced by amphibole (Figs. 3F and 3G). The metamorphic tremolite in the ultramafic rocks of the Jacurici Complex was considered a retrometamorphic effect (Friedrich *et al.* 2020). The lower P-T conditions affecting the rocks were interpreted as being related to the transcurrence and the intrusion of potassic granitoids. Evidence for that includes shearing contacts between the mafic-ultramafic rocks with the basement (Marques *et al.* 2017), and intrusive leucogranite in the margins of the mafic-ultramafic Jacurici Complex in the Ipueira area that are slightly sheared (Silveira *et al.* 2015). The 2083 ± 11 Ma age obtained here for the intrusive leucocratic undeformed pegmatites that crosscut the Jacurici Complex (ZR-157) overlaps with the age of the slightly sheared leucogranite (2081 ± 3 Ma Silveira *et al.* 2015) and the age of the Itiúba Syenite (2084 ± 9 Ma SHRIMP U-Pb in zircons) (Oliveira *et al.* 2004a), which is compatible with the N-S transcurrence evolution (Silva *et al.* 1997, Martins de Sousa *et al.* 2020).

Rhyacian amalgamation and the Jacurici Complex

In order to illustrate our results in regards to the Rhyacian amalgamation of Archean and Paleopretorozoic terrains in the northeastern part of the São Francisco Craton, Figure 7 compiles U-Pb ages available in the literature for areas near the Jacurici Complex, within the Serrinha Block to the East and the Salvador-Curaçá Belt to the West. We highlighted the time-span for the peak of the regional metamorphism, which is linked to collision and high-grade metamorphism, and the N-S transcurrence installed just after the collision, with the time-span constrained by the intense potassic granitogenesis.

The ca 2.1 Ga age of the metamorphic outer rims from the analyzed zircons in sample JR-14, interpreted as belonging to the Santa Luz Complex, is synchronous with the Jacurici Complex norite (GB-02) zircon age obtained, both being considered to have been formed under high-grade metamorphism. The ages correspond to the peak regional metamorphism related to the early phases of the collision between the Gavião and Serrinha Blocks, generating the Salvador-Curaçá belt, and coeval with the eastward collision of the Serrinha and Ntem-Chailu blocks (Baldim and Oliveira 2021). In the Salvador-Curaçá belt, south- and northwest of the Jacurici Complex, respectively, the Cais granite (Sampaio 1992) occurs near São José do Jacuípe, and a foliated alkali granite, near the Caraíba mine (Martins de Sousa *et al.* 2020), with ages ranging from ~2100 Ma and 2093 Ma which were interpreted as resulting from early collision magmatism (Martins de Sousa *et al.* 2020). In the Serrinha Block, synchronous 2.1 Ga intrusions occur — such as the Fazenda Gavião granodiorite (Costa *et al.* 2011), the Itareru tonalite (Conceição *et al.* 2002), and 2.16–2.13 Ga plutons — all interpreted as being linked to a continental arc environment (Group 2 granitoid, Rios *et al.* 2009).

Regarding the N-S transcurrence installed just after the collision, more data are available considering it to be coeval with abundant potassic magmatism with many granitic rocks intruded and deformed with concomitant shearing. The intense granitogenesis (Carvalho and Oliveira 2003, Oliveira *et al.* 2004b, de Paula Garcia *et al.* 2018, Martins de Sousa *et al.* 2020) is associated with the degrees of deformation during syn- to late phases of the shear zone development. Intrusions are progressively less affected by mylonitic deformation, and end with undeformed intrusions (Oliveira *et al.* 2004a, Rios

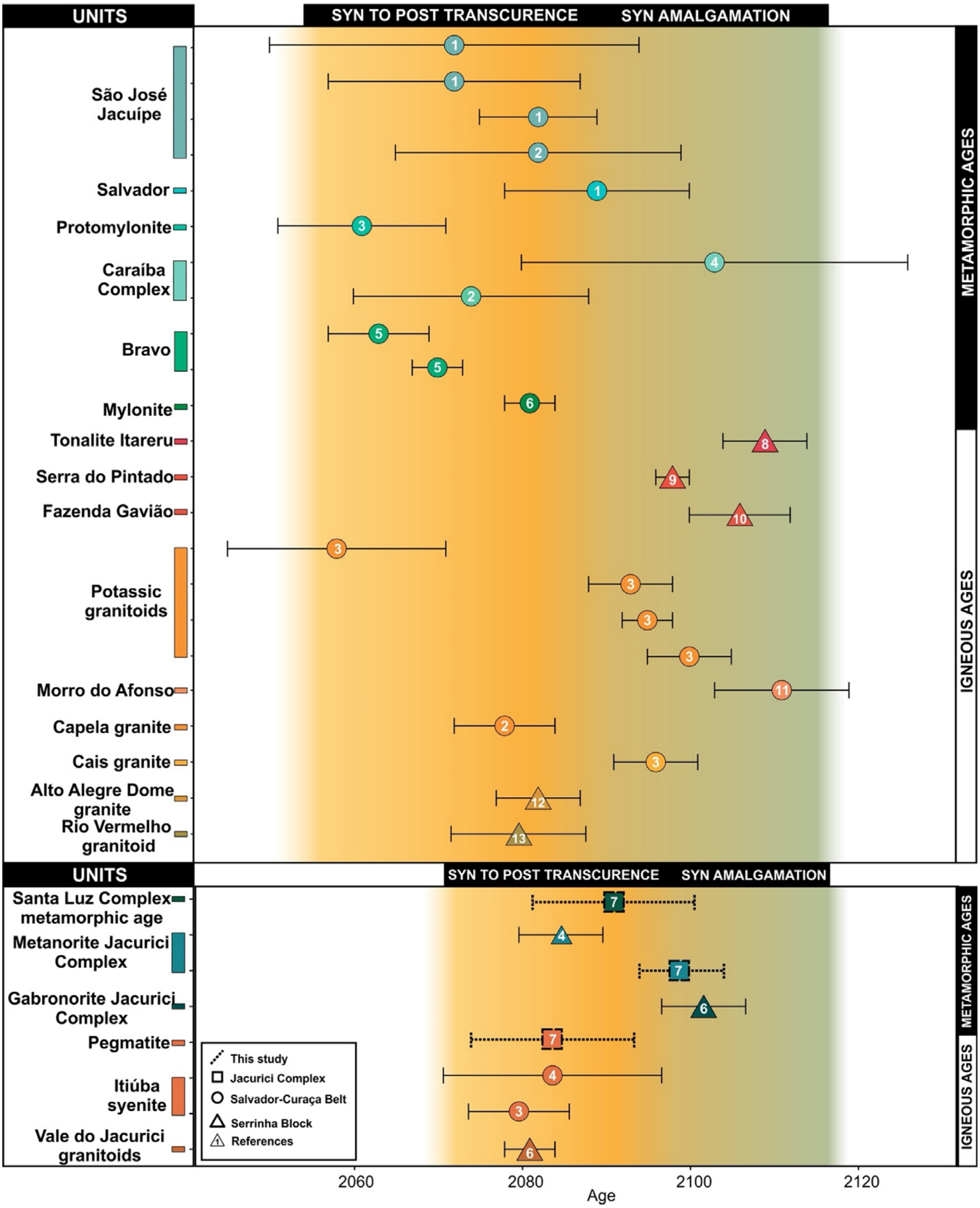


Figure 7. Metamorphic and igneous ages for the Salvador-Curaça Belt, theSerrinha Block and the Jacurici Complex Area. Syn-amalgamation tectonism conditions are registered around 2.1 Ga, with a posterior progressive transcurrence (syn- to post-) around 2.09 to 2.06 Ga. The transcurrence phase in the Jacurici Complex occurs from 2.09 to 2.08 Ga. Star- this study; (1) Silva *et al.* (1997); (2) Oliveira *et al.* (2010); (3) Martins de Sousa *et al.* (2020); (4) Oliveira *et al.* (2004a); (5) Barbosa *et al.* (2008); (6) Silveira *et al.* (2015); (7) Carvalho and Oliveira (2003); (8) Conceição *et al.* (2002); (9) Costa *et al.* (2011); (10) Rios *et al.* (2007); (11) Baldim and Oliveira (2016); (12) Rios *et al.* (2005).

et al. 2007, Martins de Sousa *et al.* 2020). The time-span for the transcurrence is considered to be 2084 Ma to 2060 Ma for syn- to late transcurrence (Martins de Sousa *et al.* 2020) in the northwestern area of the Jacurici Complex, near the Caraíba Mine, within the Salvador-Curaçá belt. Within the Santa Luz Complex, examples of potassic intrusions include the Pedra Vermelha granite (2080 ± 8 Ma; (Rios *et al.* 2005), the Itiúba syenite (2084 Ma, Oliveira *et al.* 2004a), a pink granite in the central Alto Alegre Dome (2082 ± 5 Ma, Baldim and Oliveira 2016) and the slightly sheared alkaline granite intruded at the contact between the mafic-ultramafic rocks of the Jacurici Complex and the basement rocks (2081 ± 2 Ma Silveira *et al.*

2015). Considering this last age, which is coeval within error with the age of the undeformed quartz-feldspar pegmatites that crosscut the Jacurici Complex, it's possible to conclude that in the studied area the transcurrence ended a little earlier than in the northwestern area, at around 2.08 Ga.

High-grade metamorphism direct dating, from zircon rims or metamorphic minerals, is not commonly available in the studied area and the few examples generally show a large range of ages. One example is the Caraíba norite zircon outer rims which yielded an age of 2103 ± 23 Ma SHRIMP U-Pb for the metamorphism (Oliveira *et al*. 2004b), which is similar in age to our metamorphic zircon dating, but with a larger error margin. Younger ages attributed to high-grade metamorphism within the Salvador-Curaçá belt are also reported, overlapping with both the collision- and transcurrence time-span ranging from 2082 ± 17 to 2074 ± 14 Ma (Silva *et al*. 1997, Oliveira *et al*. 2010). Discretion in interpretation of the meaning of the metamorphic rims is important considering the high influence of the granitogenesis related to the transcurrence which is well defined from 2.06 to 2.08 Ga in the Salvador-Curaçá Belt. The study of Chauvet *et al*. (1997) illustrates the deformational impact of the Rhyacian granitoids over the Archean gneissic basement. On the other hand, the 2.1 Ga ages in both the Santa Luz Complex and the Jacurici Complex point to a high-grade regional metamorphism that is coeval with the syn-collision records reported for the Rhyacian tectonic building in the northeastern portion of the São Francisco Craton,

As a consequence, we can say that the magmatic Jacurici Complex age remains unknown, but it is necessarily equal, or older than, 2.1 Ga considering that the age reported here is related to the peak of metamorphism in the region during the amalgamation of the Archean Blocks during the Rhyacian. The transcurrence that affected the whole area, shearing both the Serrinha Block and the Salvador-Curaçá basement rocks, and coeval with a potassic granitogenesis that marks all stages from high strain deformation to post- transcurrence, also affected the Jacurici Complex causing retrograde metamorphism and shearing with concomitant intrusion of the leucogranites. Later, undeformed pegmatites that crosscut the Complex at ca. 2.8 Ga marks the end of tectonism in that specific region, although deformation is reported in other areas both to the West (Martins de Sousa *et al*. 2020) and the East (Baldim and Oliveira 2021).

The northern portion of the São Francisco Craton hosts several mafic-ultramafic associations with some being related to mineralization, such as the Cr-bearing Campo Formoso Complex and the Cu-bearing Vale do Curaçá Complex. The 2.1 Ga defines the minimum emplacement age for the Jacurici Complex, so additional correlations with other São Francisco Craton mafic-ultramafic intrusions must be reconsidered. For instance, a possible relationship with the northern 2.5 Ga Cu-mineralized mafic-ultramafic intrusions of the Caraíba Complex was disregarded when the Jacurici Complex was interpreted as Paleoproterozoic (Oliveira *et al*. 2004b). However, later, sulfide Cu-Ni mineralization was described in the Jacurici northern segments (Marques *et al*. 2017). With the interpretation that the Jacurici Complex could be older than 2.1 Ga, a connection between the two complexes must not be ignored. The same must be said regarding the alkaline Paleoproterozoic magmatism reported in the southern areas, such as those of Granitoid group 2 (Rios *et al*. 2009) or those related to the precursors of the Itiúba Syenite. The age of the Jacurici Complex magmatism remains unknown, so all possibilities must be considered. To fully reconstruct the Jacurici Complex emplacement and its relationship with Northeastern São Francisco Craton magmatism, further geochronological studies are recommended as it is critical for the metallogenetic comprehension of the district, and to ensure that adequate exploration is carried out.

CONCLUSION

The ages and the tectonic setting of the Cr-rich Jacurici mafic-ultramafic Complex are not well constrained. It is located in the limit between two major terrains of the Northeast São Francisco Craton: the Serrinha Block to the East and the Salvador-Curaçá Belt to the West. In order to understand the geochronological context, we have studied a charnockite orthogneiss located to the East of the Jacurici Complex, a metamorphosed norite and a crosscuting undeformed quartz-feldspar pegmatite. The results and discussion led us to the following conclusions:

- The charnockite orthogneiss indicates a high-grade metamorphism reaching up to granulite facies with local migmatization. SHRIMP U-Pb ages of oscillatory zoned zircon cores yielded ages of 2966 ± 9 Ma for crystallization. Metamorphic outer zircon rims provided a 2091 ± 10 Ma SHRIMP U-Pb age;
- All characteristics are similar to those from the Santa Luz Complex, implying that the terrain located immediately east of the Jacurici Complex belongs to the Serrinha Block;
- The 2.11 Ga age of the outer rims, coupled with the telltale internal fir-tree patterns within the zircons of the charnockite orthogneiss leads to the interpretation of this age as the timing of the regional metamorphic peak, compatible with the time-span of the amalgamation of the Serrinha Block eastward with the Salvador-Curaçá Belt;
- The metamorphic peak is also coeval with the arc-continent-continent collision westward involving the Serrinha building blocks and the Congo Craton;
- Zircons from the metamorphosed norite of the Jacurici Complex, sampled from a drill core at the Ipueira Mine, show high grade metamorphism internal textures, which is compatible with previously reported metamorphic conditions for the Complex and the host rocks. A U-Pb LA-ICP-MS 2099 ± 6 Ma age was obtained, and interpreted as the age of the metamorphism;
- The age of the metamorphic zircons from the Jacurici Complex indicates that the Complex was already emplaced when the regional metamorphism took place around 2.1 Ga;
- Zircons from the undeformed quartz-feldspar pegmatites that crosscut the Complex provided LA-ICP-MS U-Pb ages of 2083 ± 11 Ma — coeval with other granitoids, including

the Itiúba Syenite and the slightly sheared leucogranite that occurs near the border of the Jacurici Complex — marking the end of the N-S transcurrence in this region;
- The transcurrence that affected the entire area (including the Jacurici Complex) causing localized shearing and retrograde metamorphism, ended earlier in the studied region in comparison to the northwestern area of the Salvador-Curaçá belt;
- The magmatic Jacurici Complex age remains unknown but is equal , or older than, 2.1 Ga considering that the Complex was metamorphosed during the Rhyacian tectonic building of the northeastern part of the São Francisco Craton.
- Possible correlations with alkaline magmatism and other mafic-ultramafic intrusions in the region are recommended for review, especially the northern Cu-mineralized Caraíba Complex located to the northwest.

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