

From rifting to collision: deep closure of a Wilson cycle during the Archean–Paleoproterozoic transition at the Carajás-Bacajá boundary, Amazonian Craton

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14 Abstract

15 The Carajás-Bacajá boundary preserves complementary archives of continental rifting, passive-
16 margin development, subduction, collision and post-collisional exhumation across the Archean-
17 Paleoproterozoic transition. We present whole-rock lithogeochemistry, Sm-Nd isotopes, U-Pb
18 zircon geochronology and thermobarometry from the Vila Santa Fé-Rio Preto association, a mafic-
19 felsic granulitic assemblage tectonically above the Buritirama succession. Rio Preto-type mafic
20 granulites define a comparatively juvenile pole, whereas arc-modified felsic orthogneisses have
21 negative ϵ_{Nd} at ca. 2.10 Ga, TDM ages of ca. 2.44-2.46 Ga and Archean inherited zircon. U-Pb
22 zircon records lower-crustal melt growth at 2097 ± 19 and 2093 ± 25 Ma, followed by granulite-
23 facies recrystallization, migmatization and charnockitic to enderbitic melt generation between
24 2073 ± 3 and 2067 ± 7 Ma. Thermobarometry constrains a 9-10 kbar, 760-800 °C granulitic root,

25 followed by hydrated decompression at 7-8 kbar and 690-710 °C; Carajás-side amphibolite records
 26 ca. 700-720 °C. Structural, geophysical and $^{40}\text{Ar}/^{39}\text{Ar}$ constraints define southwest-verging
 27 stacking of Bacajá lower crust over Buritirama and northern Carajás between ca. 2.10 and 2.05 Ga.
 28 Published data extend the reconstruction backward. A 2549 ± 5.9 Ma A2-type granite and proximal
 29 ca. 2.55 Ga detritus date rift initiation; upward provenance broadening, seawater-like carbonate
 30 chemistry, positive pre-ore $\delta^{13}\text{C}$ and later manganese accumulation record margin maturation and
 31 sediment starvation. Apparent Paleoproterozoic detrital ages in Buritirama are reproducible by
 32 low-discordance Pb loss from Archean zircon. The same correction applies to the Novolândia
 33 granulite belt, whose sedimentary protoliths carry a 3.32–3.18 Ga Paleoproterozoic provenance peak,
 34 2.75 and 2.55 Ga magmatic populations and a rift-type granite crystallized at 2567 ± 22 Ma with
 35 2744 ± 21 Ma inheritance, identifying the far side of the closed ocean as a detached fragment of the
 36 Carajás margin. Bacajá arc magmatism at ca. 2.21-2.13 Ga and coeval fluid-assisted re-
 37 equilibration in Carajás define upper- and lower-plate responses consistent with slab-pull
 38 extension. Decompression, rapid cooling and the unconformable Águas Claras basin, whose basal
 39 marine interval is exposed at Azul and Serra Pelada, record collapse and renewed marine
 40 transgression. The direct result is the Rhyacian collisional stack; the full Wilson cycle is the
 41 integrated model that explains the ordered regional evidence.

42 **Highlights**

- 43 • Ca. 2.55 Ga A-type magmatism records rifting of the northern Carajás margin.
- 44 • Buritirama carbonates and Mn deposits record a sediment-starved passive margin.
- 45 • Bacajá arc and Carajás fluid flow define upper- and lower-plate polarity.
- 46 • Bacajá lower crust was stacked over Carajás at ca. 2.07 Ga and 9–10 kbar.

47 • Pb loss explains apparent Paleoproterozoic detrital ages in Buritirama.

48 **Keywords:** Carajás Province; Bacajá Domain; Wilson cycle; passive margin; Rhyacian collision;
 49 granulite-facies metamorphism

50 1. Introduction

51 Wilson cycles are strongest where the opening, maturation and closure of an oceanic domain can be
 52 reconstructed within a single tectonic system (Wilson, 1966). In Precambrian terranes, each stage
 53 is commonly preserved by a different archive. Rift magmatism and basin stratigraphy remain in the
 54 lower plate, arc growth and high-grade metamorphism are concentrated in the upper plate, and
 55 collision juxtaposes these records after much of the oceanic lithosphere has been consumed. A
 56 rigorous reconstruction must therefore rank observations by their directness and spatial scale.
 57 Magmatic ages, stratigraphic relations, sedimentary geochemistry, structures, pressure-
 58 temperature estimates and mineral chronometers constrain particular stages; the Wilson-cycle
 59 trajectory is the regional synthesis that explains their ordered association.

60 Archean crust coupled with Rhyacian orogens offer an early and extensive record of this plate-
 61 boundary architecture during Columbia/Nuna assembly. Across the Amazonian Craton and coeval
 62 provinces, ca. 2.2-2.0 Ga arc construction, crustal thickening, granulite-facies metamorphism and
 63 post-collisional reorganization affected older crustal fragments (Cordani et al., 2000; Zhao et al.,
 64 2002; Rogers and Santosh, 2002; Johansson, 2009; Nance et al., 2014). The geometry and thermal
 65 structure of many of these systems remain uncertain because their shallow and deep crustal records
 66 are exposed far apart or have been reworked by younger events.

67 The Carajás-Bacajá boundary in the southeastern Amazonian Craton preserves a complementary
 68 record. Carajás contains Mesoarchean basement, the ca. 2.76-2.68 Ga Itacaiúnas volcano-
 69 sedimentary system and a younger sedimentary margin initiated by ca. 2.55 Ga within-plate
 70 magmatism. Bacajá contains Archean inheritance, Siderian juvenile additions, Rhyacian arc
 71 magmatism and a high-grade orogenic hinterland. Along their present contact, the Buritirama
 72 succession is structurally overlain by the Vila Santa Fé-Rio Preto high-grade association. The
 73 boundary therefore places the sedimentary archive of the lower-plate margin beside granulitic
 74 rocks from the collisional root.

75 The opening side of this history is principally constrained by published data from Buritirama. The
 76 2549 ± 5.9 Ma Buritirama metagranite records extension of the northern Carajás margin (Salgado
 77 et al., 2019a, 2019b). Detrital zircon spectra change upward from a strong ca. 2.55 Ga proximal
 78 component to broader Archean populations, while the stratigraphy evolves from quartz-rich clastic
 79 deposits to carbonate-silicate rocks, dolomitic marble and manganese-rich chemical sedimentation
 80 (Salgado et al., 2019a, 2019b, 2021). These observations define rift initiation and margin

81 maturation. The duration, continuity and exact geometry of the intervening ocean remain
82 interpretive questions.

83 The closure side is constrained directly by the data presented here. Earlier regional models
84 recognized Paleoproterozoic deformation and thermal reworking in northern Carajás and related
85 these effects to interaction with Bacajá (Tavares et al., 2018). Geophysical data subsequently
86 identified magnetic continuity and a gravity high along the Vila Santa Fé-Bacajá high-grade belt
87 (Motta et al., 2019; Oliveira et al., 2020; Serafim et al., 2023). Regional geochronology records
88 pre-collisional Bacajá magmatism from ca. 2.21 to 2.13 Ga, collisional and late-collisional
89 magmatism from ca. 2.11 to 2.05 Ga, and protracted high-grade metamorphism in Novolândia
90 from ca. 2.16 to 2.04 Ga (Vasquez, 2006; Vasquez et al., 2008; Neri et al., 2025, 2026). The
91 physical depth, internal components and timing of the exposed boundary root required integrated
92 constraints.

93 We present whole-rock lithochemistry, Sm-Nd isotopes, U-Pb zircon geochronology and
94 thermobarometry from the Vila Santa Fé-Rio Preto association. The dataset distinguishes primitive
95 and enriched mafic components, identifies arc-modified felsic crust, dates lower-crustal melt
96 growth and granulite-facies reworking, and constrains the pressure-temperature path of the
97 collisional root. These results are integrated with published $^{40}\text{Ar}/^{39}\text{Ar}$, structural, geophysical,
98 stratigraphic and sedimentary-geochemical records.

99 Our argument has two levels. The primary result is a directly constrained Rhyacian crustal stack
100 formed between ca. 2.10 and 2.05 Ga, with Bacajá-derived granulitic lower crust transported
101 southwestward over the Buritirama succession and the northern Carajás margin. The broader
102 interpretation links this closure to ca. 2.55 Ga rifting, a long sediment-starved drift interval,
103 renewed lower-plate extension during onset of Bacajá subduction, and late- to post-collisional
104 basin development. We state the evidential limits of each stage within an integrated Wilson-cycle
105 model.

106 **2. Regional tectonostratigraphic setting**

107 The southeastern Amazonian Craton is conventionally divided into the Carajás Province to the
108 south and the Bacajá Domain to the north (Fig. 1a, c). This division expresses a first-order contrast
109 between predominantly Archean crust in Carajás and a Paleoproterozoic high-grade domain with
110 substantial Archean inheritance in Bacajá (Cordani et al., 1984; Teixeira et al., 1989; Tassinari and
111 Macambira, 2004; Santos et al., 2000; Santos, 2003; Vasquez and Rosa-Costa, 2008). Along the
112 study transect, this geochronological boundary is also a structural, metamorphic and geophysical
113 boundary.

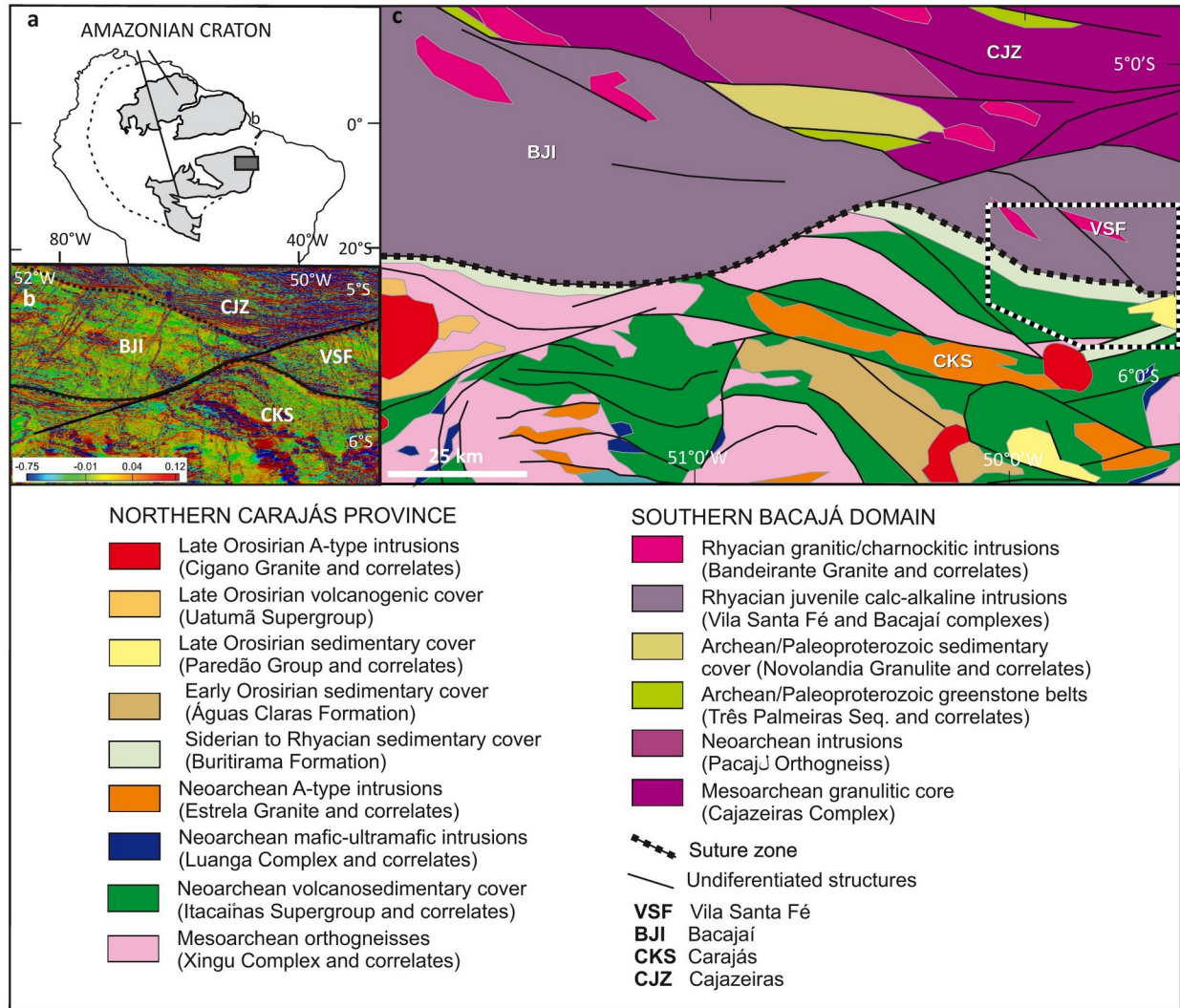


Figure 1: Regional tectonostratigraphic and geophysical context of the Carajás-Bacajá boundary. (a) Location of the Amazonian Craton in South America; the grey polygon indicates the region shown in panels b and c. (b) First vertical derivative aeromagnetic image showing the continuity of magnetic lineaments between the Vila Santa Fé area and the Bacajá region. Aerogeophysical image from Serafim et al. (2023). Abbreviations are shown in the graphical legend. (c) Simplified tectonostratigraphic map of the northern Carajás Province and southern Bacajá Domain, modified from Vasquez and Rosa-Costa (2008) and Costa et al. (2016). The dotted line marks the interpreted suture zone between the Carajás and Bacajá crustal blocks, following Tavares et al. (2018). The dashed polygon indicates the location of the study area.

114 The northern Carajás Domain comprises Mesoarchean basement overlain and intruded by the
 115 Neoarchean Itacaiúnas system. Volcanic, plutonic and mafic-ultramafic activity between ca. 2.76
 116 and 2.73 Ga accompanied extensional basin development. The Serra Sul and Igarapé Cigarra
 117 successions belong to the upper Neoarchean sedimentary architecture of this system, broadly
 118 between ca. 2.73 and 2.68 Ga. The Serra Sul Formation has a well-constrained maximum
 119 depositional age of 2684 ± 10 Ma, locally derived Archean zircon populations and sedimentary
 120 evidence of recurrent slope instability in an extensional basin (Rossignol et al., 2020). An age of
 121 2681 ± 5 Ma was obtained from a sandstone whose abundant zircon was interpreted as derived
 122 from syndepositional volcanism (Trendall et al., 1998).

123 These units form the Meso-Neoarchean basement for the younger Buritirama Formation, which is
 124 the key sedimentary marker along the northern Carajás margin. Its type section is arranged in four
 125 imbricated thrust slices and comprises three main units. A lower unit contains ca. 200 m of
 126 quartzite and mica-quartzite followed by carbonate-silicate rocks and marble. An intermediate unit
 127 hosts manganese ore developed from kutnohorite-rich marble. An upper unit begins with quartzite
 128 and mica-quartz schist and passes upward again into carbonate-silicate rocks (Salgado et al.,
 129 2019a).

130 The local basement includes the 2549 ± 5.9 Ma Buritirama metagranite, a ferroan, metaluminous,
 131 within-plate A2-type intrusion (Salgado et al., 2019a, 2019b). In the lower-unit, detrital
 132 populations at ca. 2714, 2535 and 2908 Ma comprise the spectrum. In upper-unit, dominant
 133 populations are represented at ca. 2680, 2522 and 2841 Ma (Salgado et al., 2019b). Carbonate
 134 geochemistry constrains the marine setting. Dolomitic marbles have negative Ce anomalies,
 135 seawater-like REE+Y patterns and Y/Ho ratios above 48. Their $\delta^{13}\text{C}$ values range from +3.18 to
 136 +4.96‰ V-PDB and were interpreted as a local record of the Lomagundi-Jatuli carbon-isotope
 137 excursion (Salgado et al., 2021). Manganese-bearing carbonates have positive Eu anomalies, a
 138 positive Eu-Mn relationship and $\delta^{13}\text{C}$ values from -2.56 to +0.15‰ V-PDB. These data support a
 139 multistage origin involving a hydrothermal marine Mn source, redox-controlled deposition,
 140 microbially mediated reduction and diagenetic formation of kutnohorite and Mn-calcite (Salgado
 141 et al., 2021). The succession therefore records an established marine carbonate platform before the
 142 manganese maximum.

143 The Bacajá Domain consists of granulites, migmatitic orthogneisses, granitoids, mafic rocks and
 144 metasedimentary successions. Its older framework includes Archean and Siderian components,
 145 while Rhyacian magmatism and metamorphism generated and reworked a large part of the exposed
 146 high-grade crust (Vasquez, 2006; Vasquez et al., 2008; Macambira et al., 2009; Barros et al., 2023;
 147 Magalhães et al., 2023; Neri et al., 2025, 2026). Pre-collisional magmatism is recorded from 2215
 148 ± 2 to 2133 ± 10 Ma, followed by syn- to late-collisional and post-collisional suites (Vasquez and
 149 Rosa-Costa, 2008). Genuine Siderian juvenile greenstone and felsic volcanic rocks occur in parts
 150 of Bacajá between ca. 2.45 and 2.36 Ga. Their existence requires spatial discrimination when
 151 young detrital-zircon tails are evaluated.

152 The Cajazeiras Complex represents older basement in southern Bacajá. Tonalitic to monzogranitic
 153 orthogneisses crystallized mainly at ca. 2.97-2.94 Ga and were reworked during the
 154 Paleoproterozoic. The Novolândia Granulite Belt provides a complementary high-grade record. A
 155 felsic protolith crystallized at 2744 ± 21 Ma and preserves inheritance as old as ca. 3.46 Ga.
 156 Paraderived aluminous granulites contain detrital spectra dominated by Archean populations and
 157 mainly negative ϵNd values, while a mafic protolith crystallized at 2082 ± 7 Ma. Metamorphic
 158 zircon grew during several episodes between ca. 2.16 and 2.05 Ga, followed by monazite at ca.
 159 2.052-2.044 Ga (Neri et al., 2026). Mapping and geochronology by Neri et al. (2025, 2026)
 160 establish these older sedimentary and igneous assemblages as the local basement reworked and
 161 intruded by Rhyacian orogenic magmatism. The link is therefore a published field-
 162 geochronological relation, not an inference derived only from similar age spectra. The Archean-
 163 dominated populations additionally permit a regional age-provenance correlation with crustal
 164 components represented in Carajás.

165 Rhyacian plutons emplaced into this basement include the Bandeirante Granite at ca. 2.12 Ga, the
 166 Alto Rio Preto Granite between ca. 2.10 and 2.06 Ga, the Maravilha Charnockite at ca. 2.09 Ga, the
 167 Serra Azul Charnockite at ca. 2.06 Ga and the Bernardino Granite at ca. 2.05 Ga (Neri et al., 2025).
 168 These bodies record crustal thickening, melting and late thermal reorganization at upper- to
 169 middle-crustal levels.

170 In the study area, Buritirama occupies the lower structural level beneath the Vila Santa Fé-Rio
 171 Preto association (Tavares and Silva, 2015; Tavares et al., 2018). The high-grade association
 172 contains tonalitic to granitic migmatitic orthogneisses, primitive and enriched mafic granulites,
 173 mafic autoliths and charnockitic to enderbitic bodies. It is correlated regionally with the Bacajá
 174 high-grade belt. Magnetic lineaments continue from Vila Santa Fé toward Bacajá, and a gravity
 175 high follows the granulitic rocks along the boundary (Fig. 1b; Motta et al., 2019; Oliveira et al.,
 176 2020; Serafim et al., 2023).

177 Regional structure records NE-SW shortening, top-to-SW transport and four principal
 178 imbrications involving Carajás basement, Buritirama and the high-grade hanging wall (Tavares et
 179 al., 2018). Fabric-constrained $40\text{Ar}/39\text{Ar}$ data separate an older ca. 2.20-2.15 Ga fluid-assisted
 180 thermal episode from the younger penetrative Transamazonian fabric and cooling interval at ca.
 181 2.08-2.04 Ga (Tavares et al., 2026). The new samples were selected to resolve the composition, age
 182 and pressure-temperature level of the hanging-wall root within this regional architecture.

183 3. Samples and analytical methods

184 Sample distribution and analytical coverage are shown in Fig. 2 and summarized in Table 1.

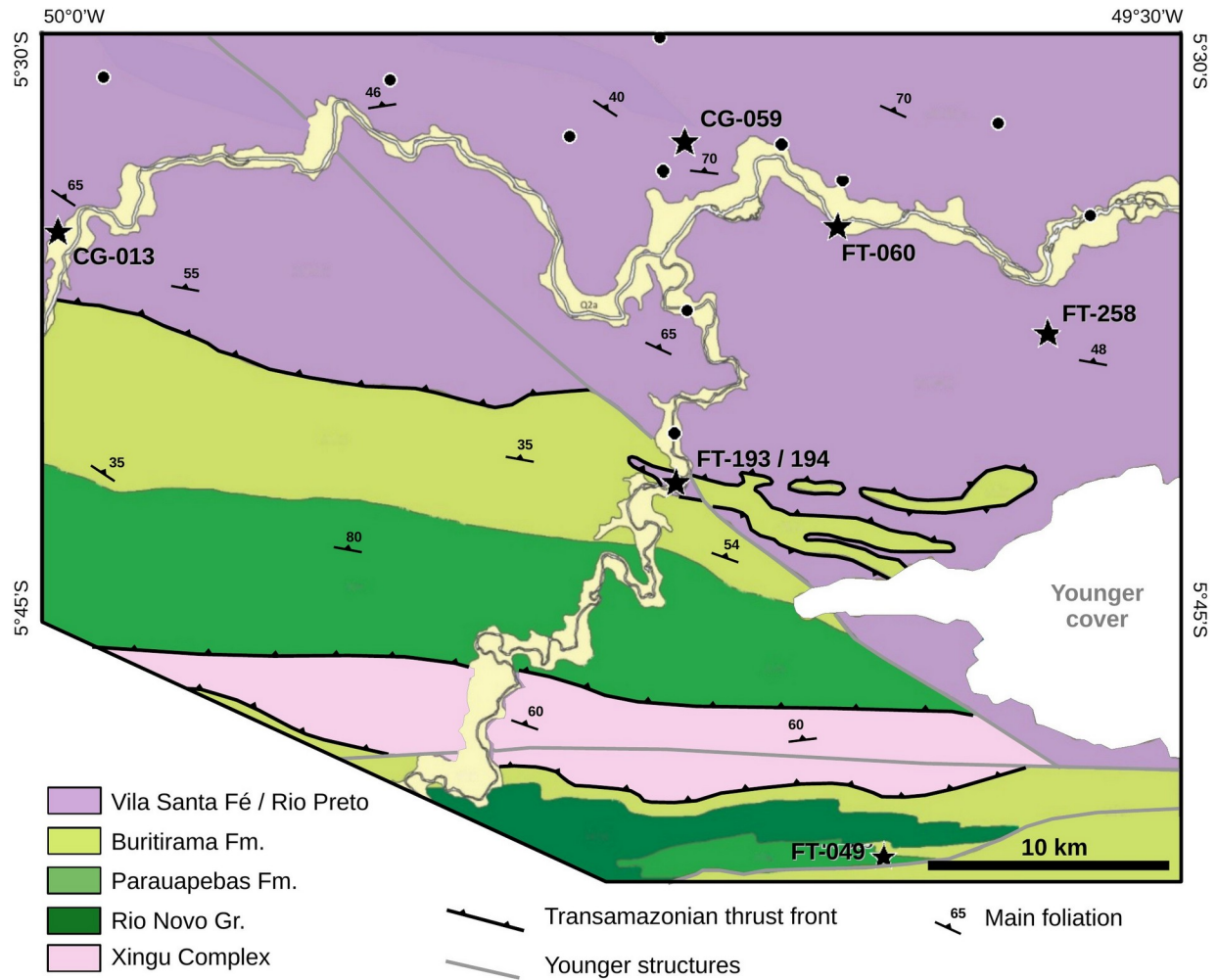


Figure 2: Geological map of the study area and location of the investigated samples. Simplified geological map of the Vila Santa Fé-Rio Preto area, showing the location of samples analysed in this study. Black circles indicate samples analysed for whole-rock lithogeochemistry. Black stars indicate samples with additional U-Pb zircon geochronology, Sm-Nd isotopic data and/or mineral chemistry and thermobarometric constraints. Map modified from Tavares et al. (2018).

Table 1. Samples and analytical coverage

Sample	Coordinates	Lithology	Whole-rock geochemistry	Sm-Nd	U-Pb zircon	EPMA / thermobarometry
FT-049	5°51.699'S, 49°37.816'W	Amphibolite (Parauapebas Fm.)				✓
FT-177A	5°47.036'S, 49°47.514'W	Mafic granulite (Rio Preto)	✓			
FT-193 / 194	5°41.683'S, 49°43.192'W	Mafic granulite (Rio Preto)	✓	✓	✓	✓
CG-009	5°47.445'S, 49°58.582'W	Mafic granulite (Rio Preto)	✓			
CG-030B	5°33.638'S, 49°43.623'W	Mafic granulite (Rio Preto)	✓			
FT-063B	5°40.528'S, 49°43.324'W	Mafic granulite (Vila Santa Fé)	✓			
FT-258	5°37.916'S, 49°33.491'W	Mafic granulite (Vila Santa Fé)				✓
CG-013B	5°35.246'S, 49°59.561'W	Mafic granulite (Vila Santa Fé)	✓			
CG-013C	5°35.246'S, 49°59.561'W	Mafic granulite (Vila Santa Fé)	✓			
CG-059B	5°32.884'S, 49°43.057'W	Mafic granulite (Vila Santa Fé)	✓		✓	
CG-060B	5°34.770'S, 49°32.346'W	Mafic granulite (Vila Santa Fé)	✓			
FT-060B	5°35.108'S, 49°39.033'W	Felsic to intermediate orthogneiss (Vila Santa Fé)	✓	✓	✓	
CG-013A	5°35.246'S, 49°59.561'W	Felsic to intermediate orthogneiss (Vila Santa Fé)	✓	✓	✓	
FT-206	5°37.278'S, 49°42.995'W	Felsic to intermediate orthogneiss (Vila Santa Fé)	✓			
FT-258D	5°37.916'S, 49°33.491'W	Felsic to intermediate orthogneiss (Vila Santa Fé)	✓			
CG-107		Felsic to intermediate orthogneiss (Vila Santa Fé)	✓			
CG-030A	5°33.638'S, 49°43.623'W	Felsic to intermediate orthogneiss (Vila Santa Fé)	✓			
CG-059A	5°32.884'S, 49°43.057'W	Felsic to intermediate orthogneiss (Vila Santa Fé)	✓			
CG-060A	5°34.770'S, 49°32.346'W	Felsic to intermediate orthogneiss (Vila Santa Fé)	✓			
CG-030C	5°33.638'S, 49°43.623'W	Charnockitic to enderbitic rock	✓			
CG-038A	5°32.938'S, 49°40.503'W	Charnockitic to enderbitic rock	✓			
CG-039	5°30.080'S, 49°43.733'W	Charnockitic to enderbitic rock	✓			
CG-045A	5°31.180'S, 49°50.854'W	Charnockitic to enderbitic rock	✓			
CG-047A	5°32.684'S, 49°46.105'W	Charnockitic to enderbitic rock	✓			
CG-050	5°31.111'S, 49°58.420'W	Charnockitic to enderbitic rock	✓			
CG-062A	5°32.338'S, 49°34.792'W	Charnockitic to enderbitic rock	✓			
CG-065A	5°33.867'S, 49°38.888'W	Charnockitic to enderbitic rock	✓			

185 3.1 Whole-rock lithogeochemistry

186 Whole-rock lithogeochemical analyses were produced by CPRM/SGB between 2009 and 2010 at
187 SGS Geosol Laboratórios Ltda., Vespasiano, Minas Gerais, Brazil. Representative samples were
188 selected from fresh outcrops of mafic granulites, granulitic orthogneisses and charnockitic to
189 enderbitic rocks. Weathered surfaces, late veins, strongly altered domains and obvious
190 heterogeneous migmatitic segregations were avoided whenever possible. Samples were crushed,
191 split and pulverized to obtain homogeneous whole-rock powders.

192 Major oxides and selected trace elements were determined by the SGS Geosol ICP95A routine,
193 based on lithium metaborate fusion followed by ICP analysis. Additional trace elements were
194 obtained by the IMS95A routine, using lithium metaborate fusion followed by ICP-MS
195 determination. Rare-earth elements were determined mainly by the IMS95R routine, also based on
196 lithium metaborate fusion and ICP-MS analysis. Selected base metals and alteration-sensitive trace
197 elements were determined by the ICM14B routine, which uses aqua-regia digestion followed by
198 ICP-OES and ICP-MS determination. Loss on ignition was determined as part of the whole-rock
199 analytical package. Analytical quality was monitored by the laboratory through certified reference
200 materials, blanks and duplicate analyses.

201 Lithium metaborate fusion data are used as the main basis for petrogenetic interpretation because
202 this procedure provides near-total digestion of silicate rocks and improves the recovery of elements
203 hosted in refractory accessory phases. Data obtained by ICM14B are treated separately because
204 aqua-regia digestion may be incomplete for silicate minerals and refractory accessory phases.
205 These results are used mainly for descriptive purposes, alteration screening and comparison with
206 the fusion dataset.

207 The geochemical dataset was screened before interpretation. Analytical totals, loss on ignition,
 208 anomalous values and possible transcription errors were checked. Total iron is reported as
 209 Fe₂O₃T. For diagrams requiring total iron as FeO*, Fe₂O₃T was converted consistently and is
 210 indicated as FeOt or FeO* in the corresponding plots. Major-element classification diagrams were
 211 prepared using volatile-free recalculated compositions when required by the diagram. Trace-
 212 element and rare-earth-element diagrams use measured concentrations.

213 Because the studied rocks are granulite-facies, locally migmatitic and partly retrogressed, the
 214 interpretation emphasizes elements and ratios that are relatively resistant to high-grade
 215 metamorphism, melt segregation and fluid-assisted alteration. Major elements are used for
 216 classification and first-order comparison. Petrogenetic interpretation relies mainly on REE
 217 patterns, high-field-strength elements and selected trace-element ratios, including Zr, Hf, Nb, Ta,
 218 Y, Ti, Th, La/Yb, Gd/Yb, Sr/Y, Nb/Yb and Th/Yb. Chondrite- and primitive-mantle-normalized
 219 diagrams were prepared using the normalization values of Sun and McDonough (1989).

220 **3.2 Sm-Nd isotopes**

221 Whole-rock Sm-Nd isotopic analyses were carried out at the Geochronology Laboratory of the
 222 Universidade de Brasília, following the procedures described by Gioia and Pimentel (2000). An
 223 aliquot of whole-rock powder was mixed with a ¹⁴⁹Sm-¹⁵⁰Nd spike solution and dissolved in
 224 Savillex capsules. Sm and Nd were separated by conventional cation-exchange chromatography in
 225 Teflon columns containing LN-Spec resin. The purified Sm and Nd fractions were loaded on Re
 226 evaporation filaments in double-filament assemblies and measured on a multi-collector Finnigan
 227 MAT 262 mass spectrometer in static mode. The ¹⁴³Nd/¹⁴⁴Nd ratios were normalized to
 228 ¹⁴⁶Nd/¹⁴⁴Nd = 0.7219, and the ¹⁴⁷Sm decay constant of $6.54 \times 10^{-12} \text{ yr}^{-1}$ was used.
 229 Depleted-mantle model ages were calculated following DePaolo (1981), where applicable.

230 The interpreted dataset comprises one Rio Preto-type mafic granulite and two Vila Santa Fé felsic
231 orthogneisses. Initial ϵNd values were calculated at reference ages appropriate to each group: 2.15
232 Ga for the Rio Preto-type mafic granulite, consistent with the earliest regional high-grade
233 metamorphic ages in southern Bacajá (Neri et al., 2026), and ca. 2.10 Ga for the Vila Santa Fé
234 orthogneisses. Because the Rio Preto-type sample has a high $^{147}\text{Sm}/^{144}\text{Nd}$ ratio, no depleted-
235 mantle model age is reported for this sample; its $\epsilon\text{Nd}(t)$ value is used only as a relative source
236 indicator. The dataset is interpreted conservatively, distinguishing a comparatively juvenile mafic
237 Rio Preto pole from a Vila Santa Fé felsic component with older crustal residence.

238 **3.3 U-Pb zircon geochronology**

239 Zircon U-Pb analyses were carried out on selected mafic granulites and granulitic orthogneisses.
240 Zircon grains were separated from crushed rock samples using conventional mineral-separation
241 procedures. The samples were crushed and milled, and the heavy-mineral fraction was
242 concentrated by density and magnetic separation. Zircon grains were hand-picked under a
243 binocular microscope, mounted in epoxy resin, polished to expose grain interiors and imaged by
244 cathodoluminescence or back-scattered electrons according to sample availability. Where internal
245 images were available, oscillatory zoning, homogeneous domains, inherited cores, rims and
246 recrystallized domains were used to guide spot selection and interpretation. Where imaging
247 constraints were limited, preferred age populations were based primarily on isotopic coherence,
248 concordance, spot position and geological context.

249 Samples CG-059B, FT-193 and FT-060B were analyzed by LA-MC-ICP-MS at the Isotope
250 Geology Laboratory of the Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil.
251 Analyses were performed using a multi-collector ICP-MS coupled to a New Wave UP213 laser-
252 ablation system. Instrumental drift and U-Pb fractionation were monitored by repeated analyses of

253 the zircon reference material GJ-1, and analytical accuracy was checked against secondary zircon
254 standards. The acquisition sequence followed standard sample-standard bracketing procedures,
255 and data reduction included corrections for background, common Pb, instrumental drift and laser-
256 induced fractionation, following the procedures described by Chemale Jr. et al. (2012). The FT-
257 193, CG-059B and FT-060B grain mounts are no longer archived and could not be re-imaged;
258 back-scattered electron images are therefore available for representative grains only
259 (Supplementary Material 4).

260 Sample CG-013A was analyzed by SHRIMP at the Research School of Earth Sciences, Australian
261 National University, Canberra, Australia. Zircon domains were selected on the basis of internal
262 structure and spot position. The sample retains a complete cathodoluminescence mount in which
263 every analysed spot is imaged and located (Supplementary Material 4). U, Th and Pb isotopes were
264 measured by secondary-ion mass spectrometry using standard SHRIMP analytical procedures. U
265 and Th concentrations and Pb/U calibration were monitored using zircon reference materials, and
266 data were reduced using SQUID and plotted with Isoplot, following the procedures of Williams
267 (1998) and Ludwig (2003).

268 The analytical data include isotopic ratios, apparent ages, discordance, common-Pb information
269 and Th/U ratios. Concordia ages, upper-intercept ages and selected weighted means were
270 calculated from coherent analytical populations, taking into account discordance, internal zircon
271 structure, spot position and geological context. Analyses excluded from preferred age calculations
272 are retained in the analytical dataset. Reported uncertainties follow the convention adopted for
273 each analytical dataset. For Paleoproterozoic and Archean zircons, $^{207}\text{Pb}/^{206}\text{Pb}$ ages are
274 emphasized where appropriate.

275 The U-Pb results were interpreted using isotopic coherence and zircon-domain context. Zircon
276 populations with homogeneous internal structures, concordant to near-concordant ages and
277 coherent $^{207}\text{Pb}/^{206}\text{Pb}$ results were evaluated as possible high-grade growth or recrystallization
278 domains. Core and rim populations were treated separately where images and spot positions allow
279 such distinction. Archean and older Paleoproterozoic grains were considered inherited or
280 antecrystic components unless supported by additional evidence for crystallization of the host rock.
281 Th/U ratios were used as an auxiliary criterion. High Th/U values in some homogeneous Rhyacian
282 zircon populations and rims are interpreted cautiously because granulite-facies and melt-present
283 systems may produce zircon with igneous-like Th/U ratios. The distinction between protolith
284 crystallization, granulite-facies metamorphism, migmatization and zircon recrystallization is based
285 on age, internal structure, spot position, petrographic context and regional consistency.

286 **3.4 Mineral chemistry and thermobarometric calculations**

287 Major-element compositions of metamorphic minerals were obtained by electron-probe
288 microanalysis at the Federal University of Rio de Janeiro using a JEOL JXA-8230 electron
289 microprobe. Analyses were carried out with an accelerating voltage of 15 kV and a beam current of
290 20 nA. Quantitative spot analyses used a circular beam with a diameter of 10 μm .

291 The analyzed mineral compositions were screened for analytical totals, stoichiometry and textural
292 position before thermobarometric calculation. Only analyses from petrographically constrained
293 mineral domains were retained. Mineral formulae were recalculated on standard oxygen bases for
294 each mineral group, and analyses with anomalous totals or unrealistic site occupancies were
295 excluded. Mineral assemblages were calculated separately according to their textural position,
296 distinguishing relic granulite-facies domains from hydrated amphibolite-facies re-equilibration in
297 retrogranulitic rocks and from amphibolite-facies assemblages in the Parauapebas Formation.

Average pressure-temperature calculations were performed with THERMOCALC 3.33 (Powell and Holland, 1988), using the internally consistent thermodynamic database of Holland and Powell (1998). Conventional exchange thermometers and net-transfer barometers were also applied where appropriate. Garnet-clinopyroxene Fe-Mg thermometry followed Ellis and Green (1979). Clinopyroxene-garnet-plagioclase-quartz barometry followed Moecher et al. (1988). Amphibole-plagioclase thermometry followed Holland and Blundy (1994). Garnet-amphibole-plagioclase-quartz barometry followed Kohn and Spear (1990). Two-pyroxene thermometry followed Wood and Banno (1973) and Wells (1977). Ti-in-biotite thermometry followed Henry et al. (2005) and was used only as a semiquantitative temperature check because of its calibration basis.

4. Results

4.1 Field relations and petrography

The Vila Santa Fé-Rio Preto association forms a high-grade, mafic-felsic crustal package exposed along the Carajás-Bacajá boundary. Outcrops are scarce because the unit occurs in low-relief areas covered by thick soils. Fresh exposures occur mainly as isolated slabs, blocks and river-bed outcrops along the Preto, Parauapebas and Itacaiúnas rivers and in smaller streams. Despite the poor exposure, the same lithological association recurs across the mapped belt, showing migmatitic tonalitic to granitic orthogneisses, mafic granulites, charnockitic to enderbitic bodies and local leucocratic segregations (Fig. 2).

The Vila Santa Fé orthogneisses dominate the exposed high-grade package (Fig. 3a-c). They are grey to greenish-grey when fresh and pale yellow to orange when altered. They are tonalitic, granodioritic to granitic in modal composition, commonly homogeneous to weakly banded, and locally nebulitic, metatexitic or diatexitic. The main mineral assemblage is Qtz + Pl + Kfs $\pm$ Bt $\pm$

320 Hbl $\pm$ Opx $\pm$ Cpx (mineral abbreviations after Whitney and Evans, 2010). Zircon, apatite, allanite,
321 titanite and oxides occur as accessories. Epidote, chlorite, prehnite, actinolite and muscovite occur
322 as retrograde or late phases. Garnet is rare and was observed only in specific structural positions.

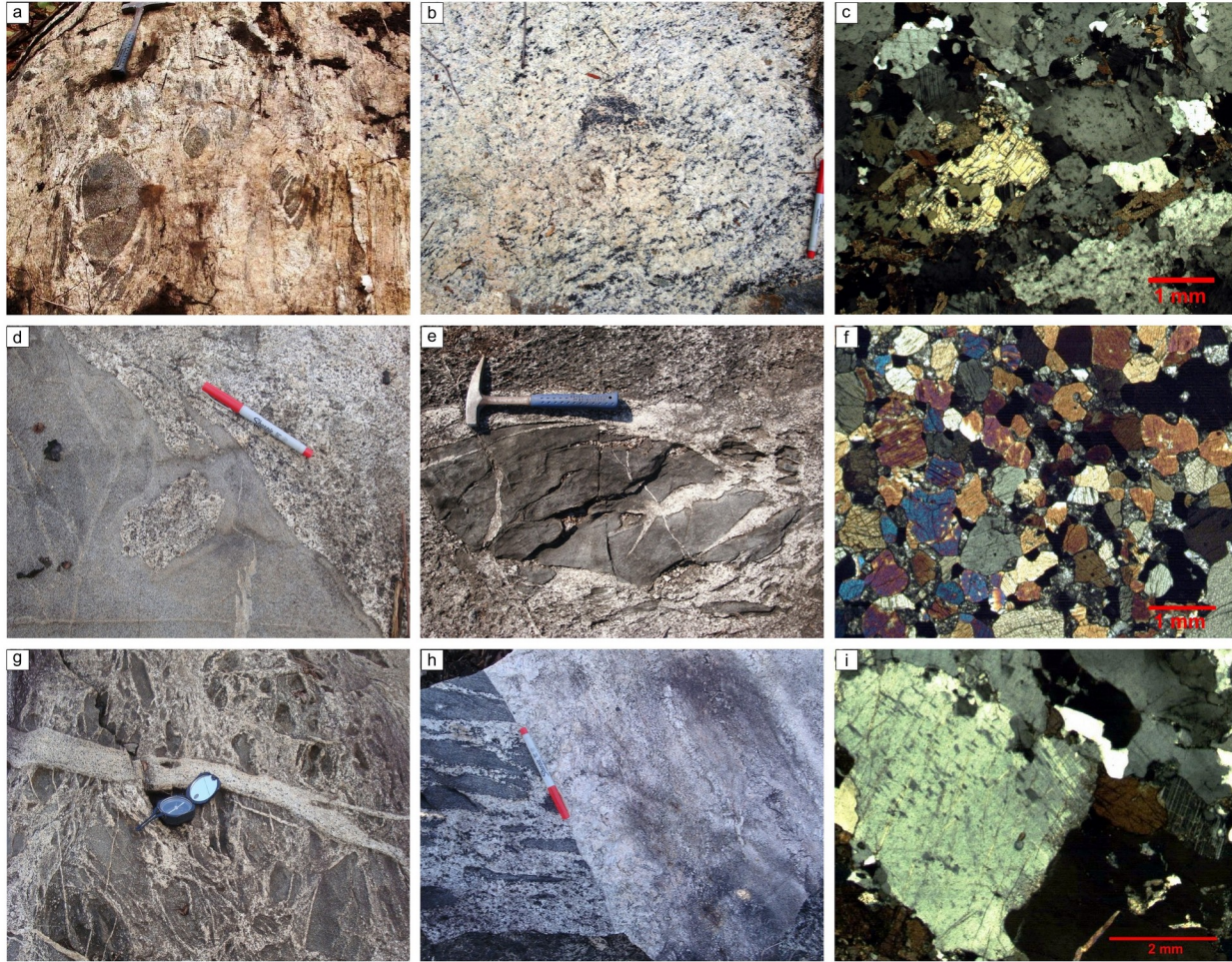


Figure 3: Field and petrographic relationships of the Vila Santa Fé-Rio Preto high-grade association. (a) Field aspect of the Vila Santa Fé orthogneiss, showing mafic autoliths/enclaves and migmatitic textures, including anatectic veins interacting with the mafic domains [station: FT-206]. (b) Felsic portion of the Vila Santa Fé Complex orthogneiss, showing its leucocratic and foliated character and a mafic autolith/enclave [station: FT-060]. (c) Photomicrograph of the same orthogneiss, showing an oriented enstatite/orthopyroxene crystal within a foliation defined by aligned quartz and feldspar [sample: FT-060B]. (d) Contact between mafic and felsic portions of the Vila Santa Fé association, showing evidences of magma mixing during crystallization (station: CG-059). (e) Xenolith of Rio Preto Mafic granulite in Vila Santa Fé orthogneiss, with anatectic pockets and injections, in part related to in situ partial melting [station: CG-030]. (f) Photomicrograph of Rio Preto mafic granulite showing granoblastic texture and a stable high-temperature assemblage of plagioclase, clinopyroxene, orthopyroxene and Ti-rich amphibole [sample: FT-193]. (g) Vila Santa Fé Mafic-felsic association, crosscut by charnockitic injections (station: CG-059). (h) Vila Santa Fé-Rio Preto association crosscut by large charnockitic body [station: CG-030]. (i) Photomicrograph of enderbite showing plagioclase phenocrysts/porphyrocrysts with antiperthitic texture [sample: CG-050].

323 The dominant texture in the orthogneisses is granoblastic to polygonal. Quartz, feldspar and locally
 324 mafic minerals define the main foliation (Fig. 3b, c). Quartz and feldspar commonly occur as
 325 ribbons or elongated aggregates. In weakly deformed domains, the rocks preserve massive to
 326 weakly foliated igneous-looking textures, but the polygonal fabric indicates high-temperature
 327 recrystallization. In more deformed domains, the same rocks become strongly foliated to mylonitic
 328 and contain a stretching lineation. Orthopyroxene and clinopyroxene, where preserved, are partly
 329 replaced by green hornblende, actinolite, biotite and chlorite. Symplectitic textures around
 330 pyroxenes are common. These relations record granulite-facies recrystallization followed by
 331 hydration during amphibolite-facies re-equilibration.

332 Migmatitic textures are widespread in the orthogneisses (Fig. 3a, d, e). Leucocratic quartz-feldspar
 333 domains occur as lenses, patches, veins and diffuse segregations. Mafic minerals concentrate along
 334 the borders of leucocratic domains and form melanocratic selvages or schlieren. Some feldspar
 335 crystals are subidiomorphic and appear to have grown in melt-present domains.

336 Mafic rocks occur as enclaves, autoliths, discontinuous bodies and local slabs (Fig. 3a, b, d, e).
 337 They are medium- to coarse-grained and range from massive to strongly foliated. Some bodies are
 338 enclosed in the Vila Santa Fé orthogneisses, whereas others form local mafic-dominated outcrops.
 339 Their contacts with the felsic host may be sharp, diffuse or transposed into the main foliation. The
 340 field relations indicate mechanical association between mafic and felsic rocks during high-
 341 temperature deformation.

342 The mafic granulites have assemblages dominated by Pl + Opx + Cpx + brown to green Hbl $\pm$ Qtz
 343 $\pm$ Grt $\pm$ Bt $\pm$ Ttn $\pm$ Ilm $\pm$ Fe oxides (Fig. 3e, f). Apatite, allanite and zircon occur as traces.
 344 Plagioclase is abundant and locally recrystallized. Brown hornblende is associated with high-

345 temperature assemblages, whereas green hornblende, actinolite, chlorite and epidote mark
346 hydration and retrogression. Orthopyroxene and clinopyroxene commonly show symplectitic or
347 replacement textures. In retrogranulitic samples, green hornblende and plagioclase form corona-
348 like domains around earlier phases, defining a late hydrated overprint on an earlier granulite-facies
349 assemblage.

350 Leucocratic veins and patches also occur in the mafic rocks (Fig. 3d, e). They consist mainly of Qtz
351 + Pl $\pm$ Kfs and occur as discontinuous veins, pressure-shadow-like domains and irregular patches.
352 These leucocratic domains are locally parallel to the main foliation and locally crosscut earlier
353 mafic layering. They record melt segregation or melt infiltration during the high-temperature
354 evolution of the mafic granulites.

355 Charnockitic to enderbitic rocks occur as coarse to very coarse-grained bodies within the high-
356 grade association (Fig. 3g-i). Some bodies are mappable at the local scale, whereas smaller bodies
357 occur throughout the unit, mainly north of the Itacaiúnas River. Their contacts with the Vila Santa
358 Fé host are commonly diffuse. The rocks are greenish-grey to pale grey when fresh and consist
359 mainly of Qtz + Pl + Kfs $\pm$ Opx $\pm$ Cpx $\pm$ brown Hbl $\pm$ Bt. Zircon, apatite and monazite occur as
360 accessory phases.

361 The charnockitic to enderbitic rocks are commonly massive to weakly foliated. Some samples
362 preserve coarse igneous-looking textures, whereas others show polygonal recrystallization or
363 stretching parallel to the main fabric. Orthopyroxene is partly replaced by amphibole and biotite,
364 and quartz-feldspar domains may occur as coarse patches or veins. These relations link the
365 charnockitic to enderbitic rocks to melt-present high-temperature conditions within the same high-
366 grade package.

367 **4.2 Whole-rock lithogeochemistry**

368 Whole-rock lithogeochemical results are summarized in Fig. 4 and Supplementary Material 1;
369 sample locations and analytical coverage are shown in Fig. 2 and Table 1.

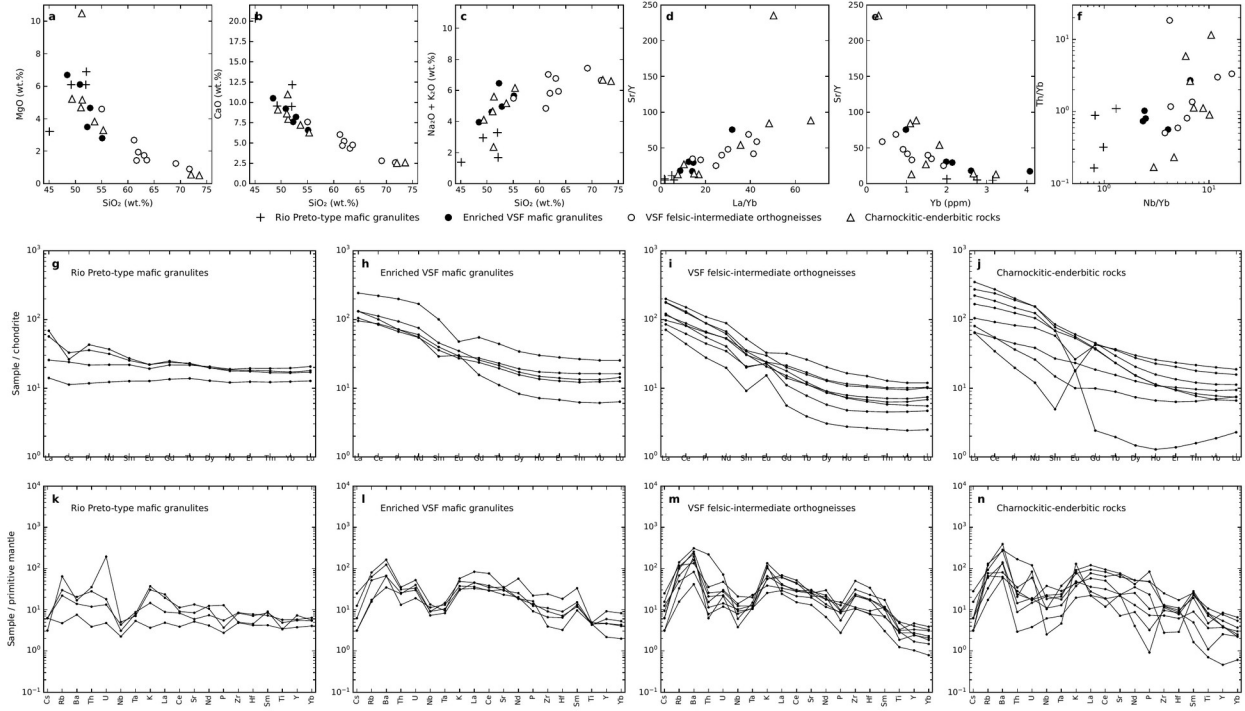


Figure 4: Whole-rock lithogeochemical features of the Vila Santa Fé-Rio Preto high-grade rocks. (a-c) Major-element variation diagrams showing MgO, CaO and Na₂O + K₂O versus SiO₂. (d-f) Trace-element discrimination diagrams, including Sr/Y versus La/Yb, Sr/Y versus Yb, and Th/Yb versus Nb/Yb. (g-j) Chondrite-normalized rare earth element patterns. (k-n) Primitive mantle-normalized multi-element patterns. Samples are grouped into Rio Preto-type mafic granulites, enriched Vila Santa Fé mafic granulites, Vila Santa Fé felsic-intermediate orthogneisses, and charnockitic-enderbitic rocks. Normalization values after Sun and McDonough (1989).

370 **4.2.1 Rio Preto-type mafic granulites**

371 The Rio Preto-type mafic group is represented by FT-193, CG-009 and two samples of CG-030B
 372 (Table 1; Fig. 4a-c). These samples have SiO₂ between 45.10 and 52.12 wt.%, MgO between 3.20
 373 and 6.89 wt.%, CaO between 9.58 and 20.36 wt.%, low Na₂O between 0.45 and 2.52 wt.% and low
 374 K₂O between 0.11 and 0.92 wt.%. They have low incompatible-element contents, with Nb
 375 between 1.6 and 3.6 ppm, Zr between 54 and 95 ppm, Sr between 109 and 178 ppm and Y between
 376 17.1 and 33.2 ppm.

377 The REE patterns are flat to weakly LREE-enriched (Fig. 4g). La/Yb ratios range from 1.7 to 5.9.
 378 Sr/Y ratios are low, between 4.7 and 6.4. These values separate the Rio Preto-type samples from
 379 both the enriched Vila Santa Fé mafic granulites and the felsic to intermediate orthogneisses (Fig.
 380 4d-f). On multi-element diagrams, the Rio Preto-type samples have low absolute abundances and
 381 subdued enrichment in incompatible elements (Fig. 4k). Negative Nb-Ta anomalies are present but
 382 less coupled to strong LREE enrichment than in the enriched Vila Santa Fé rocks.

383 **4.2.2 Enriched Vila Santa Fé mafic granulites**

384 The enriched Vila Santa Fé mafic group is represented by CG-013B, CG-013C, CG-059B, CG-
 385 060B and FT-063B (Table 1; Fig. 4a-c). These samples have SiO₂ between 48.46 and 55.12 wt.%,
 386 MgO between 2.80 and 6.69 wt.%, CaO between 6.58 and 10.52 wt.%, Na₂O between 3.00 and
 387 4.73 wt.% and K₂O between 0.90 and 1.73 wt.%. They have higher Sr contents than the Rio Preto-
 388 type group, between 489 and 748 ppm, and higher Nb and Zr values, with Nb between 5.2 and 9.6
 389 ppm and Zr between 44 and 270 ppm.

390 The enriched mafic granulites have fractionated REE patterns (Fig. 4h). La/Yb ranges from 8.7 to
 391 31.8. Sr/Y ranges from 17.2 to 75.6. The highest Sr/Y value occurs in FT-063B. Multi-element

392 diagrams show LILE and LREE enrichment coupled with Nb-Ta depletion (Fig. 4l). This pattern
 393 identifies an enriched, subduction-modified or arc-modified geochemical component within the
 394 mafic dataset.

395 The enriched Vila Santa Fé mafic granulites differ from the Rio Preto-type group by their higher
 396 incompatible-element contents, stronger LREE fractionation and higher Sr/Y (Fig. 4d-f). Their
 397 petrographic similarity to the Rio Preto-type rocks reflects high-grade recrystallization, but their
 398 geochemical signature indicates a different source composition or a different level of enrichment.

399 **4.2.3 Vila Santa Fé felsic to intermediate orthogneisses**

400 The Vila Santa Fé felsic to intermediate group is represented by CG-013A, CG-030A, CG-059A,
 401 CG-060A, CG-107, FT-060B, FT-206 and FT-258D (Table 1; Fig. 4a-c). These rocks have SiO₂
 402 between 55.03 and 71.73 wt.%, MgO between 0.90 and 4.59 wt.%, Na₂O between 3.21 and 5.06
 403 wt.% and K₂O between 0.77 and 4.05 wt.%. They are tonalitic, granodioritic to granitic in modal
 404 composition.

405 Trace-element contents vary but define a coherent felsic to intermediate association. Sr ranges
 406 from 276 to 640 ppm, Y from 4.7 to 21.3 ppm, Zr from 117 to 562 ppm and Nb from 2.7 to 15 ppm.
 407 La/Yb ranges from 14.2 to 42.8. Sr/Y ranges from 25.2 to 68.8. These values indicate fractionated
 408 REE patterns, low to moderate HREE contents and high Sr/Y in several samples (Fig. 4d-f, i).

409 On chondrite-normalized REE diagrams, the orthogneisses display strong LREE enrichment and
 410 fractionated HREE patterns (Fig. 4i). Eu anomalies are variable. Multi-element diagrams show
 411 enrichment in LILE and LREE relative to HFSE and clear Nb-Ta-Ti depletion (Fig. 4m). The felsic
 412 to intermediate orthogneisses therefore preserve an arc-modified chemical signature. This

signature is treated as source memory of the high-grade association, not as direct evidence that all dated Rhyacian zircon domains crystallized during active arc magmatism.

4.2.4 Charnockitic to enderbitic rocks

The charnockitic to enderbitic group is represented by CG-030C, CG-038A, CG-039, CG-045A, CG-047A, CG-050, CG-062A and CG-065A (Table 1; Fig. 4a-c). These rocks span a wide compositional range, with SiO₂ between 49.38 and 73.61 wt.%. Two samples, CG-030C and CG-047A, are felsic, with SiO₂ above 72 wt.%. The remaining samples are intermediate to mafic, consistent with enderbitic to mafic charnockitic compositions. MgO ranges from 0.51 to 10.48 wt.%, Na₂O from 1.77 to 4.17 wt.% and K₂O from 0.59 to 3.92 wt.%.

The trace-element dataset also shows wide variation. Sr ranges from 151 to 1609 ppm, Y from 2.1 to 38.5 ppm, Zr from 31 to 280 ppm and Nb from 1.8 to 27 ppm. La/Yb ranges from 7.6 to 66.9. Sr/Y ranges from 12.9 to 235.2 (Fig. 4d-f). The highest Sr/Y occurs in the most felsic sample CG-030C and in the intermediate samples CG-062A and CG-065A. These variations indicate that the charnockitic to enderbitic group includes more than one melt composition or more than one degree of interaction with residual and source phases.

Chondrite-normalized REE patterns are enriched in LREE and commonly fractionated toward the HREE (Fig. 4j). Multi-element diagrams show LILE enrichment and relative Nb-Ta depletion (Fig. 4n). The charnockitic to enderbitic rocks overlap the Vila Santa Fé felsic to intermediate orthogneisses in several trace-element features, but extend toward more mafic and more Sr-rich compositions. Their chemical spread matches their field and petrographic character: they are melt-bearing, coarse-grained bodies within a heterogeneous high-grade association.

434 4.3 Sm-Nd isotopic results

435 The Sm-Nd dataset comprises one Rio Preto-type mafic sample and two Vila Santa Fé
 436 orthogneisses (Table 1; Supplementary Material 2). The Rio Preto-type sample represents the
 437 comparatively primitive mafic group defined by the lithogeochemical classification. The two Vila
 438 Santa Fé orthogneisses represent the felsic to intermediate arc-modified association.

439 The Rio Preto-type mafic granulite FT-193 has Sm = 1.99 ppm, Nd = 6.08 ppm, $^{147}\text{Sm}/^{144}\text{Nd} =$
 440 0.198 and $^{143}\text{Nd}/^{144}\text{Nd} = 0.512712 \pm 0.000012$. Because the crystallization age of the mafic
 441 protolith is not directly constrained in this study, its epsilon-Nd(t) value is used only as a relative
 442 source indicator. The value calculated at 2.15 Ga is +1.06. Depleted-mantle model ages are not
 443 used for this sample because the high $^{147}\text{Sm}/^{144}\text{Nd}$ ratio makes TDM poorly constrained.

444 The two Vila Santa Fé orthogneisses have negative epsilon-Nd(t) values when calculated at ca.
 445 2.10 Ga (Fig. 5; Supplementary Material 2). CG-013A has Sm = 6.17 ppm, Nd = 35.98 ppm,
 446 $^{147}\text{Sm}/^{144}\text{Nd} = 0.104$, $^{143}\text{Nd}/^{144}\text{Nd} = 0.511289 \pm 0.000020$, epsilon-Nd(t) = -1.23 and TDM =
 447 2.44 Ga. FT-060B has Sm = 1.39 ppm, Nd = 9.84 ppm, $^{147}\text{Sm}/^{144}\text{Nd} = 0.086$, $^{143}\text{Nd}/^{144}\text{Nd} =$
 448 0.510985 ± 0.000010 , epsilon-Nd(t) = -2.26 and TDM = 2.46 Ga. These values indicate that the
 449 felsic to intermediate association contains a significant older crustal component and is not a purely
 450 juvenile Rhyacian product.

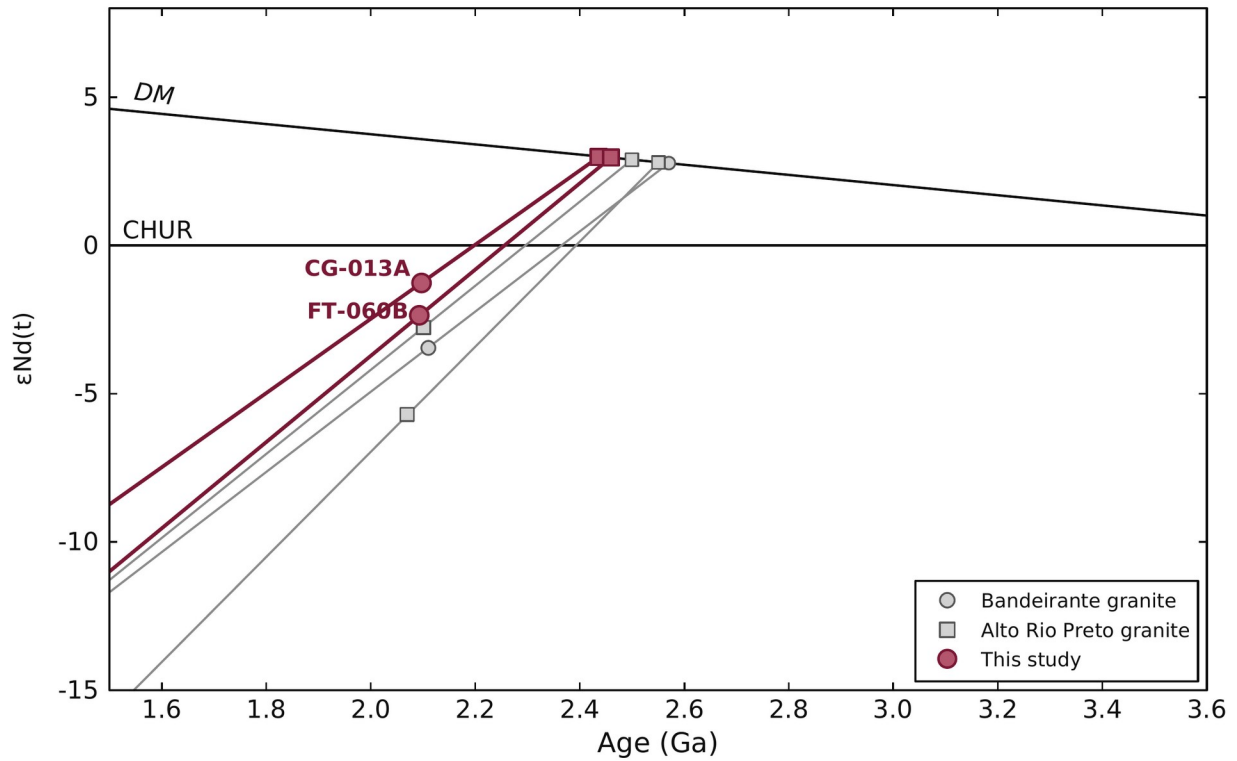


Figure 5: Sm-Nd isotopic evolution diagram for felsic rocks from the Vila Santa Fé-Rio Preto high-grade association. epsilon-Nd(t) versus age diagram comparing samples CG-013A and FT-060B from this study with published Sm-Nd data for the Bandeirante granite and Alto Rio Preto granite from Neri et al. (2025). Grey symbols and evolution lines represent the published dataset, whereas burgundy symbols and lines indicate samples analysed in this study. CHUR and depleted mantle evolution curves are shown for reference. The analysed samples yield negative epsilon-Nd(t) values at ca. 2.10 Ga and depleted-mantle model ages of ca. 2.44-2.46 Ga, indicating significant involvement of older crustal sources during Rhyacian magmatism and/or crustal reworking.

451 **4.4 U-Pb zircon geochronology**

452 The interpreted U–Pb age results are summarized in Table 2, and the complete zircon U–Pb
453 analytical dataset is provided in Supplementary Material 3.

Table 2. Summary of U-Pb zircon geochronological results

Sample	Lithology	Method	Zircon domain / population	n	Th/U range	Preferred age (Ma)	Age type	Geological interpretation
FT-193	Mafic granulite (Rio Preto)	LA-ICP-MS	Concordant to near-concordant population	19	ca. 0.07–0.24	2069 ± 7	Concordia age	Preferred Rhyacian age for melt-present granulite-facies zircon growth/recrystallization
CG-059B	Mafic granulite (Vila Santa Fé)	LA-ICP-MS	Homogeneous zircon population	13	ca. 0.12–0.35	2073 ± 3	Concordia age	Preferred Rhyacian age for melt-present granulite-facies zircon growth/recrystallization
FT-060B	Felsic orthogneiss (Vila Santa Fé)	LA-ICP-MS	Core domains	4	ca. 0.02–0.04	2093 ± 25	Upper-intercept age	Crystallization or melt-related zircon growth
FT-060B	Felsic orthogneiss (Vila Santa Fé)	LA-ICP-MS	Rim domains	5	ca. 0.01–0.07	2082 ± 29	Upper-intercept age; lower intercept 311 ± 45 Ma	High-grade Rhyacian reworking/migmatitic zircon growth
CG-013A	Felsic orthogneiss (Vila Santa Fé)	SHRIMP	Core domains	17	ca. 0.25–1.22	2097 ± 19	Upper-intercept age; lower intercept 504 ± 110 Ma	Crystallization or melt-related zircon growth
CG-013A	Felsic orthogneiss (Vila Santa Fé)	SHRIMP	Rim domains	5	ca. 0.25–1.22	2067 ± 7	Upper-intercept age; lower intercept 291 ± 130 Ma	High-grade Rhyacian reworking/migmatitic zircon growth

454 **4.4.1 Mafic granulites**

455 Two mafic granulite samples are retained in the main U-Pb dataset: CG-059B and FT-193 (Fig. 6a,
456 b, e, f). Both yielded Rhyacian zircon populations with limited internal age dispersion, but their
457 zircon textures and inherited components differ.

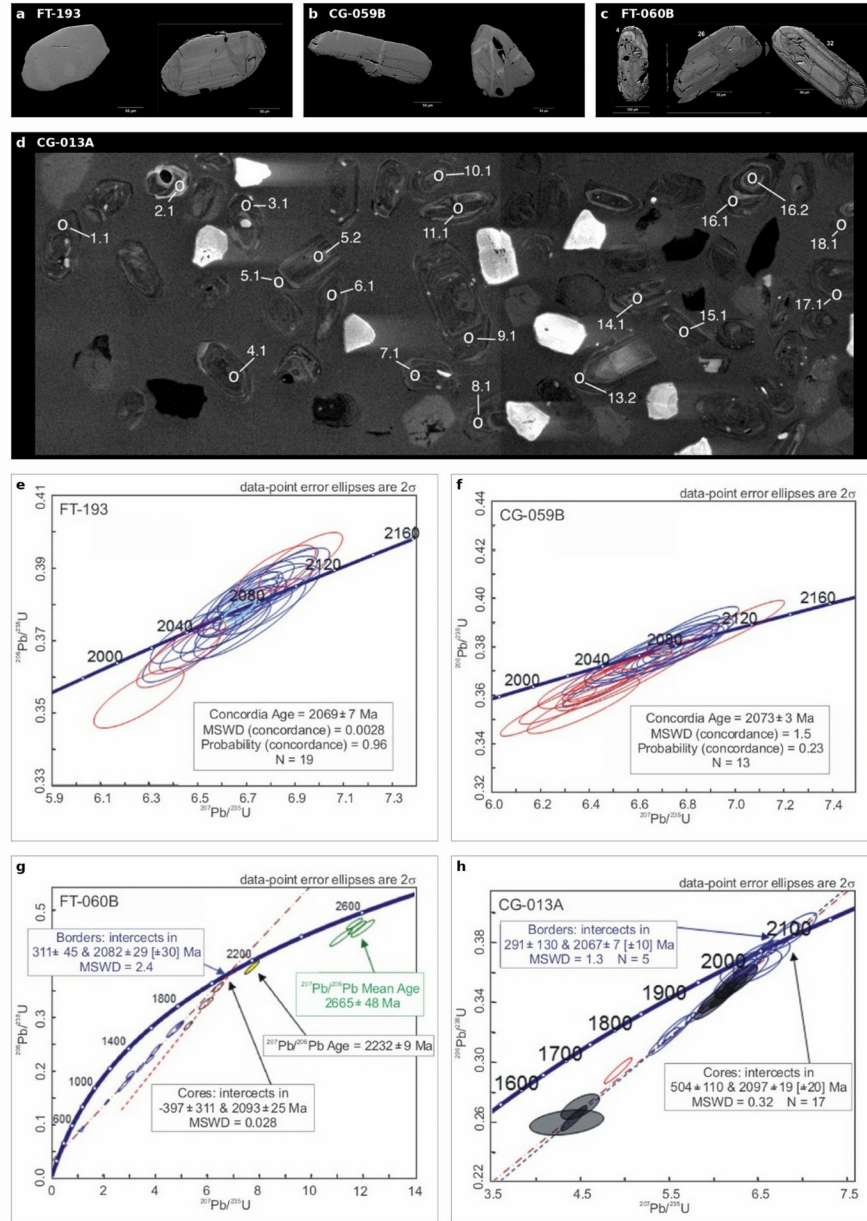


Figure 6: Zircon BSE and CL images and U-Pb geochronological results. (a-c) Back-scattered electron images of representative zircon grains from samples FT-193, CG-059B and FT-060B, respectively. (d) Cathodoluminescence image of the zircon population from sample CG-013A, showing analysed spots and internal domains. (e-f) Concordia diagrams for FT-193 and CG-059B, yielding Rhyacian concordia ages of 2069 ± 7 Ma and 2073 ± 3 Ma, respectively. (g) U-Pb concordia diagram for FT-060B, showing inherited Neoproterozoic zircon components ($^{207}\text{Pb}/^{206}\text{Pb}$ weighted mean of 2665 ± 48 Ma and an isolated core at 2232 ± 9 Ma) and Paleoproterozoic upper-intercept ages obtained from distinct zircon domains. (h) U-Pb concordia diagram for CG-013A, showing core and border populations with Paleoproterozoic upper-intercept ages. Error ellipses are shown at the 2 sigma level.

458 Sample CG-059B is a mafic granulite with zircon grains that are mostly small to medium, prismatic
459 and internally homogeneous (Fig. 6b). No clear inherited cores or oscillatory-zoned domains were
460 identified in the analyzed population. Although homogeneous internal structure is common in
461 metamorphic zircon, Th/U ratios are commonly around 0.3. The analyzed grains yield a coherent
462 Rhyacian population, with $^{207}\text{Pb}/^{206}\text{Pb}$ ages between approximately 2061 and 2088 Ma. The
463 most concordant analyses define a concordia age of 2073 ± 3 Ma (Fig. 6f; Table 2). This age is
464 retained as the preferred age for zircon growth or recrystallization in this mafic granulite.

465 Sample FT-193 is a hornblende mafic granulite collected near the contact between the Vila Santa
466 Fé-Rio Preto high-grade rocks and the Buritirama Formation. Zircon grains are small, rounded to
467 short-prismatic, colorless and mostly internally homogeneous (Fig. 6a). One grain preserves
468 oscillatory zoning and yields an older Neoproterozoic age. The Rhyacian zircon population has Th/U
469 ratios between approximately 0.07 and 0.24, with most values near 0.15. The $^{207}\text{Pb}/^{206}\text{Pb}$ ages
470 are tightly grouped around 2071 Ma. Nineteen concordant to near-concordant spots define a
471 concordia age of 2069 ± 7 Ma (Fig. 6e; Table 2). This age, first reported in preliminary form on the
472 geological map of Tavares and Silva (2015) and formally presented here with full analytical
473 support, is retained as the preferred Rhyacian zircon age for FT-193. The single older grain yields
474 an age near 2598 Ma and is reported separately as an inherited or relic component.

475 The two mafic granulite samples define a narrow age interval between 2073 ± 3 Ma and 2069 ± 7
476 Ma. Their homogeneous zircon populations, high-grade mineral assemblages and low to moderate
477 Th/U values, locally reaching ca. 0.3, are compatible with zircon growth or recrystallization under
478 high-temperature, melt-present conditions.

479 4.4.2 Granulitic orthogneisses

480 Two granulitic orthogneiss samples, FT-060B and CG-013A, provide the main constraints on
 481 zircon domains in the felsic Vila Santa Fé association (Fig. 6c, d, g, h). Both samples contain
 482 complex zircon populations with cores, rims and inherited components, but they differ in Th/U
 483 ratios and internal structure.

484 Sample FT-060B is a granulitic orthogneiss with elongate, rounded zircon grains (Fig. 6c). Back-
 485 scattered electron images show complex internal structures, including rounded cores and
 486 homogeneous rims. Some cores preserve faint oscillatory zoning, whereas others are
 487 homogeneous. The analytical dataset separates into inherited Archean grains, an isolated older
 488 Paleoproterozoic grain, low-Th/U core domains and rim domains.

489 Four Archean core analyses yield $^{207}\text{Pb}/^{206}\text{Pb}$ ages around 2.66 Ga. Their weighted mean age is
 490 2665 ± 48 Ma (Fig. 6g). These grains have relatively high Th/U ratios and are reported as inherited
 491 or relic zircon components. One high-Th/U core gives a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2232 ± 9 Ma (Fig.
 492 6g). This isolated age has no equivalent population in the dataset.

493 The low-Th/U core domains in FT-060B define an upper-intercept age of 2093 ± 25 Ma (Fig. 6g;
 494 Table 2). These domains are homogeneous and have low Th/U ratios. The rim domains also have
 495 low Th/U ratios, show significant Pb loss and define an upper-intercept age of 2082 ± 29 Ma, with
 496 a lower intercept at 311 ± 45 Ma (Fig. 6g; Table 2). The two Paleoproterozoic ages overlap within
 497 uncertainty, but the core-rim distinction indicates two zircon-domain groups within the same
 498 Rhyacian interval. The 2093 ± 25 Ma age is reported as the older Rhyacian zircon domain in FT-
 499 060B, whereas the 2082 ± 29 Ma age, which rests on discordant, Pb-loss-affected analyses from a
 500 sample without spot-located imaging, is the least well-constrained result of the dataset and is used
 501 only as corroboration.

Sample CG-013A is a granulitic orthogneiss with euhedral, medium-sized, bipyramidal zircon grains (Fig. 6d). Cathodoluminescence images show complex internal structures, including cores and rims with oscillatory zoning, thin highly luminescent intermediate overgrowths, locally convolute domains and some homogeneous rims. The analyzed domains have high Th/U ratios, ranging from approximately 0.25 to 1.22. Most analyses are concordant or near-concordant.

Core analyses from CG-013A define an upper-intercept age of 2097 ± 19 Ma, with a lower intercept near 504 ± 110 Ma (Fig. 6h; Table 2). Rim analyses define an upper-intercept age of 2067 ± 7 Ma, with a lower intercept near 291 ± 130 Ma (Fig. 6h; Table 2). The high Th/U ratios, oscillatory to convolute zoning and homogeneous domains are consistent with zircon growth or recrystallization in melt-bearing igneous to migmatitic domains. The 2097 ± 19 Ma age is reported as the older zircon domain in CG-013A, whereas the 2067 ± 7 Ma age is reported as the younger rim or migmatitic domain.

Taken together, FT-060B and CG-013A define two closely spaced Rhyacian zircon age domains in the felsic orthogneisses. The older domain occurs between 2097 ± 19 Ma and 2093 ± 25 Ma. The younger domain occurs between 2082 ± 29 Ma and 2067 ± 7 Ma. The distinction is supported by zircon-domain position and internal structure, although the ages partially overlap within uncertainty. Notably, both FT-060B domains are reproduced by better-imaged or concordant samples: its ca. 2093 Ma core age matches the CG-013A core population (2097 ± 19 Ma), and its ca. 2082 Ma rim age matches the concordant CG-059B and FT-193 ages (2073 ± 3 and 2069 ± 7 Ma) and the CG-013A rim (2067 ± 7 Ma).

4.4.3 Inherited zircon components

Inherited zircon components are present but unevenly distributed among the analyzed samples. FT-060B contains the clearest Archean inheritance, with a group of grains around 2665 ± 48 Ma. These

525 grains have relatively high Th/U ratios and are interpreted as older zircon components incorporated
 526 into the Rhyacian orthogneiss or migmatitic system. FT-193 contains a single older zircon grain
 527 near 2598 Ma, which may represent a relic of the mafic protolith or inherited zircon incorporated
 528 before Rhyacian high-grade recrystallization.

529 CG-059B does not preserve inherited zircon grains in the analyzed population. Its homogeneous
 530 Rhyacian zircon population suggests efficient zircon recrystallization during high-grade
 531 conditions or crystallization of zircon during the Rhyacian event with no older grains preserved.
 532 CG-013A is dominated by Rhyacian core and rim domains with high Th/U ratios and does not
 533 provide a clear Archean inherited population in the analyzed dataset.

534 The inherited components indicate older crustal material in the Vila Santa Fé-Rio Preto system, but
 535 they do not define a single inherited population across all samples. Their distribution is
 536 heterogeneous, consistent with variable interaction between Rhyacian magmas or melts and older
 537 crustal components.

538 **4.5 Thermobarometric constraints**

539 Thermobarometric calculations were performed for three samples: FT-194 and FT-258 from the
 540 Vila Santa Fé-Rio Preto association, and FT-049 from the Parauapebas Formation (Table 3,
 541 Supplementary Materials 5 and 6). In the granulitic association, the retained dataset distinguishes
 542 early granulite-facies assemblages from late hydrated amphibolite-facies re-equilibration in
 543 retrogranulitic rocks. FT-049 is treated separately as a Carajás-side constraint on Transamazonian
 544 amphibolite-facies metamorphism in the Parauapebas Formation.

Table 3. Thermobarometric summary

Sample	Lithology	Assemblage	Method / calibration	Pressure	Temperature	Preferred P–T estimate	Interpretation
FT-194	Mafic granulite (Rio Preto)	Grt + Cpx + Pl + Qz ± Ilm	Grt–Cpx Fe–Mg thermometry; THERMOCALC average P–T; Cpx–Grt–Pl–Qz barometry	THERMOCALC: 9.9 ± 1.3 kbar; Cpx–Grt–Pl–Qz: ca. 8–10 kbar	Grt–Cpx: 760 ± 30 °C; THERMOCALC: 842 ± 93 °C	9–10 kbar 760–800 °C	Intermediate P granulite facies
FT-194	Mafic granulite (Rio Preto)	Hbl + Pl ± Grt ± Cpx ± Qz	Hbl–Pl thermometry; Grt–Hbl–Pl–Qz barometry	7.4 ± 0.7 kbar	690–710 °C	7–8 kbar 690–710 °C	Amphibolite-facies hydration and partial re-equilibration
FT-258	Mafic granulite (Vila Santa Fé)	Opx + Cpx + Bt + Pl + Qz ± Fe–Ti oxides	Two-pyroxene thermometry; Ti-in-biotite thermometry	-	Two-pyroxene: 770 ± 60 °C; Ti-in-biotite: 740–770 °C	750–780 °C	Granulite-facies
FT-049	Amphibolite (Parauapebas Fm.)	Hbl + Pl + Ttn ± Ilm ± Fe oxides	Holland & Blundy Hbl–Pl thermometer B	-	701.7–725.8 °C	700–720 °C	High-T amphibolite facies

545 **4.5.1 FT-194: mafic retrogranulite from the Vila Santa Fé-Rio Preto association**

546 FT-194 is a mafic retrogranulite that preserves relics of an early granulite-facies assemblage
 547 composed of Grt + Cpx + Ti-rich brown Hbl + Pl + Qz $\pm$ Ilm (Table 3). Garnet cores have average
 548 compositions around Alm55Prp14Grs27Sps4. Clinopyroxene cores and least retrogressed
 549 plagioclase domains, with plagioclase around An70, were used with quartz for the peak
 550 calculations.

551 Garnet-clinopyroxene Fe-Mg thermometry gives temperatures of ca. 760 ± 30 °C.
 552 THERMOCALC average pressure-temperature calculation for the Grt + Cpx + Pl + Qz subset of
 553 the early granulite-facies assemblage gave $P = 9.9 \pm 1.3$ kbar and $T = 842 \pm 93$ °C, with sigfit =
 554 0.96. The THERMOCALC result provides the best formal pressure estimate, whereas garnet-
 555 clinopyroxene thermometry gives a more conservative temperature estimate. The preferred early-
 556 stage condition therefore combines the THERMOCALC pressure with the garnet-clinopyroxene
 557 temperature.

558 Clinopyroxene-garnet-plagioclase-quartz barometry after Moecher et al. (1988) gives pressures
 559 around 8-10 kbar, consistent with the THERMOCALC result. The preferred early-stage estimate
 560 for FT-194 is therefore ca. 9-10 kbar and 760-800 °C (Table 3).

561 FT-194 also records a late hydrated amphibolite-facies overprint defined by green hornblende,
 562 plagioclase border domains, garnet rims and quartz. Holland and Blundy (1994) amphibole-
 563 plagioclase thermometry gives temperatures of ca. 690-710 °C. Kohn and Spear (1990) garnet-
 564 amphibole-plagioclase-quartz barometry gives $P = 7.4 \pm 0.7$ kbar. These estimates indicate
 565 decompression and hydration after the granulite-facies stage (Table 3). The plagioclase coronas

566 around garnet and the replacement of clinopyroxene and brown hornblende by green hornblende
567 record this re-equilibration.

568 **4.5.2 FT-258: mafic granulite from the Vila Santa Fé-Rio Preto association**

569 FT-258 is a relatively dry mafic granulite with the assemblage Opx + Cpx + Bt + Pl + Qz ± oxides
570 (Table 3). This assemblage is treated as an early granulite-facies assemblage. Minor
571 cummingtonite and actinolite are interpreted as retrograde products and were not used for peak
572 calculations.

573 Representative orthopyroxene compositions are around En₅₆Fs₄₃Wo₁. Clinopyroxene
574 compositions are around Wo₄₆En₃₆Fs₁₈. Biotite is Ti-rich, with Ti contents of ca. 0.42-0.51 apfu
575 and XMg of ca. 0.60-0.62. Plagioclase is around An₄₀.

576 Two-pyroxene thermometry gives temperatures of ca. 770 °C with the Wells (1977) calibration
577 and ca. 767 °C with the Wood and Banno (1973) calibration. The preferred two-pyroxene estimate
578 is ca. 770 ± 60 °C. Ti-in-biotite thermometry gives ca. 740-770 °C, with a mean value near 750 °C.

579 This agreement supports the interpretation that biotite belongs to the high-temperature assemblage.

580 No formal pressure estimate was obtained for FT-258 because the high-temperature assemblage
581 lacks garnet or another robust pressure-sensitive equilibrium. The sample nevertheless confirms
582 that granulite-facies temperatures of ca. 750-780 °C were reached in garnet-free, relatively dry
583 mafic rocks of the Vila Santa Fé-Rio Preto association (Table 3).

584 **4.5.3 FT-049: amphibolite from the Parauapebas Formation**

585 FT-049 is an amphibolite from the Neoproterozoic Parauapebas Formation on the Carajás side of the
586 boundary (Table 3). The preserved assemblage is Hbl + Pl + Ttn ± Ilm ± Fe oxides, with minor late
587 epidote and sericite after plagioclase. This assemblage is treated as a constraint on amphibolite-

588 facies metamorphism. No U-Pb data were obtained for this sample. Thermobarometric and
 589 $^{40}\text{Ar}/^{39}\text{Ar}$ determinations were made on split blocks of the same collected sample, reported here
 590 as FT-049 and as FT-049C by Tavares et al. (2026).

591 The preferred calculation used core domains of hornblende and plagioclase. The selected
 592 plagioclase core has composition around An₄₆. Hornblende has Si around 6.56 apfu, total Al
 593 around 1.98 apfu, Ti around 0.09 apfu and XMg around 0.63 after standard stoichiometric
 594 recalculation. Anomalous amphibole analyses were excluded.

595 Holland and Blundy (1994) amphibole-plagioclase thermometer B gives temperatures of 701.7 °C
 596 at 4 kbar, 709.7 °C at 5 kbar, 717.8 °C at 6 kbar and 725.8 °C at 7 kbar. For a plausible mid-crustal
 597 amphibolite-facies pressure range, the preferred estimate is ca. 700-720 °C. Thermometer A gives
 598 temperatures around 734 °C between 4 and 7 kbar, but this result is treated only as a secondary
 599 check because quartz was not petrographically confirmed in the analyzed assemblage.

600 No formal pressure estimate was calculated for FT-049. The sample records high-temperature
 601 amphibolite-facies conditions in the Parauapebas Formation (Table 3).

602 **5. Discussion**

603 The Vila Santa Fé-Rio Preto association defines the high-grade hanging wall above the northern
 604 Carajás margin. The discussion first establishes the direct record of lower-crustal composition,
 605 collision and exhumation from the new data. It then integrates the published evidence for rifting,
 606 drift and subduction.

607 **5.1 Lower-crustal components and the memory of the Bacajá arc**

608 The geochemical data distinguish two mafic components, a felsic to intermediate orthogneiss
 609 association and a charnockitic to enderbitic melt-bearing group (Fig. 4). Vila Santa Fé felsic rocks,
 610 enriched mafic granulites and charnockitic to enderbitic rocks share calc-alkaline affinity, LREE
 611 and LILE enrichment, fractionated REE patterns and Nb-Ta-Ti depletion. The coherent signature
 612 across mafic, felsic and melt-rich lithologies records a subduction-modified lower-crustal source.

613 Its tectonic meaning is strengthened by the independent presence of a Rhyacian magmatic arc in
614 Bacajá.

615 Rio Preto-type mafic granulites define the comparatively primitive pole. They have flatter REE
616 patterns, lower incompatible-element contents and tholeiitic affinity. FT-193 yields $\epsilon\text{Nd}(2.15\text{ Ga})$
617 $= +1.06$; its high $^{147}\text{Sm}/^{144}\text{Nd}$ ratio prevents a robust depleted-mantle model age. The ϵNd value
618 remains close to +1 over plausible reference ages and therefore establishes relative juvenility
619 without independently dating the protolith. Regional correlations permit an older juvenile mafic
620 lower crust, a Rhyacian mafic input, or a mixture of both. The robust conclusion is compositional,
621 as a mafic component more juvenile than the Vila Santa Fé felsic crust survived as bodies, slivers
622 and autoliths within the granulitic association.

623 The two Vila Santa Fé felsic orthogneisses yield negative ϵNd values at ca. 2.10 Ga and TDM ages
624 of ca. 2.44-2.46 Ga (Fig. 5). Their Rhyacian zircon ages therefore record melting or crystallization
625 after a substantial interval of crustal residence. Inherited zircon at ca. 2.67 and 2.60 Ga provides
626 direct evidence for Archean input. The lower crust exposed at Vila Santa Fé was heterogeneous
627 before terminal collision and combined comparatively juvenile mafic material, Rhyacian arc-
628 modified components and older crustal substrates.

629 The term Rio Preto-type is lithological in this paper. Regional compilations have also applied Rio
630 Preto to ca. 2.6 Ga rocks, and FT-193 contains a single oscillatory-zoned zircon near 2598 Ma.
631 Nineteen concordant low-Th/U analyses from the same sample yield $2069 \pm 7\text{ Ma}$ and define its
632 high-grade Rhyacian zircon population. We interpret the ca. 2.60 Ga grain as inheritance. The arc-
633 modified signature of the association is assigned to the independently dated Bacajá arc at ca. 2.21-
634 2.13 Ga; the older grain may record the substrate on which that arc and its lower crust were built.

635 **5.2 Collision, crustal stacking and the maximum metamorphic pile**

636 The U-Pb data define an older melt-growth interval and a younger high-grade reworking interval
637 (Fig. 6; Table 2). CG-013A gives $2097 \pm 19\text{ Ma}$ and FT-060B gives $2093 \pm 25\text{ Ma}$ for
638 crystallization or melt-related zircon growth in felsic lower crust. FT-060B rims at $2082 \pm 29\text{ Ma}$
639 provide a less precise transition toward the younger domain. The strongest younger ages are $2073 \pm$
640 3 Ma in CG-059B, $2069 \pm 7\text{ Ma}$ in FT-193 and $2067 \pm 7\text{ Ma}$ in CG-013A rims. These ages date
641 granulite-facies recrystallization, migmatization and charnockitic to enderbitic melt generation.
642 Agreement among independent samples establishes a regional ca. 2.07 Ga thermal maximum
643 following lower-crustal melt growth near 2.10 Ga.

644 Regional chronometers place this evolution within terminal convergence. Bacajá monazite at 2109
645 $\pm 9\text{ Ma}$ was interpreted as the collisional peak, followed by low-pressure granulitic reorganization
646 at $2071 \pm 3\text{ Ma}$ (Vasquez, 2006). Novolândia records a protracted high-grade history, with older
647 metamorphic zircon at 2162 ± 3 , 2157 ± 7 and $2139 \pm 3\text{ Ma}$, renewed zircon growth near 2.11-2.09
648 and 2.07-2.05 Ga, and monazite at 2052-2044 Ma (Neri et al., 2026). Cajazeiras-hosted
649 magmatism evolves from the ca. 2.12 Ga Bandeirante Granite through the 2.10-2.06 Ga Alto Rio

650 Preto Granite, ca. 2.09 Ga Maravilha Charnockite, ca. 2.06 Ga Serra Azul Charnockite and ca. 2.05
 651 Ga Bernardino Granite (Neri et al., 2025). The collective record defines progressive thickening and
 652 heating, followed by lower-pressure reorganization and melt emplacement.

653 Thermobarometry fixes the physical level of the exposed root (Table 3). FT-194 preserves an early
 654 granulite-facies assemblage of Grt + Cpx + Ti-rich brown Hbl + Pl + Qz $\pm$ Ilm at ca. 9-10 kbar and
 655 760-800 °C. These conditions correspond to approximately 35-40 km depth for typical crustal
 656 densities. The same sample records a late hydrated assemblage with green hornblende, plagioclase
 657 border and corona domains, garnet rims and quartz at ca. 7-8 kbar and 690-710 °C. Garnet
 658 destabilization, plagioclase-corona formation and replacement of clinopyroxene and brown
 659 hornblende record decompression with fluid access.

660 FT-258 independently confirms granulite-facies temperatures in a drier assemblage. Its Opx + Cpx
 661 + Bt + Pl + Qz $\pm$ oxides assemblage gives ca. 770 $\pm$ 60 °C by two-pyroxene thermometry,
 662 supported by Ti-in-biotite estimates near 740-770 °C. The absence of garnet prevents a formal
 663 pressure estimate. On the Carajás side, FT-049 records Hbl + Pl + Ttn equilibration at ca. 700-720
 664 °C and lacks granulite-facies relics. The contrast defines a thermal section from the granulitic
 665 hanging wall into upper-amphibolite-facies Carajás crust.

666 The thermal section is also temporal. FT-193 and FT-194 were collected from the same continuous
 667 outcrop: zircon in FT-193 gives 2069 $\pm$ 7 Ma, while FT-194 supplies the 9-10 kbar and 760-800 °C
 668 constraint. Hornblende from the same collected FT-193 sample gives a $^{40}\text{Ar}/^{39}\text{Ar}$ inverse-isochron
 669 age of 2047 $\pm$ 16 Ma (Tavares et al., 2026). FT-049 and FT-049C are split blocks of one collected
 670 Parauapebas amphibolite; thermometry yields ca. 700-720 °C and hornblende gives 2078 $\pm$ 15 Ma.
 671 More internal Carajás fabrics contain biotite with a 2075 $\pm$ 14 Ma closure age. Minerals with
 672 different growth and retention temperatures therefore record a coherent Transamazonian thermal
 673 structure rather than unrelated local events.

674 The structural geometry converts the thermal section into a collisional stack. NE-SW shortening
 675 and top-to-SW transport place the Vila Santa Fé-Rio Preto root above imbricated Buritirama rocks
 676 and the northern Carajás margin. Metamorphic grade rises from Carajás into the high-grade belt,
 677 and fabrics can be followed across the boundary (Tavares et al., 2018, 2026). A gravity high along
 678 the granulites, the corresponding two-dimensional density model and the magnetic continuity
 679 between Vila Santa Fé and Bacajá provide independent constraints at crustal scale (Fig. 7; Oliveira
 680 et al., 2020; Serafim et al., 2023). These observations directly support tectonic stacking of Bacajá-
 681 derived lower crust over the Carajás margin between ca. 2.10 and 2.07 Ga.

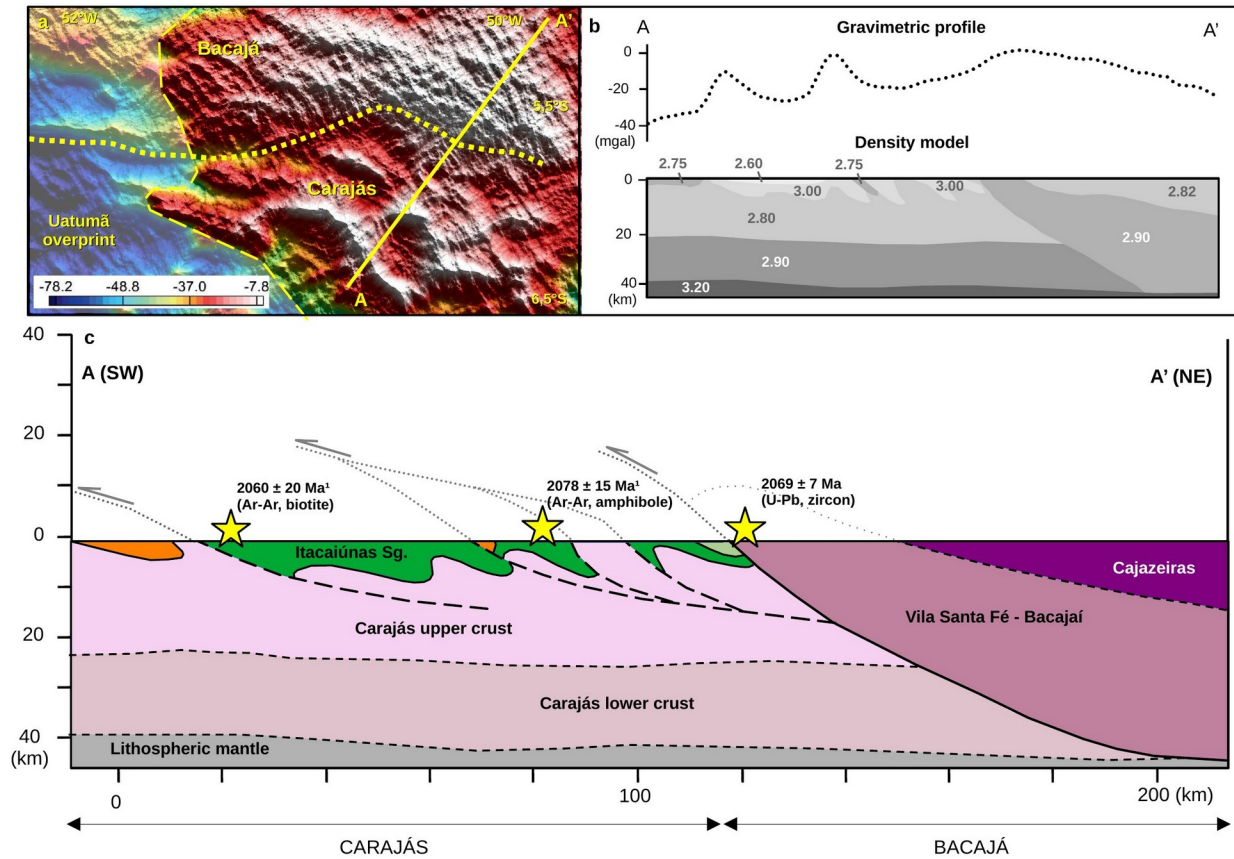


Figure 7: Integrated gravity-constrained crustal section across the Carajás-Bacajá boundary during Rhyacian closure at ca. 2.07 Ga. (a) Bouguer anomaly map of the Carajás-Bacajá boundary region, extracted from the Carajás aerogeophysical atlas of Serafim et al. (2023). The image shows a high-gravity anomaly broadly following the granulitic rocks exposed along the Carajás-Bacajá suture zone. This anomaly is attenuated westward where lower-density felsic rocks related to the Uatumã magmatic overprint generate a gravity low. The A-A' transect marks the location of the sections shown in panels b and c. (b) Gravimetric profile and two-dimensional density model along the same transect, modified from Oliveira et al. (2020). The upper panel shows a gravity profile with a characteristic high near the collisional boundary, whereas the lower panel shows the corresponding density model used as a geophysical constraint for the geological interpretation. Density values are in g cm⁻³. (c) Gravity-constrained geological section integrating surface geology, gravimetric constraints, structural interpretation, metamorphic pressure-temperature estimates and U-Pb/⁴⁰Ar-³⁹Ar age constraints. The section shows Archean Carajás upper and lower crust structurally juxtaposed against the Vila Santa Fé-Bacajá high-grade unit and Cajazeiras basement. Yellow stars indicate projected key constraints from Tavares et al. (2026) and this study. The section records crustal thickening, southwest-verging tectonic stacking and exhumation during deep closure of the Buritirama margin.

Carajás records the same collision through metamorphic and tectonically-assisted hydrothermal perturbation. Foliation-related mineral systems yield ca. 2.10-2.07 Ga ages, the late magnetite population at Salobo gives a Pb-Pb age of 2112 ± 12 Ma, and Bacaba-Bacuri hydrothermal monazite records a ca. 2.06 Ga overprint (Tassinari et al., 2003; Moreto et al., 2015; Tavares et al., 2026). Each system has its own geological meaning and uncertainty, yet their regional concentration within the collisional interval is consistent with heating, deformation and fluid redistribution across the lower plate.

5.3 Pre-rift architecture and ca. 2.55 Ga rifting

The rift developed on an inherited Archean architecture. In Carajás, ca. 2.76-2.73 Ga magmatism, mafic-ultramafic emplacement and extensional basin development constructed the Itacaiúnas system. The Serra Sul maximum depositional age of 2684 ± 10 Ma, its local provenance and slope-instability facies place it near the top of this Neoproterozoic evolution (Rossignol et al., 2020).

Novolândia preserves the older crustal archive on which the Rhyacian Bacajá system was built, and that archive is a Carajás archive. Neri et al. (2025, 2026) mapped and dated the older sedimentary and igneous assemblages and the Rhyacian magmatic units that intrude and rework them, establishing the basement-arc relation independently of our reconstruction. Four elements of their dataset bear directly on the reconstruction proposed here.

First, the felsic granulite ASM10 carries two Archean core populations, with upper intercepts at 2744 ± 21 Ma and 2567 ± 22 Ma, together with a xenocrystic core at 3461 ± 5 Ma, while rims and homogeneous grains give 2094 ± 9 Ma. The two Archean ages are the two ages that define the Carajás basin and its rift: the 2.76–2.73 Ga Itacaiúnas magmatism and the 2.57–2.55 Ga rift system to which the 2549 ± 5.9 Ma Buritirama metagranite belongs. Two magmatic populations at precisely those two ages, inside a body mapped as Bacajá, are not a coincidence of numbers.

Second, the internal relation between those two populations is resolved by asymmetry rather than by preference, because inheritance can only be older than crystallization and never the reverse. With the majority of the analyses defining the younger population, the parsimonious reading is crystallization at 2567 ± 22 Ma carrying inheritance at 2744 ± 21 Ma. That makes ASM10 a member of the Buritirama-type rift granite family and places one such body on the far side of the boundary. The inheritance is expected rather than anomalous: granites of that generation are derived from crust reworked at ca. 2.75 Ga and should carry 2.75 Ga zircon, and away from the locus of the 2.75 Ga magmatism there is no 2.75 Ga granite to be found, only the 2.55 Ga one that inherited from it. Whether the protolith was granitic or a felsic volcanic rock converted to orthogneiss at granulite facies is not resolved by the published data and does not affect the argument.

Third, the sedimentary protoliths carry the strongest Paleoproterozoic provenance signal so far reported in this sector. Sample ASM09A yields a detrital spectrum from 3320 ± 31 to 2608 ± 18 Ma with principal peaks at 3.32–3.18 Ga and 2.98–2.86 Ga, and monazite from the same sample gives individual ages from 2360 ± 59 to 2781 ± 43 Ma with a principal population near 2.67 Ga. A provenance *peak* at 3.32–3.18 Ga, as opposed to isolated grains, is not a feature of the interior

721 of the Carajás basin, where Paleoproterozoic zircon occurs sparsely: a 3643 ± 28 Ma grain in the Rio
 722 Fresco Group, grains between 3.15 and 3.09 Ga in drill core, ca. 3.1–3.0 Ga inherited or detrital
 723 grains at Salobo, and 3.08 Ga basement components in the southern belt. A peak of that
 724 magnitude is what a sector of the basin should carry if it was deposited directly on the
 725 Paleoproterozoic substrate rather than on the Neoproterozoic pile that covers it elsewhere.

726 Fourth, the same interval is what the Hf record of Carajás returns independently and by a
 727 different route. Zircon Lu-Hf in Parauapebas Formation basalts gives two-stage crustal model
 728 ages of 3224–3345 Ma with $\epsilon\text{Hf}(t)$ of -0.79 to -2.75 (Martins et al., 2017); basement zircon
 729 gives Hf model ages of 3.2–3.4 Ga (Xavier et al., 2025); and detrital zircon from modern
 730 drainages across the eastern province gives single-stage model ages of 3.06–3.17 Ga, equivalent
 731 to ca. 3.2–3.3 Ga in two-stage terms (Ganade et al., 2020). Three isotopic routes and one detrital-
 732 age route converge on a crustal source extracted at 3.2–3.3 Ga. The Paleoproterozoic provenance
 733 peak at Novolândia is therefore not merely old: it is the *same* Paleoproterozoic reservoir that the
 734 Carajás block reworks throughout its history.

735 Taken together, these elements identify the sedimentary and older igneous archive of Novolândia
 736 not as an exotic basement accreted to Carajás but as material derived from the same
 737 Paleoproterozoic substrate on which Carajás was built, carrying Carajás basin magmatism at 2.75
 738 Ga, Carajás rift magmatism at 2.55 Ga and Carajás provenance including its Paleoproterozoic
 739 source. That is what the reconstruction proposed here predicts. If the ocean closed at ca. 2.10–
 740 2.05 Ga between two fragments of one margin, then the far side must carry the ages, the
 741 magmatism and the provenance of the near side, and the correlation with Carajás is consequently
 742 an identification rather than a resemblance. The most economical reading of the whole dataset is
 743 that the block carrying the Novolândia protoliths is a piece of the Carajás Paleoproterozoic substrate
 744 that was detached during ca. 2.55 Ga rifting and returned by Transamazonian collision.

745 Rift initiation minimal age is dated by the 2549 ± 5.9 Ma Buritirama metagranite (Salgado et al.,
 746 2019a, 2019b). Its ferroan, metaluminous, A2-type and within-plate character identifies
 747 lithospheric extension. The granite constrains rift-related magmatism; it does not alone prove that
 748 oceanic crust formed at 2.55 Ga. That distinction allows the magmatic age to mark the onset of a
 749 process whose preserved sedimentary and oceanic consequences developed later.

750 Detrital zircon and stratigraphy record the basin response. In lower-unit sample BUR-3, the ca.
 751 2535 Ma population forms 37% of the spectrum, essentially equal to the 39% ca. 2714 Ma
 752 population. The prominence of the young population requires a nearby exposed rift source. In
 753 upper-unit sample BUR-2, the equivalent ca. 2522 Ma population falls to 24%, while the ca. 2680
 754 Ma population rises to 41%. The upward change records dilution of the proximal rift source as
 755 drainage expanded across the Neoproterozoic Carajás substrate.

756 The basal quartzite and mica-quartzite interval records substantial relief and efficient clastic
 757 delivery during rift development. Its transition into carbonate-silicate rocks and marble records a
 758 decrease in terrigenous dilution as accommodation increased and relief decayed. A first

759 peneplanation event is the geomorphic interpretation of this stratigraphic change. The evidence is
 760 the coupled upward loss of the proximal 2.55 Ga source, widening of Archean provenance and
 761 replacement of clastic by chemical sedimentation.

762 **5.4 Drift, low-relief sediment starvation and manganese accumulation**

763 The strongest evidence for drift is sedimentary and geochemical. Dolomitic marbles have negative
 764 Ce anomalies, Y/Ho ratios above 48 and seawater-like REE+Y patterns, establishing deposition on
 765 an open marine platform (Salgado et al., 2021). The progression from basal quartz-rich clastics to
 766 carbonate-silicate rocks, dolomitic marble and manganese-bearing carbonates records a sustained
 767 decline in terrigenous dilution. Carbonate abundance alone cannot demonstrate tectonic
 768 quiescence; together with marine trace-element signatures, stable Carajás-dominated provenance
 769 and the lack of a younger local detrital population, it supports a mature, sediment-starved margin.
 770 These observations establish locally non-glaciogenic marine conditions in Buritirama but are not
 771 used to reinterpret the much older Serra Sul succession.

772 Positive $\delta^{13}\text{C}$ values of +3.18 to +4.96‰ V-PDB occur in the non-manganiferous dolomitic
 773 marbles. Salgado et al. (2021) interpreted them as the Lomagundi-Jatuli excursion.
 774 Stratigraphically, the carbonate platform was established before the manganese maximum, and the
 775 positive excursion is already recorded in pre-ore carbonates. Manganese-bearing carbonates
 776 subsequently shift to $\delta^{13}\text{C}$ values of -2.56 to +0.15‰ V-PDB, acquire positive Eu anomalies and
 777 define an Eu-Mn correlation. Their chemistry records hydrothermal marine metal supply coupled
 778 to redox stratification, microbial reduction and diagenetic precipitation of kutnohorite and Mn-
 779 calcite. The evidence therefore orders the environmental evolution, with marine carbonate
 780 deposition, onset of the positive carbon-isotope excursion, and culmination in Mn accumulation
 781 under exceptionally low clastic dilution, in an spreading sea with available metals in its water
 782 column.

783 The interval between rift initiation near 2.55 Ga and clear subduction-related activity near 2.21-
 784 2.20 Ga approaches 300 Myr. It should be understood as a tectonic window. The preserved
 785 Buritirama record must contain condensation, non-deposition, erosion, tectonic omission, or some
 786 combination of these. The long interval is recorded most strongly by the absence of a local
 787 magmatic and juvenile detrital signal in the southern Carajás-Cajazeiras margin sector and by the
 788 environmental dominance of chemical sedimentation.

789 The Great Australian Bight and Eucla Basin provide a useful process analogue. A rifted passive
 790 margin there contains a Mesozoic syn-rift to early post-rift terrigenous megasequence, followed
 791 above a regional unconformity by a Cenozoic succession that is almost entirely carbonate except
 792 for a basal siliciclastic unit. Since the late Eocene, negligible terrigenous input, absence of major
 793 rivers and tectonic stability of the flat southern Australian hinterland have sustained carbonate
 794 dominance; Holocene studies likewise document carbonate accumulation on a sediment-starved
 795 shelf with minimal terrigenous delivery (James et al., 1994; Feary et al., 2004). Buritirama differs,
 796 however, in age, biosphere, carbonate factory and preservation.

797 The apparent 2.50-2.20 Ga zircon ages require the same spatial discipline. Southern Carajás lacks a
 798 known zircon-fertile Siderian or early Rhyacian magmatic source, and the Buritirama spectra are
 799 overwhelmingly derived from local Archean rocks. Genuine Siderian juvenile rocks occur farther
 800 north in Bacajá. As in the Great Australian Bight analogue, absence gains geological weight only
 801 when embedded in a positive sedimentary context, like stable provenance, post-rift carbonate
 802 dominance, negligible juvenile input and prolonged terrigenous starvation. In the Buritirama basin,
 803 this combined record supports passive-margin quiescence more strongly than magmatic silence
 804 alone and places the burden on demonstrating that a few young analyses record provenance rather
 805 than isotopic disturbance.

806 **5.5 Detrital-zircon tails and the duration of the Buritirama margin**

807 The Paleoproterozoic detrital ages reported from Buritirama are the principal basis for a Rhyacian
 808 maximum depositional age (Salgado et al., 2019b). In the lower-unit quartzite, the
 809 Paleoproterozoic grains are Siderian and the youngest is ca. 2347 Ma. In the upper-unit quartzite,
 810 the tail is also mainly Siderian and the Rhyacian constraint rests on very few analyses, including ca.
 811 2272 and 2186 Ma. The youngest coherent population is near 2365 Ma, whereas the published
 812 maximum depositional age adopts the youngest single grain. The imbricated type section adds a
 813 structural limitation: a grain from one thrust slice cannot automatically date every unit in the
 814 formation.

815 Partial Pb loss reproduces the entire tail at very low discordance. If the ca. 2.53 Ga parent
 816 population lost Pb during the ca. 2.10 Ga Transamazonian event, apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages of
 817 2365, 2347, 2272 and 2186 Ma can be generated at only ca. 1.0-1.6% discordance. Starting from
 818 the dominant ca. 2.68-2.71 Ga populations produces the same apparent ages at ca. 1.4-2.9%
 819 discordance. All values lie well within the 10% discordance filter applied to the published dataset.
 820 This behavior is consistent with documented detrital-zircon systematics in which ancient Pb loss
 821 produces spuriously young ages that can survive conventional discordance filtering, and with
 822 forward models showing that apparent Pb loss may shift in situ dates along or close to concordia
 823 (Nemchin and Cawood, 2005; Sharman and Malkowski, 2024). Concordance at that threshold
 824 therefore cannot discriminate a true Siderian-Rhyacian detrital grain from an Archean grain
 825 partially reset during Transamazonian metamorphism (Fig. 8).

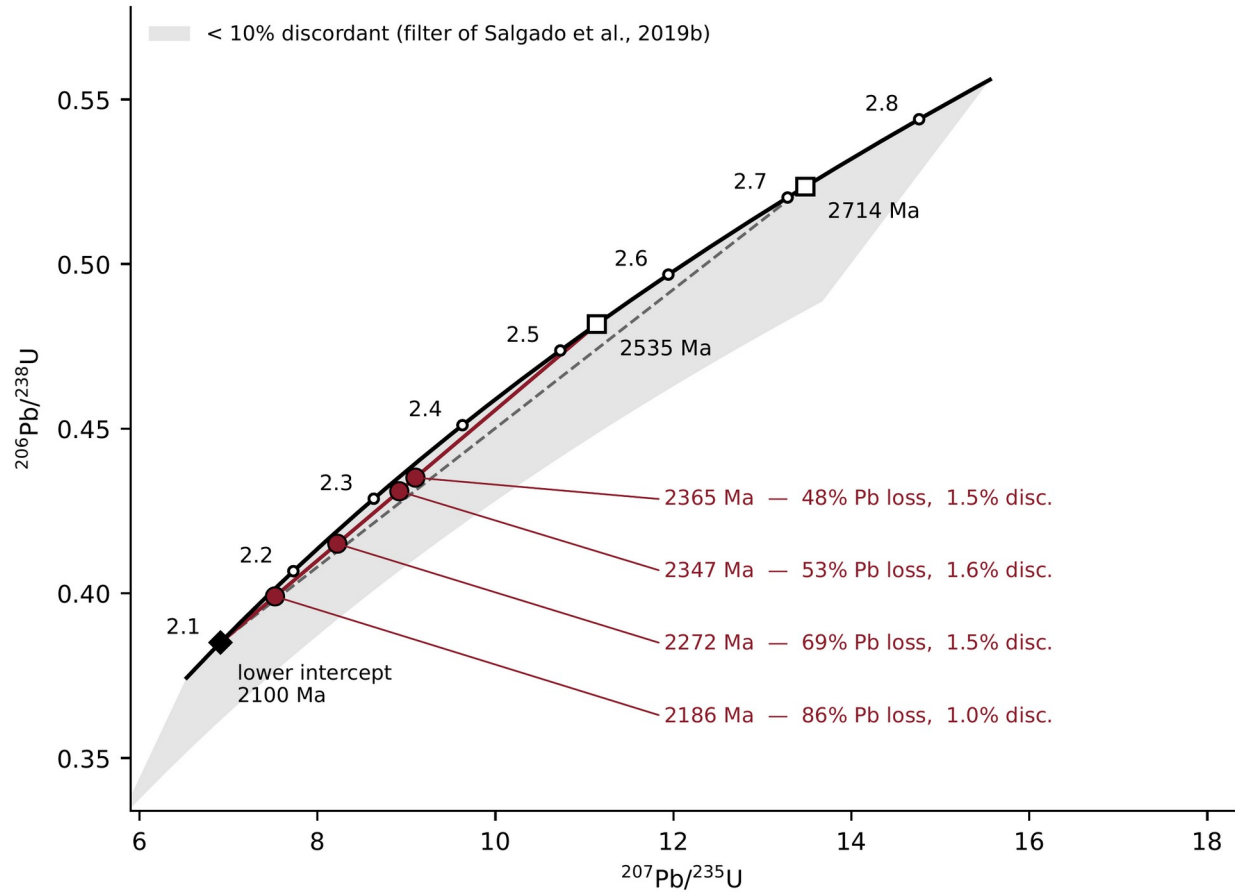


Figure 8: Quantitative Pb-loss test for the Paleoproterozoic detrital-zircon tail of the Buritirama Formation. The concordia curve is labelled in Ga. Open squares mark the dominant Archean detrital populations at ca. 2535 and 2714 Ma (Salgado et al., 2019b), and chords join them to a lower intercept at 2100 Ma, representing Transamazonian deformation and metamorphism. Filled circles show positions that reproduce the reported apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages of ca. 2365, 2347, 2272 and 2186 Ma. The ca. 2.53 Ga parent produces these ages at only ca. 1.0-1.6% discordance; the ca. 2.68-2.71 Ga parents produce them at ca. 1.4-2.9% discordance. All lie inside the 10% discordance filter applied to the published dataset, demonstrating that concordance alone cannot distinguish genuine Siderian-Rhyacian detritus from Archean zircon partially reset during the Transamazonian event.

826 The geology makes Pb loss plausible. Buritirama was metamorphosed and imbricated during
 827 collision, experienced a ca. 2.20-2.15 Ga fluid-assisted episode and was affected by younger
 828 hydrothermal reactivation. Its abundant ca. 2.53 and 2.68-2.71 Ga parent populations supply many
 829 grains from which a small reset fraction could generate the observed tail. The Pb-loss model is
 830 consequently the parsimonious interpretation for Buritirama. It remains a hypothesis pending
 831 reinspection of raw spot positions, internal zircon domains and common-Pb behavior, especially
 832 for the ca. 2186 Ma analysis.

833 Novolândia requires the same calibration and provides a more severe test of it, because there the
 834 resetting is documented rather than inferred. Its paraderived granulites underwent granulite-facies
 835 metamorphism and partial melting between ca. 2.16 and 2.04 Ga, and the sector records high-grade
 836 metamorphism before ca. 2.1 Ga and again at ca. 2.07 Ga (Neri et al., 2026). In sample ASM19A
 837 only seven of sixty analyses met the concordance criterion, the authors noting that most of the
 838 grains are highly discordant; the surviving spectrum runs from 2758 ± 7 to 2310 ± 8 Ma with
 839 declared peaks at 2.79 and 2.31 Ga.

840 A parent population near 2.79 Ga losing Pb toward ca. 2.05 Ga generates apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages
 841 across the 2.6–2.3 Ga range at discordances below the 10% filter applied to the dataset. A 2790 Ma
 842 grain reset at 2050 Ma reports 2330 Ma at 3.9% discordance; a 3080 Ma parent reports 2620 Ma at
 843 7.4%; a 3300 Ma parent reports 2620 Ma at 9.8%. The sensitivity in this configuration is
 844 approximately 40 Myr of apparent age for each 1% of discordance, so the difference between a 5%
 845 and a 10% filter is 200 Myr of apparent age and is invisible to any concordance test. The declared
 846 2.31 Ga peak therefore has the position, the discordance and the host metamorphism expected of a
 847 Pb-loss tail rather than of a source population. The same reasoning applies to the 2608 ± 18 Ma
 848 lower limit of ASM09A and to the 2336 ± 8 Ma grain of ASM19B, whereas the 2500 ± 6 Ma grain
 849 in the same leucosome is a plausible primary detrital age and is compatible with a basal Buritirama
 850 source.

851 Two consequences follow, and both are testable in the supplementary data already published. The
 852 maximum depositional age of the Novolândia sedimentary protoliths rises from ca. 2.3 Ga to ca.
 853 2.5 Ga, which removes them from the Rhyacian and places them in the Itacaiúnas–basal Buritirama
 854 window; on that reading the attribution of the belt to Bacajá is a statement of structural position
 855 rather than of basin age. And the upper intercept of 2157 ± 7 Ma obtained by the authors for the
 856 disturbed array is not a nuisance parameter but a direct measurement of the age of the resetting that
 857 the correction invokes. The test is specific: if the young analyses are a tail, they should align on a
 858 discordia with a lower intercept near 2.05 Ga and their $^{207}\text{Pb}/^{206}\text{Pb}$ ages should correlate with
 859 degree of discordance; a genuine source population would show neither. Bacajá does contain
 860 genuine 2.45–2.36 Ga juvenile sources, so a subordinate Siderian detrital contribution cannot be
 861 rejected. The claim is that the tail is dominated by resetting, not that no Siderian grain exists.

862 This interpretation removes the requirement that Buritirama sedimentation continued until 2.186
 863 Ga. It does not yield a precise depositional age for the upper unit. The formation remains

864 constrained between ca. 2.55 Ga rift initiation and Transamazonian deformation, with its internal
 865 chemical record carrying the stronger environmental chronology. A long drift interval with
 866 condensation and hiatuses is compatible with the available data, while continuous Rhyacian
 867 sedimentation is not required.

868 **5.6 Subduction initiation, lower-plate extension and renewed sedimentation**

869 Convergence is first recorded directly in the upper plate. Pre-collisional Bacajá magmatism spans
 870 2215 ± 2 to 2133 ± 10 Ma (Vasquez and Rosa-Costa, 2008), and the isolated 2232 ± 9 Ma zircon
 871 core in FT-060B is compatible with this interval. In Novolândia, metamorphic zircon at 2162 ± 3 ,
 872 2157 ± 7 and 2139 ± 3 Ma shows that high-grade reworking began before terminal collision (Neri
 873 et al., 2026). These ages provide the clock for subduction initiation and progressive heating of the
 874 upper plate.

875 Carajás records a complementary lower-plate response. A selective ca. 2.20-2.15 Ga thermal and
 876 fluid episode is expressed by recrystallization of Neoproterozoic hydrothermal minerals in several Cu-
 877 Au deposits, as biotite at Corta Goela at 2193 ± 4 Ma, amphibole at Sossego-Sequeirinho at $2199 \pm$
 878 13 Ma and titanite at Antas North at 2162.9 ± 28.1 Ma (Marschik et al., 2003; Pollard et al., 2019;
 879 Hühn et al., 2025; Tavares et al., 2026). The episode lacks a penetrative regional fabric and has no
 880 known coeval magmatic source within Carajás. It is therefore distinct from the younger ca. 2.10-
 881 2.07 Ga fabric-forming collision.

882 The paired upper- and lower-plate records define tectonic polarity. Arc magmatism and early high-
 883 grade metamorphism occur in Bacajá, while Carajás records fluid-assisted re-equilibration without
 884 a same-age arc. We interpret the Carajás episode as extension and permeability increase in the
 885 downgoing plate during onset of subduction. Surface and formation waters could descend through
 886 newly active structures, heat at depth and return along the inherited Carajás fault network, resetting
 887 sensitive minerals in pre-existing Neoproterozoic hydrothermal systems. In this reading, the ca. 2.20-
 888 2.15 Ga ages in mineralized districts date reactivation and isotopic resetting.

889 Slab pull provides an actualistic mechanism for this polarity. Cooling and densification of oceanic
 890 lithosphere allow it to sink, placing the attached lower plate in tension; bending and outer-rise
 891 faulting enhance extension and fluid access (Forsyth and Uyeda, 1975; Weissel and Karner, 1989;
 892 Naliboff et al., 2013). The mechanism is consistent with the age match between Bacajá arc
 893 initiation and Carajás fluid-assisted extension. It is not directly measured by a single structure or
 894 age. Its testable predictions are coeval upper-plate arc growth, lower-plate amagmatic extension,
 895 renewed lower-plate relief, persistence of Carajás-derived sediment and eventual contractional
 896 inversion.

897 Buritirama preserves a possible sedimentary response. Above the manganese-rich intermediate
 898 unit, the upper unit begins with quartzite and mica-quartz schist and then returns to carbonate-
 899 silicate rocks (Salgado et al., 2019a). The renewed clastic pulse requires restoration of relief after
 900 the mature carbonate-platform stage. Its detrital spectrum remains dominated by Carajás

901 populations, as expected if extension rejuvenated the lower-plate hinterland. The subsequent return
 902 to carbonate records a second decay of relief and renewed reduction of terrigenous supply and
 903 possibly a second peneplanization event.

904 This is an integrated correlation rather than a direct depositional date. The upper clastic pulse lacks
 905 a secure syn-depositional age, and the Pb-loss argument weakens use of its youngest grains. Its
 906 stratigraphic position, repeated clastic-to-carbonate architecture, persistent Carajás provenance
 907 and regional ca. 2.20-2.15 Ga fluid episode jointly make slab-pull-related rejuvenation a viable
 908 working hypothesis. The timing for manganese deposition, therefore, may be constrained both by
 909 its relation with the Lomagundi-Jatuli excursion and by its burial after the slab-pull related
 910 extension.

911 **5.7 Post-collisional decompression, exhumation and renewed marine transgression**

912 The collisional root began to decompress while still hot. FT-194 records a transition from 9-10 kbar
 913 and 760-800 °C to 7-8 kbar and 690-710 °C with hydration. In FT-193, 2069 ± 7 Ma zircon growth
 914 in the melt-present granulitic assemblage is followed by hornblende Ar retention at 2047 ± 16 Ma
 915 in the same collected sample (Tavares et al., 2026). Using central ages and approximate thermal
 916 windows gives a nominal cooling rate of ca. 10-12 °C/Myr. Zircon growth is not a closure
 917 thermometer, so the rate is an order-of-magnitude estimate. It nevertheless exceeds the ca. 3-5
 918 °C/Myr conductive cooling estimated for the Oyapok Transamazonian transect (Nomade et al.,
 919 2002) and supports tectonically assisted exhumation.

920 Regional metamorphic chronology records the same transition. The 2109 ± 9 Ma collisional
 921 monazite population in Bacajá is followed by 2071 ± 3 Ma low-pressure granulitic reorganization
 922 (Vasquez, 2006), while late- to post-collisional magmatism expands between ca. 2.086 and 2.05
 923 Ga. Decompression, rapid cooling and late magmatism are consistent with gravitational
 924 readjustment of a thick, hot crustal pile. Orogenic collapse is the integrated interpretation of these
 925 datasets.

926 A new sedimentary basin formed on the Carajás side after deformation. At Serra Pelada goldfield,
 927 the Águas Claras Formation rests in angular unconformity on both Neoproterozoic rocks and the
 928 deformed Buritirama Formation; elsewhere in Serra dos Carajás, it overlies the Itacaiúnas
 929 Supergroup (Fabre et al., 2011; Tavares et al., 2018). The basal marine interval of the Águas Claras
 930 Formation is exposed both at the Azul manganese mine and in the Serra Pelada region. At Azul,
 931 syndiagenetic sulfides and framboidal pyrite yield ca. 2.06 Ga Pb-Pb ages (Mougeot et al., 1996).
 932 This basal interval records a post-tectonic marine transgression across the exhuming orogen.

933 Up-section, the Águas Claras Formation records regression into a continental clastic succession
 934 containing arkose and wacke with a strong terrigenous signature (Fabre et al., 2011). Feldspar-rich
 935 detritus requires renewed crystalline relief, rapid erosion and efficient continental sediment
 936 delivery. The post-collisional basin therefore differs fundamentally from the sediment-starved

937 Buritirama platform: its basal transgressive sea was progressively filled and replaced by
938 continental sedimentation as uplift, erosion and exhumation continued.

939 **5.8 A Wilson cycle across the Archean-Paleoproterozoic transition**

940 The Carajás-Bacajá boundary preserves a sequential tectonic record from ca. 2.55 to 2.05 Ga. At
941 ca. 2.55 Ga, within-plate A2-type magmatism and a proximal detrital population record rift
942 initiation in an Archean crustal system. Up-section dilution of the rift source, widening Archean
943 provenance and replacement of clastic by marine carbonate sedimentation record thermal
944 subsidence and relief exhaustion. Seawater-like REE+Y patterns, positive pre-ore $\delta^{13}\text{C}$ values and
945 later Mn-rich chemical sedimentation define a mature platform connected to the global ocean. The
946 poorly represented interval to ca. 2.2 Ga is a long drift window containing hiatuses or condensed
947 sections.

948 At ca. 2.21-2.13 Ga, Bacajá arc magmatism and early high-grade metamorphism mark subduction
949 in the upper plate. A coeval 2.20-2.15 Ga fluid-assisted, amagmatic episode in Carajás records
950 increased permeability in the lower plate. Slab pull accounts for the paired polarity and predicts
951 renewed lower-plate relief, represented tentatively by the upper Buritirama clastic pulse. Terminal
952 convergence produced lower-crustal melt growth near 2.10 Ga, granulite-facies reworking near
953 2.07 Ga and southwest-verging tectonic stacking of the Bacajá root over Buritirama and Carajás.

954 Collision is constrained on concordant U-Pb zircon ages, thermobarometry, U-Pb- $^{40}\text{Ar}/^{39}\text{Ar}$
955 relations, regional metamorphic chronometers, penetrative fabrics, southwest-directed transport,
956 metamorphic-grade variation and geophysical architecture. Collapse and exhumation are
957 supported by decompression, hydration, rapid nominal cooling and the angularly unconformable
958 Águas Claras basin, including its basal marine interval exposed at Azul and Serra Pelada.

959 No exposed ca. 2.55 Ga oceanic-crustal fragment has been identified, and the width and lifetime of
960 the ocean cannot be measured directly. Oceanic separation is inferred from the ordered association
961 of rift magmatism, open-marine passive-margin sedimentation, later upper-plate arc magmatism
962 and final collisional stacking. The Wilson-cycle model gains strength from this ordered polarity
963 while retaining explicit gaps in the oceanic record.

964 **6. Conclusions**

965 The Vila Santa Fé-Rio Preto association exposes the deep crust of the Rhyacian Carajás-Bacajá
966 collision. Its primitive Rio Preto-type mafic component, enriched mafic granulites, arc-modified
967 felsic orthogneisses and charnockitic to enderbitic melts define a heterogeneous lower crust
968 assembled from comparatively juvenile mafic material, Rhyacian arc components and reworked
969 older crust. Zircon dates lower-crustal melt growth at ca. 2.10 Ga and granulite-facies
970 recrystallization, migmatization and melt generation at ca. 2.07 Ga.

971 Thermobarometry places the exposed root at ca. 9-10 kbar and 760-800 °C, followed by hydrated
 972 re-equilibration at ca. 7-8 kbar and 690-710 °C. The same-outcrop relation between FT-193 and
 973 FT-194, the same-sample U-Pb zircon and $^{40}\text{Ar}/^{39}\text{Ar}$ hornblende record in FT-193, the
 974 FT-049/FT-049C thermometric-chronometric link, and ca. 2.08-2.04 Ga foliation-mineral ages
 975 across Carajás define a thermally structured crustal section. NE-SW shortening, top-to-SW
 976 transport, increasing metamorphic grade toward Bacajá and gravity-magnetic anomalies
 977 demonstrate stacking of the high-grade Bacajá root above Buritirama and northern Carajás.

978 The older margin history is preserved by complementary archives. The 2549 ± 5.9 Ma A2-type
 979 Buritirama metagranite and a strong proximal ca. 2.55 Ga detrital population date rift initiation.
 980 Upward dilution of this source, expansion of Neoproterozoic provenance, decline of clastic
 981 sedimentation and development of an open-marine carbonate platform record transition to drift.
 982 Positive $\delta^{13}\text{C}$ values in pre-ore dolomitic marbles place the Lomagundi-Jatuli signal before the
 983 Mn maximum; Mn-carbonate chemistry subsequently records hydrothermal metal supply, redox
 984 stratification, microbial reduction and diagenetic carbonate formation under very low clastic
 985 dilution.

986 The ca. 2.55-2.20 Ga interval is best treated as a tectonically quiet, sediment-starved window
 987 containing hiatuses and condensed deposition. Apparent Paleoproterozoic zircon ages in
 988 Buritirama can be generated from its dominant Archean populations by Transamazonian Pb loss at
 989 only ca. 1-3% discordance, so they do not securely date continued Rhyacian sedimentation.
 990 Genuine Siderian sources in Bacajá require a qualified reading of the Novolândia tail, but the same
 991 Pb-loss geometry applies there with stronger justification, because the belt underwent granulite-
 992 facies metamorphism and partial melting between ca. 2.16 and 2.04 Ga and considering the
 993 reported upper intercept of 2157 ± 7 Ma for the disturbed array. Corrected on that basis, the
 994 maximum depositional age of the Novolândia protoliths rises from ca. 2.3 to ca. 2.5 Ga. The belt
 995 then carries, in one place, the two magmatic ages of the Carajás basin and its rift, a rift-type granite
 996 crystallized at 2567 ± 22 Ma with 2744 ± 21 Ma inheritance, and a 3.32–3.18 Ga Paleoproterozoic
 997 provenance peak that matches the 3.2–3.3 Ga crustal extraction age returned independently by
 998 zircon Hf across Carajás. The far side of the ocean that closed at ca. 2.10–2.05 Ga is therefore best
 999 read as a detached fragment of the Carajás margin, which is what a Wilson cycle at this boundary
 1000 requires.

1001 Subduction initiation is recorded by ca. 2.21-2.13 Ga Bacajá arc magmatism and early high-grade
 1002 metamorphism. Coeval fluid-assisted re-equilibration in Carajás at ca. 2.20-2.15 Ga records the
 1003 lower-plate response. Slab pull explains this upper-plate/lower-plate polarity and the renewed
 1004 clastic pulse above the Buritirama manganese interval; it remains a testable mechanism because the
 1005 clastic pulse lacks a direct depositional age.

1006 Post-collisional evolution combines decompression, hydration, nominal cooling near 10-12
 1007 °C/Myr and an angularly unconformable basin. Basal marine flooding within the Águas Claras
 1008 Formation, exposed at Azul and Serra Pelada and dated near 2.06 Ga at Azul, was followed upward

1009 by regression into feldspar-rich continental sedimentation as crystalline relief was exhumed. These
1010 data complete a ca. 500 Myr trajectory from rift initiation to collision and collapse. The direct core
1011 of the model is the Rhyacian crustal stack; the full Wilson cycle is the regional interpretation that
1012 best accounts for the ordered magmatic, stratigraphic, geochemical, structural, metamorphic and
1013 thermochronological evidence.

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1016 **CRediT authorship contribution statement**

1017 Felipe Mattos Tavares: Conceptualization, Methodology, Investigation (fieldwork, geological
1018 mapping and sampling), Formal analysis and interpretation, Visualization (figures and tables),
1019 Writing – original draft, Project administration. Cíntia Maria Gaia da Silva: Investigation
1020 (geological mapping and sampling), Writing – review & editing. Joseneusa Brilhante Rodrigues:
1021 Investigation and Data curation (U–Pb and Sm–Nd geochronology, including laboratory liaison
1022 with the Universidade de Brasília, the Universidade Federal do Rio Grande do Sul and the
1023 SHRIMP facility at the Australian National University), Formal analysis (age calculations,
1024 concordia and discordia diagrams and isotopic interpretation), Writing – review & editing.
1025 Rudolph Allard Johannes Trouw: Supervision, Writing – review & editing. Julio Cezar Mendes:
1026 Resources (electron-microprobe analysis, LABSONDA, UFRJ), Writing – review & editing.

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1032 microprobe analyses were carried out at LABSONDA, Universidade Federal do Rio de Janeiro.

1033 **Declaration of competing interest**

1034 The authors declare that they have no known competing financial interests or personal
1035 relationships that could have appeared to influence the work reported in this paper.

1036 **Data availability**

1037 The analytical data underlying this study (whole-rock lithogeochemistry, Sm–Nd isotopes, U–Pb
1038 zircon isotopic data, zircon cathodoluminescence and back-scattered electron images, mineral
1039 chemistry and thermobarometric calculations) are provided as Supplementary Materials 1–6. The
1040 complete machine-readable datasets and the source data for the analytical figures will be deposited
1041 in Mendeley Data, and the DOI will be added before publication. The gravity profile and density
1042 model shown in Fig. 7b are redrawn from a published source (Oliveira et al., 2020) and contain no
1043 new primary data. The Pb-loss model in Fig. 8 is calculated from published detrital-zircon data
1044 (Salgado et al., 2019b). The $^{40}\text{Ar}/^{39}\text{Ar}$ data cited from Tavares et al. (2026) are openly available in
1045 Mendeley Data (<https://doi.org/10.17632/cgx6zx9m3n.1>).

1046 **Declaration of generative AI and AI-assisted technologies in the manuscript preparation** 1047 **process**

1048 During the preparation of this work, the authors used OpenAI's ChatGPT and Anthropic's Claude
1049 to assist with language editing, the organization and development of the manuscript text,
1050 consistency checks, and the writing and debugging of scripts used to process the authors' data and
1051 to plot analytical diagrams and tables. No generative AI tool was used to create or alter images,

1052 including field photographs, photomicrographs, zircon images and maps, or to generate primary
 1053 analytical data. All AI-assisted outputs, including calculations, interpretations, diagrams and
 1054 tables, were critically reviewed, verified and edited by the authors, who take full responsibility for
 1055 the content of the published article.

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