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Archean tectonics resembled modern-style plate tectonics? Pre-Columbia early plate tectonics in the São Francisco-Congo Craton

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A R T I C L E I N F O

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A B S T R A C T

The geological record is known to be biased, especially for records of high- to ultra-high-pressure metamorphic rocks, which are key components for understanding one of the most fundamental questions of geoscience: how, when, and why did plate tectonics initiate on Earth? Detrital minerals can serve as proxies for tectonic and metamorphic processes, and their use help mitigate preservation bias in the geological record. Since rutile only crystallizes under pressure above 08 – 1.0 GPa, the study of detrital rutile, through the combination of trace elements, Zr-in-rutile thermometry, and U-Pb geochronology, can be used as a proxy for low temperature-pressure (*T/P*) metamorphic conditions through geological time. We combine new detrital rutile data from São Francisco-Congo Craton Mesoproterozoic sedimentary rocks with literature compilation to investigate *T/P* conditions through time and address plate tectonics evolution. Our data reveal: (i) the presence of low temperature rutile, and therefore, low *T/P* conditions since at least the early Archean, coexisting with intermediate *T/P* conditions; (ii) diversity of *T/P* conditions increasing from 2.1 – 1.8 Ga during the Columbia early assembly phase, and again after 0.7 Ga; (iii) average *T/P* conditions exhibiting marked changes through time, with lower *T/P* dominant in the Archean and the mid-Proterozoic. Intriguingly, this pattern stands in contrast to the higher *T/P* conditions determined for the mid-Proterozoic from the metamorphic bedrock record. These observations indicate that both the rutile and bedrock records are likely affected by preservation and erosional biases in different ways and should not be interpreted in isolation. The presence of low *T/P* since the Mesoarchean points to the presence of a tectonic regime involving low thermal gradients, most easily explained by some form of subduction.

1. Introduction

The stabilization of the first cratons and the initiation of plate tectonics are key phases in Earth's evolution. Both are considered fundamental processes that facilitated the emergence of life on Earth. Despite much research, major relevant questions remain on how, when, and why plate tectonic process was initiated on Earth. The causes of shifts between different geodynamic regimes through time, the timing of the onset of global-scale plate tectonics, and how it operated since the earliest continental crust generation remain a matter of great debate. It is generally thought that plate tectonics has operated on Earth at least since the Archean-Proterozoic boundary (*ca.* 2.5 Ga onwards), but its style (*e.g.*, mobile-lid *versus* stagnant-lid) and continuity of plate boundaries (*e.g.*, single-lid, globally linked continuous systems) are still

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controversial (*e.g.*, Sizova et al., 2014; Spencer et al., 2018; Stern, 2020; Palin et al., 2020). Several factors including mantle heating due to supercontinent insulation (Brown and Johnson, 2018), decrease in the velocity of plate motions (O'Neill et al., 2022), and the return to a single-lid regime followed by a restart or reinitiation of plate tectonics in Paleoproterozoic (Stern, 2020) have been proposed to explain the onset of plate tectonics.

Independent horizontal motion of lithospheric plates at divergent plate boundaries by seafloor spreading, strike-slip fault motion at transform boundaries, and one-sided subduction at convergent boundaries are considered the hallmarks of modern-day plate tectonics (Gerya et al., 2008, and references therein). Thus, to prove the existence of plate tectonics at any time in Earth's history, requires evidence that at least parts of the Wilson Cycle were in operation (Palin et al., 2020).

Exhumed metamorphic rocks that record low temperature-pressure (*T/P*) gradients (*e.g.*, blueschists and low-temperature eclogites) are considered indicators of cold and steep subduction, which itself is one of the indicator of plate tectonics (Stern, 2005; Pearce, 2008; Brown and Johnson, 2019; Palin et al., 2020); however, low *T/P* rocks are extremely rare in the rock record before the Tonian (*ca.* 0.85 Ga; Brown and Johnson, 2019; Brown et al., 2024). Various studies have suggested that paired metamorphic belts represent an important hallmark of plate tectonics (*e.g.*, Brown, 2006; Brown and Johnson, 2019; Brown et al., 2020a), where low *T/P* metamorphism in the subducting lithosphere occurs concurrently with high *T/P* metamorphism in the overlying arc, even during local and short-lived subduction (Ivan et al., 2022).

Several characteristics make rutile an excellent proxy for low *T/P* metamorphism. Rutile occurs in a wide range of lithologies, and numerous studies have demonstrated that its stability and crystallization in metamorphic rocks are strongly pressure-controlled. Phase-equilibrium modelling of mafic and intermediate compositions indicates that rutile is the stable Ti-bearing phase at pressures above ~0.8 – 1.0 GPa, whereas ilmenite is stable at lower to moderate pressures (Johnson and White, 2011; Palin et al., 2016; Green et al., 2016; Feisel et al., 2018). A similar relationship is observed in pelitic systems, in which rutile represents the high-pressure titanium phase (*e.g.*, White et al., 2014). Relevant for the current contribution is the fact that rutile forms at pressures exceeding ~1.0 GPa in oceanic crust and associated pelitic sediments that experience eclogite and/or blueschist facies metamorphism (*e.g.*, Angiboust and Harlov, 2017; Pereira et al., 2021). In Si and Zr saturated systems, the Zr incorporation in rutile is temperature dependent. Calibrations of the Zr-in-rutile thermometer have been presented in the literature (Tomkins et al., 2007; Kohn, 2020) and show that pressure has a minimal effect on the Zr incorporation. Due to its high-pressure affinity, rutile is thus commonly used to fingerprint high-pressure metamorphism in the geological record, which commonly results from subduction at convergent plate margins. Due to the characteristics highlighted above, detrital rutile is often used as a proxy for metamorphic conditions that can be applied at the basin- to global-scale (Pereira et al., 2021; Pereira and Storey, 2023; Cerri et al., 2024). The use of detrital accessory minerals to study secular change in Earth's tectonic and geodynamic processes provides an alternative to whole-rock records, which potentially circumvent issues of sample bias and the lack of preserved rocks from early Earth history (*e.g.*, Condie et al., 2005; Roberts and Spencer, 2015; Pereira et al., 2021; Pereira and Storey, 2023).

In this contribution, we present new U-Pb geochronology and trace element analysis of detrital rutile from the Mesoproterozoic (1.8 – 1.0 Ga) Espinhaço Supergroup sedimentary rocks (São Francisco-Congo Craton). Building on the work of Pereira et al. (2021), we combine these new data with an updated literature compilation to evaluate the detrital rutile record of metamorphic conditions through Earth history. Critically, we demonstrate (i) contrasting results to those derived from bedrock-based metamorphic records (*e.g.*, Brown and Johnson, 2019), which questions the validity of interpreting these records in isolation, and (ii) we highlight the occurrence of low *T/P* conditions since the Mesoarchean, pointing to the likely presence of subduction tectonics since that time.

2. Materials and methods

Detrital rutile grains from the Mesoproterozoic Espinhaço Supergroup (Chapada Diamantina, Paramirim Aulacogen; Tombador and Açuruá formations; Fig. S1, Supplementary Material A) in northeastern Brazil were analyzed for trace elements and U-Pb geochronology (Supplementary Material B). The Espinhaço Supergroup, one of the largest Precambrian intracratonic basins in the São Francisco Craton, was deposited between 1.8 Ga and 0.9 Ga, and was sourced mostly from the São Francisco-Congo Craton (*e.g.*, Guadagnin et al., 2015a, b). The sedimentary sequences of the Espinhaço Supergroup thus record the evolution, both within and proximal to, the São Francisco-Congo Craton from its assembly in the Paleoproterozoic to its partial breakup in the Neoproterozoic Brasiliano Orogeny (*e.g.*, Danderfer et al., 2015; Guadagnin et al., 2015a, 2015b).

In total, 96 detrital rutile grains from the Tombador Formation and 111 grains from the Açuruá Formation (Fig. S1, Supplementary Material A) were analyzed for trace elements (Mg, Al, *Ca*, Cr, Zr, Nb, Sb, Hf, and W) and U-Pb geochronology by LA-ICP-MS. Details of the analytical procedures can be found in Supplementary Material C.

2.1. Rutile as a proxy for subduction-related metamorphism

The Zr-in-rutile geothermometer is widely applied in both metamorphic and provenance studies. Experimental calibration indicates that the pressure dependence of Zr incorporation in rutile is relatively minor, with increasing pressure resulting in slightly lower Zr contents at a given temperature (Tomkins et al., 2007). Using this calibration, temperatures calculated for a Zr concentration of 50 ppm at pressures of 0.8, 1.0, and 1.2 GPa are approximately 518, 525, and 532 °C, respectively. Assuming an average continental crust density of 2.7 g/cm^3, these pressures correspond to depths of roughly 30, 37, and 44 km. Thus, a substantial difference in depth produces only a small variation in calculated temperature. Furthermore, Pereira et al. (2021) demonstrated that geothermometers based on element exchange between mineral pairs generally yield larger uncertainties than the Zr-in-rutile approach. Since at low temperatures, rutile is not stable at pressure lower than *circa* 10 kbar, Pereira et al. (2021) use rutile with temperatures lower than 580 – 550 °C as a proxy for low *T/P* condition (that is, blueschist or eclogite facies). This assumption is also used in the present work. We stress that variations of pressure within the thickness of the continental crust will not significantly change this interpretation, as previously shown. Using the diffusivity of Zr in rutile, experimentally determined by Cherniak et al. (2007), Pereira et al. (2021) evaluated the potential effects of diffusion on the re-equilibration of Zr across different temperature regimes. For a 200 μm size rutile, their results indicate that, although Zr concentrations in rutile may re-equilibrate relatively rapidly at high temperatures (on the order of ~1 Ma under granulite-facies conditions), re-equilibration at lower temperatures (500 – 550 °C) would require unrealistically slow cooling rates or prolonged thermal overprinting. This supports the use of a 550 °C threshold as a conservative filter that selectively includes rutile grains formed under low temperature, therefore, low *T/P* conditions. Moreover, because diffusion is negligible within this temperature range, the calculated Zr-in-rutile temperatures are interpreted to record the peak thermal conditions of rutile growth.

Rutile crystallization temperatures were determined using the Zr-in-rutile geothermometer (*e.g.*, Tomkins et al., 2007; Kohn, 2020) at three estimated pressures (0.8 GPa, 1.0 GPa, and 1.2 GPa), since rutile is rarely stable below 1.0 GPa (Luvizotto et al., 2009). We stress that, even for a temperature of *ca.* 750 °C and considering a pressure variation of ± 0.5 GPa (resulting in 0.5 – 1.5 GPa), a difference of *ca.* ± 50 °C is observed using both Tomkins et al. (2007) and Kohn (2020) calibration (Fig. S2, Supplementary Material A).

The early studies of Zack et al. (2002) and Zack et al. (2004a) have shown that rutile is the main carrier of the whole-rock High Field Strength Elements (HFSEs) as well as an important carrier of incompatible elements such as Cr. Therefore, the Cr/Nb ratio in rutile can be used to differentiate between rutile formed in mafic (or metamafic) and pelitic (or metafelsic) rocks. In this work, we use the log(Cr/Nb) ratio in detrital rutile to identify grains derived from metamafic and metafelsic sources (*e.g.*, Zack et al., 2002, 2004b; Triebold et al., 2005, 2012; Meinhold et al., 2008). Recent studies have drawn attention to the use of log(Cr/Nb) for source discrimination, as it can lead to a little mismatch between metafelsic (*i.e.*, metapelitic) and metamafic rutile (Pereira and Storey, 2023); however, since the goal of this study is not the discrimination between source rocks, a possible mismatch will not affect the main findings. Also, Pereira and Storey (2023) performed the log (Cr/Nb) discrimination and concluded that the discrimination works well for metamorphic rutile grains. Metamorphic rutile was identified using Sb and W contents (*e.g.*, Agangi et al., 2019, 2020; Pereira et al., 2021): detrital rutile grains with values of Sb > 20 ppm and W between 10 – 10,000 ppm were classified as magmatic/hydrothermal (Supplementary Material B).

As pointed out above, rutile is a Ti-bearing mineral that occurs predominantly in intermediate to high-pressure metamorphic rocks, but also secondarily in magmatic rocks, mantle ultramafic rocks, and hydrothermally related rocks associated with ore deposits (*e.g.*, Pereira and Storey, 2023). Rutile is also unstable at low-temperatures and low-pressure conditions, being replaced by other polymorphs like anatase and brookite (Jamieson and Olinger, 1969). Considering this, rutile formation is linked to low *T/P* metamorphic conditions, *ca.* < 475 °C/GPa (also considering that cold eclogite and HP-granulite can form rutile), related to the onset of plate tectonics and secular evolution of metamorphism.

Based on the classification of Brown et al. (2020b), metamorphism can be classified in three main types based on their *T/P* conditions: (i) high *T/P* (> 775 °C/GPa; migmatite and UHT-granulite); (ii) intermediate *T/P* (775 – 375 °C/GPa; HP-granulite and medium- and HT-eclogite), and (iii) low *T/P* (<375 °C/GPa; blueschist, LT and UHP eclogite). However, rutile temperature estimates based on Zr-in-rutile thermometry using detrital rutile depend on "guessing" a given pressure estimation. Given its detrital nature, the exact pressure at which these grains crystallized is unknown. Thus, calculating *T/P* conditions using detrital rutile Zr-in-rutile crystallization temperatures can generate an overestimation or underestimation and, consequently, elevating or decreasing the calculated *T/P* ratios. By this, the low *T/P* conditions calculated here can be higher than those estimated by Brown et al. (2020b). In this contribution, we follow the work of Pereira et al. (2021), that propose a filter to identify low *T/P* conditions using detrital rutile. In their work, all rutile grains with crystallization temperatures below 580 – 550 °C within the specified pressure range (0.8 – 1.2 GPa; rutile is not commonly stable below this pressure range) are taken as indicators of low *T/P* metamorphic conditions, for all types of rock composition. Herein, rutile-based *T/P* conditions were calculated based on rutile instability below 0.8 GPa – 1.2 GPa. To avoid overestimating *T/P* conditions, we chose to be conservative and use the minimum pressure at which rutile is stable (*i.e.*, 1.0 – 1.2 GPa). Therefore, all rutile grains with Zr-in-rutile crystallization temperatures below 550 – 580 °C are considered indicators of low *T/P* metamorphism in general (please refer to Pereira et al., 2021 for more details). Consequently, all detrital rutile grains with temperatures > 580 – 550 °C are considered indicators of intermediate/high *T/P* conditions. Literature data on age and composition are additionally compiled in Supplementary Material D.

3. Results

3.1. Detrital rutile record of the São Francisco Craton

Detrital rutile U-Pb data for the Espinhaço Supergroup sedimentary rocks (Tombador and Açuruá Formations) are mostly concordant to subconcordant (Fig. S3, Supplementary Material A), with most grains exhibiting only 1 to 5 % discordance, and the whole population being generally restricted to discordance < 10 % (Supplementary Material B). Primary U-Pb age peaks are recognized at *ca.* 2.1 Ga, 2.3 Ga, and 2.8 Ga for the Tombador Formation, and at *ca.* 2.0 Ga and 2.6 Ga for the Açuruá Formation (Fig. S3, Supplementary Material A). A secondary peak at *ca.* 3.6 Ga (early Archean) is also recognized for the Tombador Formation, and at *ca.* 2.8 Ga and 3.1 Ga (Mesoarchean) for the Açuruá Formation (Fig. S3, Supplementary Material A).

Based on their Nb and Cr contents, over 65 % of the detrital rutile grains are derived from metapelitic (*i.e.*, metafelsic) sources (74 and 73 grains for Açuruá and Tombador Formations, respectively), while over 20 % are derived from metamafic sources (37 and 23 grains for Açuruá and Tombador Formations, respectively) (Fig. 1). Temperatures calculated using the Zr-in-rutile geothermometer (1.0 and 1.2 GPa; Kohn, 2020) show that over 78 % of the grains have temperatures characteristic of the amphibolite/eclogite metamorphic facies (78 % of metapelitic grains for Açuruá and Tombador Formations), followed by granulite (19 % and 9 % of metapelitic grains for Açuruá and Tombador Formations, respectively) and greenschist/blueschist facies (3 % and 4 % of metapelitic grains for Açuruá and Tombador Formations, respectively) (Fig. 1). The abundances do not change significantly if only metamafic- or metapelitic-sourced grains are considered, nor do they vary significantly across the range of pressure estimates (Fig. 1). In the São Francisco Craton, 2.2 Ga eclogite (E-MORB protolith; 1.7 – 2.0 GPa and 600 – 700 °C; Chaves and Porcher, 2020) and 2.1 Ga lawsonite/barroisite-bearing (E-MORB) metagabbro (E-MORB protolith; 1.6 GPa and ~450 °C; Chaves, 2024) have recently been described, with ages matching subpopulations in our detrital rutile U-Pb ages spectra.

Rutile grains with calculated crystallization temperatures below 550 – 580 °C are considered a proxy for low *T/P* metamorphic conditions (Pereira et al., 2021). The evolution of *T/P* data with time, based just on metamorphic rutile (magmatic and hydrothermal rutile grains were excluded to generate LOWESS curves), from the sedimentary rocks of the Tombador and Açuruá formations is presented in Fig. 2 (all data) at both 1.0 GPa and 1.2 GPa. The results are presented individually in Figure S4. Metamorphic rutile grains are plotted in two groups: grains with Zr-in-rutile temperatures < 550 °C (*i.e.*, low *T/P* conditions), and > 550 °C (*i.e.*, intermediate to high *T/P* conditions). These data show that (Fig. 3): (i) low *T/P* rutile is evident since at least *ca.* 3.8 Ga within these formations; (ii) average *T/P* gradients are low throughout the Archean until a step-change at *ca.* 2.1 Ga, and (iii) the *T/P* data comprising a *ca.* 2.0 Ga age peak are more diverse than the older grains, and have higher average *T/P*. It is important to highlight that, even considering the Zr analytical uncertainties, the Zr-in-rutile temperature varies by ~ 10 %, without changing the observed pattern. Also, considering the Zr uncertainties together with elevated pressures (*i.e.*, 2.0 GPa), the observed pattern remains the same (Supplementary Material B).

4. Discussion

4.1. Metamorphic conditions through time and supercontinent cycle

The youngest well-defined detrital rutile U-Pb age peak is *ca.* 2.1 Ga, with only minor U-Pb peaks before the early Paleoproterozoic (Fig. 4A). Since rutile forms under low *T/P* conditions, these thermal gradients must have been established prior to *ca.* 2.1 Ga in the São Francisco-Congo Craton. The evolution of *T/P* conditions with time shows relatively low values before 2.1 Ga, when it increases significantly (Figs. 3

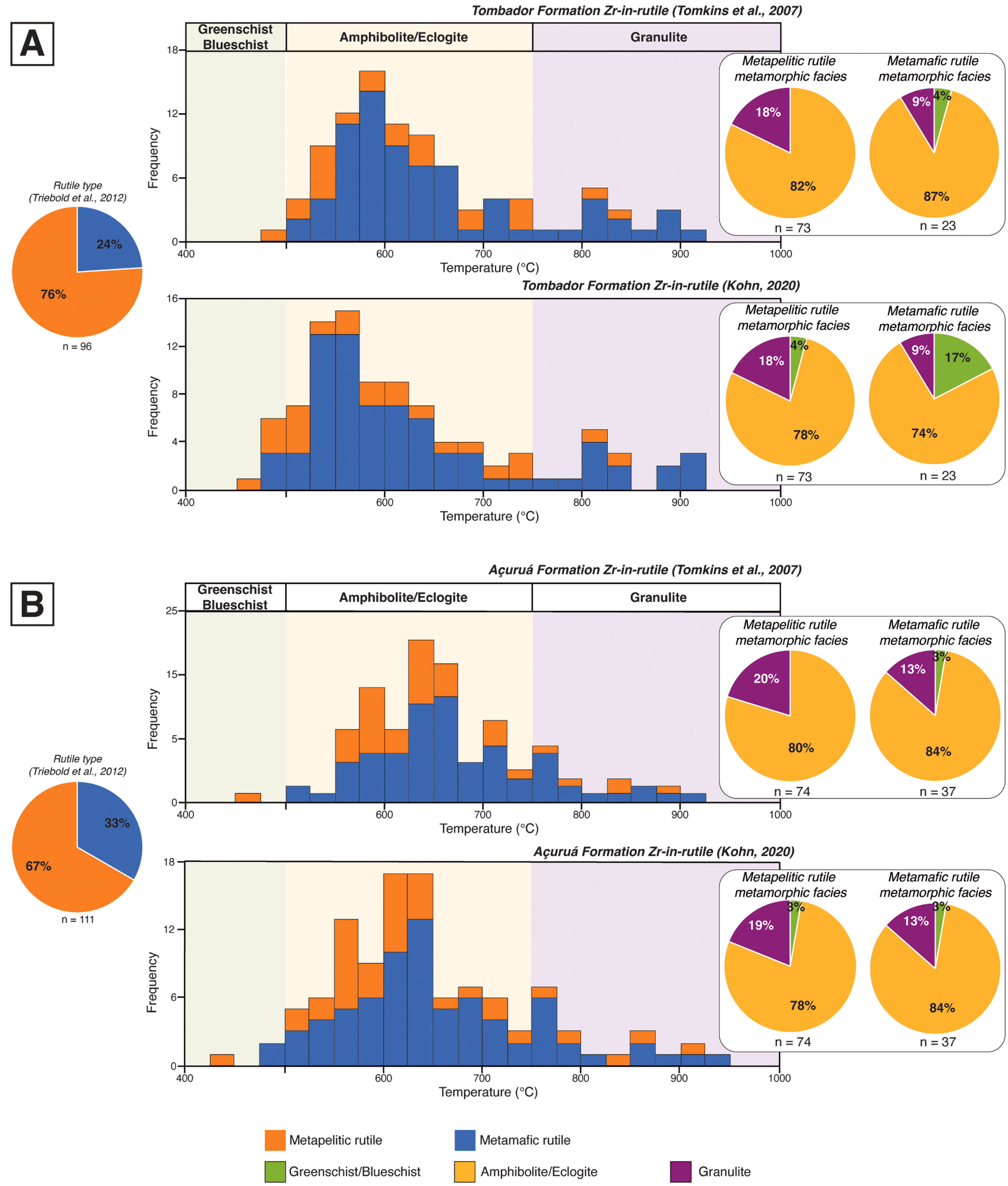

Fig. 1. Temperatures derived from the Zr-in-rutile geothermometer (at 1.2 GPa) for the (A) Tombador and (B) Açuruá Formations, Mesoproterozoic, Espinhaço Supergroup, using the calibrations of Tomkins et al. (2007) and Kohn (2020).

and 4A). Before 2.1 Ga, most rutile grains recorded T/P conditions between 400 °C/GPa and 550 °C/GPa, while from 1.8 – 2.1 Ga, the T/P gradient reached higher values of up to 750 °C/GPa (Fig. 4A).

This wide range of T/P conditions from 1.8 – 2.1 Ga may indicate the presence of paired metamorphic belts and is coincident with the formation of the Columbia supercontinent (Fig. 4A), with high, intermediate, and low T/P metamorphism recorded by detrital rutile and by the metamorphic bedrock record (Fig. 4B; Kuang et al., 2023; Brown et al., 2024; Volante and Kirscher, 2024). Paired metamorphism during the amalgamation of the supercontinent Nuna/Columbia was coincident with extensive Paleo- to Mesoproterozoic orogenesis (Liu et al., 2022; Volante and Kirscher, 2024), marked by elevated T/P gradients and high-temperature felsic magmatic activity in hot, thin, low-relief orogens (*e.g.*, Spencer et al., 2021; Roberts et al., 2023, and references

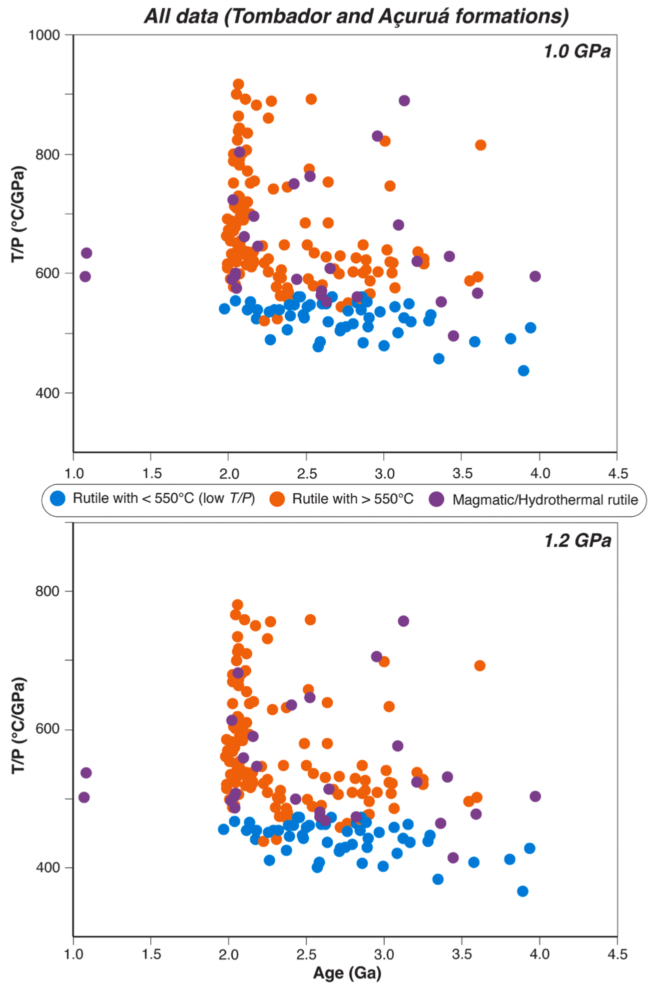

Fig. 2. Detrital rutile U-Pb ages *versus* T/P (°C/GPa) for all detrital rutile grains (Tombador and Açuruá Formations), assuming crystallization at 1.0 GPa and 1.2 GPa, respectively. Rutile with temperatures lower than 580 °C (green circles) are used as proxies for low T/P metamorphic conditions.

therein). The detrital rutile data also agrees, at least in part, with the evolution of the global bedrock T/P record of Brown et al. (2024) and Kuang et al. (2023) (Fig. 4B). The appearance of low T/P metamorphic conditions at *ca.* 2.1 Ga in the metamorphic bedrock record (Brown et al., 2024), is contemporaneous with high, intermediate, and low T/P conditions and in agreement with our rutile data. In contrast, during the Kenor period (2.7 – 2.5 Ga), only intermediate and high T/P conditions are found in the bedrock record (Fig. 4B; Brown et al., 2024). On the other hand, the Kuang et al. (2023) metamorphic bedrock dataset (Fig. 4B) shows low T/P conditions in the Archean (*ca.* 2.5 Ga and *ca.* 2.8 Ga), inferred low T/P zones at *ca.* 3.7 Ga, as well as intermediate T/P related to warm subduction. The detrital rutile in the Espinhaço Supergroup, sourced from the São Francisco-Congo Craton, records low T/P conditions long before 2.1 Ga (4.0 – 2.1 Ga), indicating the coexistence of high, intermediate, and low T/P conditions during the Archean (Fig. 4A). The Kenor period coincides with the sudden drop of the rutile LOWESS curve that is evident in the Tombador Formation detrital rutile (Fig. 3A). Interestingly, rutile grains with crystallization temperatures lower than 550 – 580 °C are present before 3.0 Ga. Low T/P rutile older than 3.0 Ga may indicate, for example, the operation of localized and short-lived subduction systems (*e.g.*, Brown et al., 2020a). The rutile T/P record also coincides with 3.0 – 2.5 Ga Neoarchean cratonization (Cawood et al., 2022; Gardiner et al., 2023), during which Archean blocks accreted along crustal-scale shear zones (*e.g.*, Ivan et al., 2022).

Zircon crystallization pressures using the Lu-Hf proxy (Moreira et al., 2023) were calculated using the Lu-Hf dataset from the Tombador and Açuruá Formations (Guadagnin et al., 2015a). The rutile T/P estimates and zircon Lu-Hf crystallization pressures (Fig. 4C) consistently show that: (i) before 3.0 Ga, the majority of detrital zircon grains have crystallization pressures < 1.0 GPa (shallower than the rutile stability field); (ii) between 3.0 – 2.5 Ga, there are a range of pressures with most values > 1.0 GPa, and (iii) during Columbia assembly (2.1 – 1.8 Ga), the highest pressures are reached and coinciding with the highest T/P values (up to 650 °C/GPa). Following Columbia formation and its associated orogenesis, zircon crystallization pressures decrease as expected (Fig. 4C). Both zircon crystallization pressures and rutile T/P estimates increase up to 2.1 Ga, reaching a maximum value during the Columbia supercontinent phase.

In the São Francisco-Congo Craton, high, intermediate, and low T/P metamorphic conditions coexisted between 3.0 – 2.5 Ga (Kenor period) and between 2.1 – 1.8 Ga (Columbia assembly), likely reflecting the formation of paired metamorphic belts linked to subduction-related metamorphism. The evidence for low T/P metamorphic conditions in the São Francisco-Congo Craton recorded by detrital rutile extend back in time the range of low T/P rutile data from that of Pereira et al. (2021) and others (Fig. 4D). Our data complement global rutile and bedrock T/P gradients (Fig. 4D), expanding the field of low T/P metamorphic conditions throughout the Archean, and older than previously described in the literature. Considering that, for example, mantle temperature modelling suggests steeper subduction beginning around 3.2 – 2.5 Ga (Sizova et al., 2010), HP-eclogite and UHT metamorphism starting at *ca.* 2.7 Ga (Brown, 2014), our rutile data can be: (i) related to crustal reworking at least since *ca.* 3.0 Ga, indicative of crustal amalgamation and accretion between Archean blocks; (ii) related to the production of localized and intermitted subduction environments (although in a hotter environment), (iii) related with localized high-pressure conditions along wide metamorphic belts (*e.g.*, Roberts and Spencer, 2015; Cerri et al., 2024). Potential evidence from the bedrock record for low T/P metamorphism before *ca.* 2.5 Ga can be found in North China (Ning et al., 2022), Bundelkhand Craton (India; Saha et al., 2011), and, inferred low T/P metamorphism in SW Greenland (Nutman et al., 2020) (Fig. 4B). The Pilbara (Australia) and Kaapvaal (Africa) cratons also have evidence of warm subduction zones (intermediate T/P gradients; Kuang et al., 2023; Fig. 4B).

4.2. Thermobarometric evolution and geodynamics

Although heavily debated (*e.g.*, Harrison, 2024), many workers agree on a geodynamic transition from stagnant-lid tectonics to mobile-lid tectonics likely occurring during the late Archean, during which time a global network of subduction zones would have become established (*e. g.*, Palin and Santosh, 2021; Brown and Johnson, 2022, and references therein). Our detrital rutile data for the São Francisco-Congo Craton indicate that high, intermediate, and low T/P gradients coexisted before *ca.* 2.5 Ga, with rutile indicative of low T/P gradients common at *ca.* 2.1 Ga. After 2.1 Ga, T/P values increase globally and remain high during the mid-Proterozoic, linked to geodynamic changes to hot, truncated, collisional orogens with subduction zones related to hot, wide, continental back-arcs (*e.g.*, Spencer et al., 2021; Roberts et al., 2023). Global compilations of rutile T/P data from detrital samples and the metamorphic bedrock record (Cerri et al., 2024) show three different tectonothermal styles with time: high to intermediate T/P prior to 2.1 – 1.8 Ga (before Columbia), higher T/P in the mid-Proterozoic, and a colder, modern-style, plate tectonics after Gondwana assembly. The Proterozoic marked a transition between two different subduction styles, from hot and shallow before the mid-Proterozoic to cold and steep in the Neoproterozoic (Roberts et al., 2022, and references therein).

The wide range in T/P gradients shown by the metamorphic rock record preceding the assembly of the supercontinent Columbia (2.1 – 1.8 Ga) supports interpretations of diverse orogenic events (accretionary

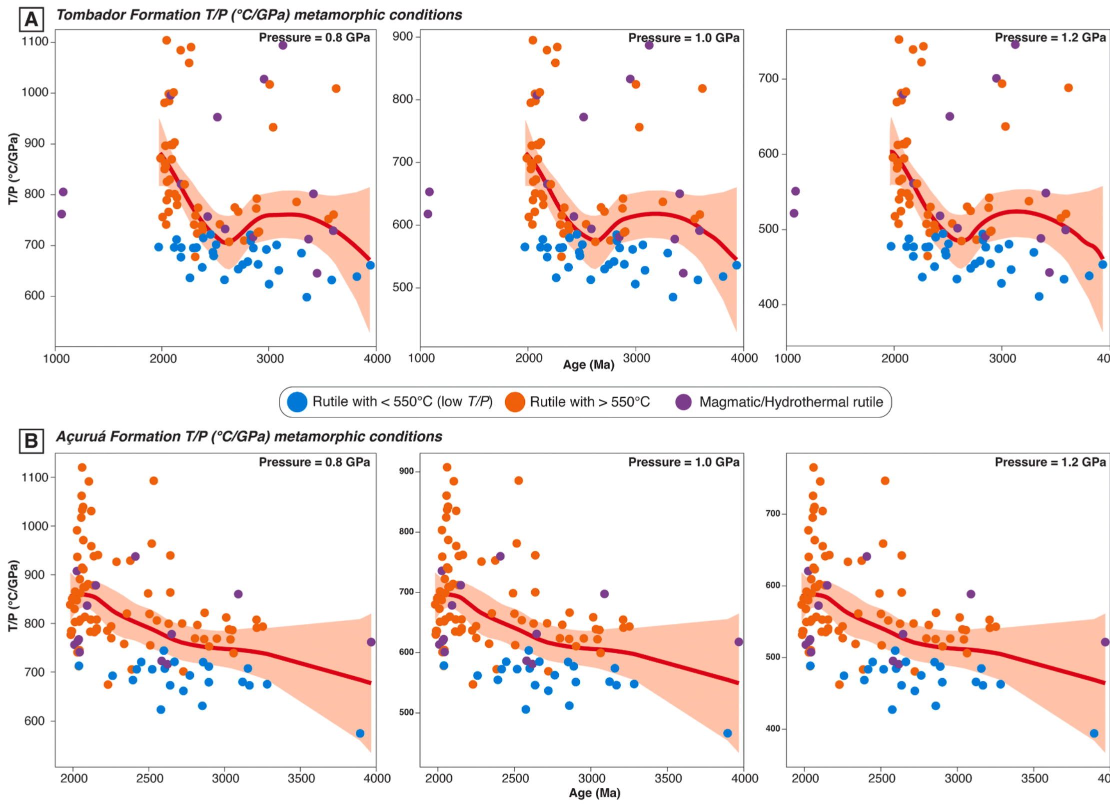

Fig. 3. Locally weighted scatterplot smoothing (LOWESS) curve (with 2σ uncertainties) of *T/P* with time using detrital rutile U-Pb ages and calculated Zr-in-rutile temperatures at 0.8 GPa, 1.0 GPa, and 1.2 GPa (only for metamorphic detrital rutile). (A) LOWESS curve for the Tombador Formation. (B) LOWESS curve for the Açuruá Formation.

and collisional orogens), which in turn mark the beginning of a global mantle overturn event, where both rutile-based and metamorphic bedrock record *T/P* conditions starts to increase (*e.g.*, Condie et al., 2022; Roberts et al., 2023). The metamorphic bedrock record related to the two-stage assembly of Columbia (2.0 – 1.8 Ga and 1.8 – 1.6 Ga; Volante and Kirscher, 2024) and the significance of low *T/P* in this period (emergence of bimodal metamorphic belts) may be related to the beginning of globally widespread and continuous mobile-lid tectonics. This would be closer to a modern-style plate tectonic regime, which led to the formation of Columbia, where a network of large-scale subduction zones started to operate (Volante and Kirscher, 2024). Our detrital rutile agrees with the exposed bedrock record, where high-pressure metamorphism started to operate since, at least, 3.2 – 3.0 Ga, becoming more diverse and frequent until reaching the full diversity around 2.1 – 1.8 Ga (*i.e.*, high, intermediate, and low *T/P* conditions coexisting).

Numerical modeling of early Earth tectonic regimes shows that both high and low *T/P* gradients can form in a non-plate tectonic setting (*e.g.*, Capitanio et al., 2019). Capitanio et al. (2019) show that high and low *T/P* conditions can coexist under an Archean non-plate tectonic regime: rocks can be translated and metamorphosed in a hot environment (lithospheric asymmetric drip) and later transported and overprinted by high-pressure (warm and subsequently cold) lithospheric downwelling (*e.g.*, Capitanio et al., 2019). In the latter setting, different metamorphic facies can potentially be accreted as paired metamorphic belts, and potentially, such paired metamorphic belts could even have emerged in the Hadean (Capitanio et al., 2019). This would support the presence of Archean (since *ca.* 4.0 Ga) low *T/P* rutile seen in our dataset, potentially implying convergent tectonics within a mobile lithospheric lid. Thereby, our detrital rutile data sustain mobility of lithospheric lids and sustained divergent and convergent tectonics (as proposed by Capitanio et al., 2019) in opposition to a stagnant- or sluggish-lid regime. Other models (Chowdhury et al., 2020) have interpreted low *T/P* gradients seen in the Archean/Hadean as representing peel-back convergent tectonics. However, in their modelling, few rock markers reached the low *T/P* conditions seen in our detrital rutile dataset since at least *ca.* 4.0 Ga. Other models have inferred episodic and localized subduction events or lid overturns, suggesting that a stagnant-lid regime was dominant in the Archean, but characterized by episodic and localized subduction and mobile-lid tectonics (*e.g.*, Sizova et al., 2015). Sagduction in the Archean can also be responsible for generating mid-pressure and high-temperature mineralogical assemblages similar to those produced in collisional settings (modeled low end with *ca.* 350 °C/GPa; 9 – 11 kbar and 450 – 550 °C); in this sense, similarities can be traced between petrological and thermobaric settings resulting from both sagduction and subduction (*e.g.*, François et al., 2014). Heat-pipe tectonic model numerical simulations, in which volcanism is responsible for surface heat transport, suggest that cold and thick lithosphere can be developed by volcanic eruptions advecting surface materials downwards (*e.g.*, Moore and Webb, 2013).

Regardless of the Archean tectonic regime (lithospheric downwelling, peel-back tectonics, sagduction, heat-pipe, or episodic and localized subduction), our detrital rutile data confirms that low *T/P* gradients and bimodal metamorphism were active since the Mesoarchean. Despite geochemical evidence for both subduction-related and non-subduction-related magmatism in the Archean, there are key lines of geological evidence for plate tectonics becoming gradually more dominant over localized and episodic subduction (Hawkesworth et al., 2024). These include lithospheric strength changes (*e.g.*, the onset of major sedimentary formation and brittle dyke swarms that both require a strong, cold crust), a change in structural style (from vertical dome-and-keel kinematics to lateral accretion), and a decrease in crustal growth rates.

Our detrital rutile data mark the progressive evolution towards mobile-lid tectonics or an early and primitive form of plate tectonics

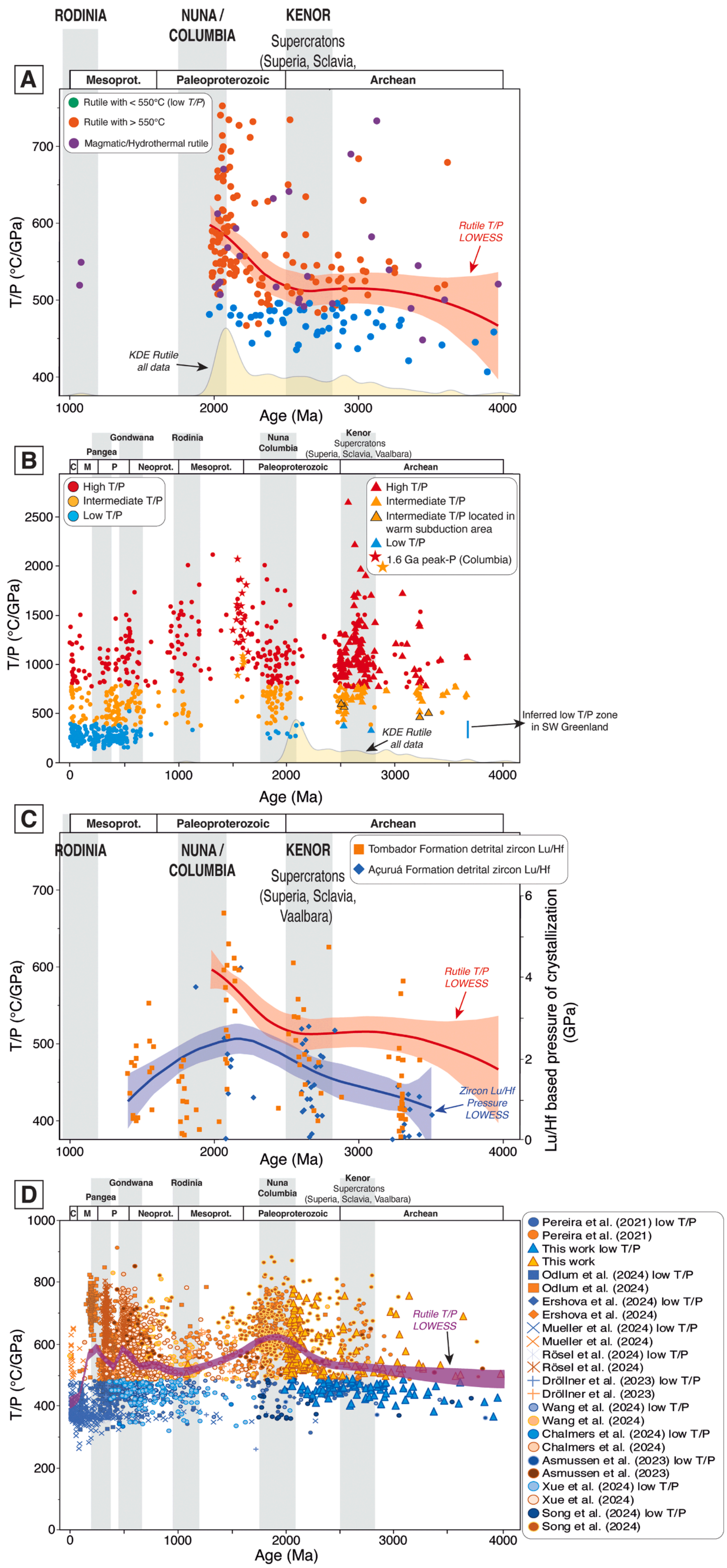

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Fig. 4. (A) T/P evolution with time for all detrital rutile data from the Espinhaço Supergroup, together with a kernel density estimate (KDE) plot of all detrital rutile U-Pb ages. (B) KDE of detrital rutile U-Pb ages (Açuruá and Tombador Formations) together with the bedrock metamorphic T/P compilation of Brown et al. (2024) (circles), Kuang et al. (2023) (triangles), and Volante and Kirscher (2024) rock record for the final assembly of Columbia at *ca.* 1.6 Ga (stars). Three metamorphic T/P gradients are identified: high T/P (red), intermediate T/P (orange), and low T/P (blue). (C) T/P conditions with time (LOWESS fit to detrital rutile data) together with detrital zircon Lu/Hf crystallization pressure estimates from Moreira et al. (2023). Detrital zircon Lu/Hf data for the Tombador and Açuruá Formations from Guadagnin et al. (2015a). (D) Rutile-based T/P gradients through time using this work data (triangles) and data compiled from the literature. Blue symbols indicate low T/P conditions (*i.e.*, rutile with $T < 550$–$580\ ^\circ$C), while orange symbols are related to intermediate/high T/P (*i.e.*, rutile with $T > 550$–$580\ ^\circ$C). (3681 rutile grains in total; Pereira et al., 2021 = 735 grains; Asmussen et al., 2023 = 101 grains; Dröllner et al., 2023 = 135 grains; Ershova et al., 2024 = 158 grains; Odlum et al., 2024 = 527 grains; Mueller et al., 2024 = 343 grains; Rösel et al., 2024 = 305 grains; Song et al., 2024 = 262 grains; Wang et al., 2024 = 292 grains; Chalmers et al., 2024 = 446 grains; Xue et al., 2024 = 377 grains). Data available on Supplementary Material D. *C* = Cenozoic, *M* = Mesozoic; *P* = Paleozoic; Mesoprot. = Mesoproterozoic.

with high-pressure tectonic settings since at least *ca.* 4.0 Ga, that ultimately culminated into the large-scale subduction systems of the Columbia supercontinent. Thus, the Mesoarchean to early Paleoproterozoic records early plate tectonic (mobile-lid) behavior in the São Francisco-Congo Craton (and possibly other cratons; Fig. 4B), rather than a transition from stagnant- or sluggish-lid to plate tectonics. This can be related to cold lithospheric downwelling, lithospheric lid mobility, and sustained convergence, transitioning towards a mobile-lid regime and plate tectonics. Also, different proxies for the evolution of continental crust suggest an increase in lithospheric strength in the Archean, possibly indicating that they were sufficiently strong to sustain plates and to be subducted (Hawkesworth et al., 2024). Our findings are consistent with new data from the North Atlantic Craton, which dates low T/P metamorphism (eclogite facies metamorphism) in the transition between the Mesoarchean and Neoarchean (Huang et al., 2026). These authors performed phase equilibrium modeling, Zr-in-rutile thermometry, and phengite barometry to constrain pressures of 1.5 – 2.5 GPa and temperatures of 580 – 660 °C (low T/P conditions of 230 – 440 °C/GPa). Therefore, our pre-Columbia rutile-based T/P metamorphic conditions suggest that subduction/convergence during the Archean may have operated similarly to that on the modern Earth or, at least, the presence of transient and localized subduction-like environments.

5. Conclusions

Our new detrital rutile analysis gives new insights into the secular evolution of metamorphism and plate tectonics. We identify the coexistence of high, intermediate, and low T/P conditions recorded by detrital rutile derived from São Francisco-Congo Craton since at least 3.2 – 3.0 Ga, with some detrital rutile grains older than *ca.* 3.5 Ga. The presence of low T/P metamorphism indicates the existence of high-pressure conditions since the Mesoarchean. We conclude that bimodal metamorphic belts (low and intermediate T/P conditions) existed since 3.2 – 3.0 Ga and evolved to truly paired metamorphic belts (high, intermediate, and low T/P conditions) up to and including Columbia assembly. Since the Mesoarchean, progressive installation of mobile-lid tectonics or an early/primitive plate tectonic culminated in the large-scale subduction network in the Columbia supercontinent assembly. Somehow, Archean tectonics could resemble present-day plate tectonics in a subduction-related-like environment, with high-pressure zones.

CRediT authorship contribution statement

Rodrigo I. Cerri: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Richard M. Palin:** Writing – review & editing, Writing – original draft, Validation. **David Chew:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Nick M.W. Roberts:** Writing – review & editing, Writing – original draft, Visualization, Validation. **Fabrício A. Caxito:** Writing – review & editing, Writing – original draft. **Renato Moraes:** Writing – review & editing, Writing – original draft. **George L. Luvizotto:** Writing – review & editing, Writing – original draft, Validation. **Silvia Volante:** Writing – review & editing, Writing – original draft, Validation. **Christopher Spencer:** Writing – review & editing, Writing – original draft, Visualization. **Claudio Riccomini:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known conflict of interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2026.119935.

Data availability

Data are available in the supplementary materials

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