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REPLY
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This article is a reply to a comment by Heilbron et al. (2020), https://doi.org/10.1029/2019TC005897.

Key Point:
- Data from Ribeira belt favor an intracontinental evolution

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Reply to Comment by Heilbron and Valeriano on "Tectono Metamorphic Evolution of the Central Ribeira Belt, Brazil: A Case of Late Neoproterozoic Intracontinental Orogeny and Flow of Partially Molten Deep Crust During the Assembly of West Gondwana"

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Abstract The exercise of paleogeographic/tectonic reconstruction of past orogenic belts is a complex task that includes the interpretation and integration of multi-technique approaches such as basin tectonics, structural geology, petrology, geochemistry, geochronology, and geodynamics. Proterozoic geologic records are fragmented and incomplete, which make efforts to reconstruct paleogeography and orogenic processes even more challenging. Therefore, for our understanding of the tectonic evolution of past orogenic systems to advance, it is essential that any existing model, including the ones proposed by Heilbron and Valeriano (2020, https://doi.org/10.1029/2019tc005897), are repeatedly exposed to debate and testing. In this reply we address the points raised by Heilbron and Valeriano in order to clarify the scientific foundations of our tectonic interpretation for one of the Neoproterozoic Brasiliano/Pan-African orogens in South America (the Central Ribeira Belt), presented in Meira, Garcia-Casco, Hyppolito, et al. (2019, https://doi.org/10.1029/2018TC004959). We also evaluate the proposed paleogeographic reconstructions for this part of West Gondwana and conclude that an intracontinental model better explains the currently available data and observations, including the space problem pointed out in recent publications, and that existing geochemical and geochronologic data by themselves are not conclusive with respect to an unequivocal tectonic environment.

1. Introduction

We appreciate Heilbron and Valeriano (2020) for giving us the opportunity to further clarify the tectonic implications of the data presented in Meira, Garcia-Casco, Hyppolito et al. (2019) and to discuss the different tectonic interpretations of these new data for the major Brasiliano/Pan-African Ribeira-Araçuaí-West Congo orogenic system, in particular in the context of recent papers that reevaluate the prevailing tectonic models for some Brasiliano/Pan-African orogens (Cavalcante et al., 2019; De Toni et al., 2020; Fossen et al., 2017, 2020; Konopásek et al., 2017, 2018, 2020; Meira et al., 2015; Meira, Garcia-Casco, Hyppolito et al. 2019; Meira, García-Casco, Juliani, et al., 2019; Oriolo et al., 2016, among others).

The Ribeira and Araçuaí belts are part of a broader Neoproterozoic orogenic system known as Mantiqueira Province (Figure 1; Almeida et al., 1981). This province comprises Archean to Paleoproterozoic crystalline inliers, Mesoproterozoic to Neoproterozoic metavolcanosedimentary sequences, voluminous Neoproterozoic granitoids, and fault-bounded Ediacaran-Cambrian volcanosedimentary basins in which all units were variably reworked during the Neoproterozoic Brasiliano/Pan-African orogeny (Alkmim et al., 2017; Almeida et al., 2010; Basei et al., 2018; Campanha & Sadowski, 1999; Campos Neto, 2000; Heilbron et al., 2017; Janasi et al., 2009; Silva et al., 2005; Vlach et al., 2011). The Mantiqueira Province is subdivided by an Archean/Paleoproterozoic inlier (Luis Alves and Curitiba massifs) into two major orogenic systems, the Dom Feliciano Belt, in the south, and the Ribeira-Araçuaí belts, in the north (Figure 1). The

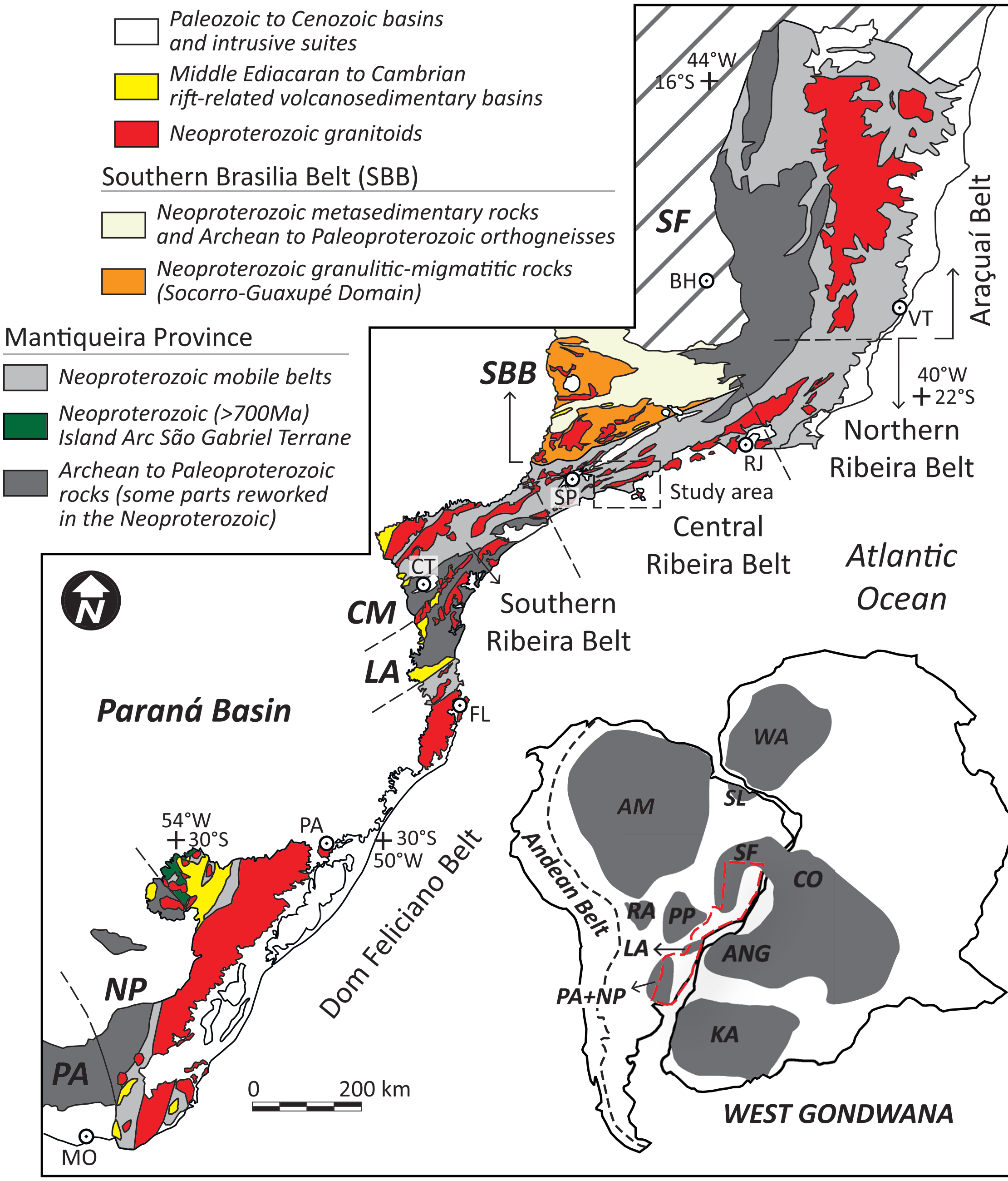

Figure 1. Tectonic map and main geologic units of the Mantiqueira Province. The inset shows the cratonic blocks of West Gondwana. Abbreviations: AM, Amazonia Craton; ANG, Angola Block; CM, Curitiba Massif; CO, Congo Craton; KA, Kalahari Craton; LA, Luis Alves Craton; NP, Nico Perez Block; PA, Pedra Alta Block; PP, Paranapanema Block; RA, Rio Apa Block; SBB, Southern Brasilia Belt; SF, São Francisco Craton; SL, São Luis Craton; WA, West Africa Craton. Cities: BH, Belo Horizonte; CT, Curitiba; FL, Florianópolis; MO, Montevideo; PA, Porto Alegre; RJ, Rio de Janeiro; SP, São Paulo; VT, Vitória.

Ribeira-Araçuaí belts form a continuous orogenic system that progressively changes its structural pattern from steep-dextral transpressional shear system in the Ribeira belt to thrust-dominated gently-dipping belt in the Araçuaí belt (Egydio-Silva et al., 2018; Silva et al., 2005). This progressive structural transition was controlled by the limits of the paleoplate and/or heterogeneous lithospheric strength within the São Francisco-Congo Craton (Egydio-Silva et al., 2018; Meira et al., 2015; Vauchez et al., 1994). Hence, the subdivisions of Ribeira and Araçuaí belts are defined by the progressive change in structural pattern and orogenic style, but the internal divisions in the Ribeira belt (Southern, Central and Northern Ribeira belts, Figure 1) are arbitrary and serve merely for descriptive purposes.

In this reply we reiterate why the data presented in Meira, Garcia-Casco, Hyppolito, et al. (2019) favor an intracontinental orogeny model for the evolution of the Central Ribeira Belt during the Ediacaran, rather than the subduction-related multiple collisional model (e.g., Heilbron et al., 2017; Heilbron & Valeriano, 2020). Considering the entire data set, including geochemical, petrologic, and geochronologic data, from the Mantiqueira Province and its African counterpart (West Congo and Kaoko belts), and the new tectonic models proposed recently, we revisit the tectonic model for this part of the West Gondwana.

2. Why Are the Costeiro and Embu Domains Key Areas to Test the Multiple Collisions Model?

The Embu and Costeiro domains in Central Ribeira Belt (study area in Figure 1) are located at the core of the Ribeira belt, in the region around São Paulo city (see Figure 1 of Meira, Garcia-Casco, Hyppolito, et al., 2019). The contact between the two domains is defined by a major dextral shear zone (Lancinha-Cubatão Shear Zone, see Figure 1 of Meira, Garcia-Casco, Hyppolito, et al., 2019), traditionally considered a major suture zone (e.g., Campos Neto & Figueiredo, 1995; Faleiros et al., 2011; Heilbron et al., 2013, 2017; Trouw et al., 2013). Campos Neto and Figueiredo (1995) were the first to propose that the "Serra do Mar Microplate" (or Costeiro Domain) had collided against the already accreted Embu "Terrane" (Embu Domain) at ca. 560–530 Ma. Later, several authors argued for multiple collisional events to assemble the Ribeira Belt (Heilbron et al., 2013, 2017; Heilbron & Machado, 2003; Peixoto et al., 2017; Trouw et al., 2013, among others). Two subsequent Ediacaran age collisions (between ca. 620 and 565 Ma) have been proposed to explain the geochemical and geochronologic data from the Central and Northern Ribeira belts (summarized in Heilbron et al., 2017), as cited by Heilbron and Valeriano (2020). In their tectonic model, the first collision (at ca. 620–595 Ma) would involve the accretion of continental arcs, including the Embu Domain, while the second collision (at ca. 605–565 Ma) is thought to be associated with accretion of the juvenile Rio Negro magmatic arc ("Oriental Terrane") onto the already amalgamated Paranapanema-São Francisco paleoplate (Heilbron et al., 2017). According to these authors, the Costeiro Domain (this study) would be part of the "Oriental Terrane" of Heilbron et al. (2017), and the major shear zone that separates the Costeiro and Embu domains (Lancinha-Cubatão Shear Zone or CTB—Central Tectonic Boundary of Heilbron et al., 2017) would represent a suture zone (see Figure 15.2 of Heilbron et al., 2017) associated with the second collisional event.

However, the data presented in Meira, Garcia-Casco, Hyppolito, et al. (2019) suggest a common tectonic evolution since at least ~650 Ma for both Embu and Costeiro domains. Deformation, metamorphic, and geochronologic constraints point to a single and continuous orogenic event including a collisional/thickening stage at ca. 640–600 Ma and a post-collisional phase (extensional/wrench tectonics) at ca. 600–560 Ma (Meira, Garcia-Casco, Hyppolito, et al., 2019). The older cluster of U-Pb SHRIMP ages from metamorphic zircons (~630–625 Ma) presented in Meira, Garcia-Casco, Hyppolito, et al. (2019) is coeval with the metamorphic ages of different rocks of the Southern Brasilia Belt (SBB), which have been estimated by detailed petrochronologic studies, including U-Pb LA-ICP-MS dating of zircon and titanite (Cioffi et al., 2019; Rocha et al., 2017, 2018; Tedeschi et al., 2017, 2018) and U-Th-Pb microprobe dating of monazite (Martins et al., 2009; Reno et al., 2012; Rocha et al., 2017). These results clearly correlate the chronology of metamorphism in both SBB and CRB (see also Duffles et al., 2016; Lobato et al., 2015; Trouw et al., 2013 for similar data within the Riberia Belt). Hence, the temporal correlation of initial collision in the SBB (~660–650 Ma) and the intracontinental response in the CRB is set by coeval orogenic thermal evolution, considering the time of ~20–30 Myr necessary for thermal maturation of a thickened orogen (e.g., England & Thompson, 1984; Jamieson et al., 2004). The tectonic evolution of the CRB, including the intracontinental thickening stage (~640–600 Ma) and the post-collisional phase (~600–560 Ma), is also in agreement with the chronology and evolution of the middle Ediacaran-early Cambrian Rift System of Southeastern South America (Almeida et al., 2010, 2012).

3. The Multi-Collision Model and the Space Problem

The multi-collision tectonic model for the Ribeira Belt (e.g., Heilbron et al., 2013, 2017; Trouw et al., 2013) and the subduction-collision model for the Araçuaí-West Congo Belt (e.g., Alkmim et al., 2006; Pedrosa-Soares et al., 2001) imply the existence of a large oceanic domain separating the São Francisco and Congo/Angola cratons (e.g., Amaral et al., 2020; Tupinambá et al., 2012). Therefore, the size of the ocean (the so-called "Adamastor ocean") is a critical aspect to test these models. Fossen et al. (2017) and Cavalcante et al. (2019) presented a critical discussion of the kinematic reconstruction of the Araçuaí belt and highlighted the space problems related to the magnitude of convergence and the timing of oceanic subduction in proposed subduction-collision models, all of which assume a confined setting of the "Adamastor ocean" (e.g., Alkmim et al., 2006; Richter et al., 2016). Fossen et al. (2020) further evaluated the fundamental implications of the subduction-collision model for the evolution of the Araçuaí belt and concluded that the available data are more consistent with evolution in a "hot" intracontinental orogeny.

Southwards in the Ribeira Belt, the multi-collision model would require a much larger ocean to accommodate more than 160 Myr of oceanic subduction and development of several magmatic arcs (~790–630 Ma, Tupinambá et al., 2012; ~860–605 Ma, Heilbron et al., 2017; Peixoto et al., 2017). Considering the geochronologic data on "pre-collisional" calc-alkaline magmatism in the Ribeira Belt (see Peixoto et al., 2017; Tupinambá et al., 2012) as a proxy for uninterrupted subduction processes and slow (2 cm/yr) to fast (10 cm/yr) subduction rates, the estimates of the width of the ocean would range from ~3,200 km to more than 16,000–20,000 km. These rough estimates imply an ocean width that cannot be accommodated in the confined setting shaped by the São Francisco-Congo-Angola paleoplate (e.g., Merdith et al., 2017; Fossen et al., 2020). To overcome this space problem, Heilbron et al. (2008) and Tupinambá et al. (2012) proposed the existence of a major transform limit or a so-called subduction-transform-edge-propagator (STEP) fault (Wortel et al., 2009) between the Angola Block and Congo Craton, represented by structures such as the Luanda Shear Zone. Such a tectonic scenario is unlikely if one considers the correlation of the metasedimentary belts of West Congo Belt (north of Luanda Shear Zone, Monié et al., 2012) and the western edge of the Angola Block (De Carvalho et al., 2000) and the crustal architecture of the Congo-Angola Craton (Jelsma et al., 2018; Thiéblemont et al., 2018). Furthermore, recent geochemical and geochronologic data from late Tonian bimodal magmatism and detrital zircon provenance studies from Cryogenian metasedimentary rocks in both Atlantic margins have also questioned the existence of a large Adamastor ocean in between the Ribeira and Dom Feliciano belts in Brazil and the Kaoko belt in Namibia (Konopásek et al., 2017, 2018, 2020; Meira, Garcia-Casco, Juliani, & Schorscher, 2019).

4. Neoproterozoic Calc-Alkaline Magmatism in the Ribeira-Araçuaí Orogenic System

The main arguments used to sustain the subduction-collision tectonic models for the Ribeira-Araçuaí orogenic system are based on geochemical and isotopic signatures of "pre-collisional" calc-alkaline magmatism (e.g., Corrales et al., 2020; Peixoto et al., 2017; Tedeschi et al., 2016; Tupinambá et al., 2012). Late Tonian to early Ediacaran calc-alkaline felsic rocks and tholeiitic to alkaline mafic rocks (Meira et al., 2015; Meira, Garcia-Casco, Juliani, & Schorscher, 2019; Passarelli et al., 2019; Peixoto et al., 2017; Tedeschi et al., 2016; Tupinambá et al., 2012 and references therein) that are usually included in this "pre-collisional" group can be subdivided chronologically into two groups: (i) an oldest late Tonian group and (ii) a younger late Cryogenian-early Ediacaran group. The late Tonian orthogneisses comprise mostly medium- to high-K calc-alkaline graintoids (Passarelli et al., 2019; Peixoto et al., 2017; Tupinambá et al., 2012), but anatectic peraluminous leucogranites also occur (Meira et al., 2015). Major and trace elements-based tectonic discriminant diagrams suggest arc-related signatures for these rocks (e.g., Peixoto et al., 2017; Tupinambá et al., 2012), but the geochemical signatures are heterogeneous along the belt (e.g., Passarelli et al., 2019). Nd and Sr isotopes signatures vary significantly from highly to poorly radiogenic, suggesting mixing of juvenile and older crustal sources (Passarelli et al., 2019; Peixoto et al., 2017; Tupinambá et al., 2012). The late Tonian metamafic rocks vary from tholeiitic to alkaline basalts with heterogeneous geochemical signatures, including MOR (normal and enriched), arc (island arc and back-arc), and within-plate affinities (Meira, Garcia-Casco, Juliani, & Schorscher, 2019; Peixoto et al., 2017). The available isotopic data for these metamafic rocks show highly radiogenic Nd and Sr signatures, suggesting juvenile mantle-derived magmatism (Peixoto et al., 2017 and references therein). The geochemical and isotopic variability recorded in both felsic and mafic magmatism along the Ribeira Belt suggests heterogeneous mixing processes of different crustal- and mantle-derived sources, which is compatible with the interpretation of extensional processes within the Rodinia supercontinent (Konopásek et al., 2018; Meira, Garcia-Casco, Juliani, & Schorscher, 2019; Passarelli et al., 2019). In this alternative interpretation, the arc-related geochemical signatures recorded in these rocks are associated with inheritance of the source rocks from older geodynamic processes (e.g., Bea et al., 2003; Konopásek et al., 2018) or are generated by magmatic interactions between mantle- and crustal-derived magmas unrelated to subduction settings (e.g., Arculus, 2003; Cambeses et al., 2015, 2019; Hawkesworth et al., 1995; Maurice et al., 2009; Zhang et al., 2011).

The late Cryogenian-early Ediacaran magmatism also includes orthogneisses and metamafic rocks with arc-related geochemical signatures and radiogenic to poorly radiogenic isotopic signatures (Corrales et al., 2020; Tedeschi et al., 2016; Tupinambá et al., 2012; and references therein). These geochemical and isotopic data suggest mixing of magmas from older and younger juvenile sources, indicating melting of old crustal and enriched and depleted mantle components. A common interpretation for these magmatic associations is the development of island arcs evolving to mature continental magmatic arc in the Ribeira Belt (e.g., Heilbron et al., 2008; Tupinambá et al., 2012) and a continental magmatic arc in the Araçuaí Belt (Corrales et al., 2020; Tedeschi et al., 2016; and references therein) active between 660 and 580 Ma. But an alternative interpretation that better fits with the confined orogenic scenario discussed above would involve the generation of widespread melting of lower to middle crust with mantle contributions, perhaps due to delamination processes driven by intracontinental orogeny as postulated by Gorczyk and Vogt (2015) and Gorczyk et al. (2015), intracontinental (Hawkesworth et al., 1995) or passive margin (Zhang et al., 2011), lithospheric thinning or magmatic underplating below the Moho (e.g., Cambeses et al., 2015, 2019).

5. The Ribeira-Araçuaí Orogen: A Hot Intracontinental Orogen

Intracontinental orogeny is a common geodynamic process consistent with plate tectonics and is recorded in both modern and ancient orogens throughout the planet (Aitken et al., 2013; Cunningham, 2005, 2013; Dyksterhuis & Muller, 2005; Raimondo et al., 2010, 2014; Walsh et al., 2015). Although many aspects regarding the evolution of these orogenic systems are still not fully understood, empirical studies in well-characterized examples (e.g., Tien Shan and Gobi-Altai mountains in central Asia, Cunningham, 2013; and Musgrave and Petermann orogens in central Australia, Gorczyk et al., 2015; Raimondo et al., 2009, 2010 and references therein) as well as fully coupled petrologic-thermomechanical numerical modeling (Gorczyk et al., 2015; Gorczyk & Vogt, 2015) have revealed different processes occurring in contractional settings far from plate boundaries. It is noteworthy that complex responses of intracontinental lithospheric deformation and associated magmatism and topographic evolution are controlled essentially by the rate of convergence and lateral heterogeneities of the continental lithosphere (Gorczyk & Vogt, 2015).

Contrary to the statement by Heilbron and Valeriano (2020), nappe systems and large-scale ductile lower crustal flow have been described in one of the best-characterized ancient intracontinental orogens (Petermann Orogen, Raimondo et al., 2009, 2010). Indeed, these authors highlighted that the whole deformational, petrologic, and geochronologic data available for the Petermann Orogen suggest a comparable evolutionary history between this intracontinental orogen and the world's foremost modern collisional orogen, the Himalayan-Tibet Orogen.

In the case of the Ribeira-Araçuaí orogenic system, the only orogenic phase that might be compared with the evolution of the Petermann Orogeny is the younger early Cambrian phase, known as the Búzios Orogeny (Monié et al., 2012; da Silva Schmitt et al., 2004). On the other hand, the main orogenic phases, including compressional and extensional/wrench tectonics, can be compared with the evolution of the long-lasting hot intracontinental orogeny in the Musgrave Province (e.g., Gorczyk et al., 2015; Walsh et al., 2015). Furthermore, several recent contributions have developed the hot orogeny hypothesis to explain the unique evolution of the Ribeira-Araçuaí orogenic system (Cavalcante et al., 2013, 2018, 2019; Fossen et al., 2017, 2020; Meira, Garcia-Casco, Hyppolito, et al., 2019; Mondou et al., 2012; Petitgirard et al., 2009; Vauchez et al., 2007, 2019; and references therein). The hot orogeny model seems to work well also as an intracontinental orogeny model (Cavalcante et al., 2019; Fossen et al., 2017, 2020; Meira, Garcia-Casco, Hyppolito, et al., 2019) in contraposition to the tectonic models involving subduction and subsequent arc-continent collision.

6. Conclusions

In their comment on Meira, Garcia-Casco, Hyppolito, et al. (2019), Heilbron and Valeriano argue that the available data for the Ribeira-Araçuaí orogenic system better support a multi-collision tectonic model.

However, Meira, Garcia-Casco, Hyppolito, et al. (2019) present abundant petrologic and geochronologic data that undoubtedly challenge, as reinforced in this reply, the chronology of events implied by the tectonic model included in their comment. In contrast to the statements by Heibron and Valeriano (2020), aspects of the models involving subduction-collision processes that are problematic have been sufficiently discussed in our paper (Meira, Garcia-Casco, Hyppolito, et al., 2019) and reinforced here. As discussed in this reply and other contributions (e.g., Cavalcante et al., 2019; Fossen et al., 2020; Konopásek et al., 2018, 2020; Meira, Garcia-Casco, Juliani, & Schorscher, 2019), these critical aspects include the space problem to accommodate large oceanic domains in the context of the semi-confined orogenic setting, the chronology of collisional events and spatial distribution of metamorphic ages along the different blocks (or the supposed "terranes"), and the interpretation of calc-alkaline magmatism as unequivocal evidence for subduction processes.

Intracontinental orogeny is an important geodynamic process compatible with other plate tectonic processes and is still underappreciated by the geologic community when ancient orogens are interpreted. Considering the important lateral heterogeneities in lithospheric rheology of modern continents and the known examples of modern and ancient intracontinental orogens, the role played by intracontinental orogeny in supercontinent assembly must be taken into account as a first-order component in models for supercontinental evolution. We emphasize that critical testing of models is a fundamental mechanism for our science to advance, and we encourage Heilbron and Valeriano and other workers in the Ribeira-Araçuaí orogenic system to take part in a timely reevaluation of current models, taking into account the abovementioned critical aspects of the subduction-collision models.

Data Availability Statement

Data are available through Meira, Garcia-Casco, Hyppolito, et al. (2019), Meira, Garcia-Casco, Juliani, and Schorscher (2019), and other cited papers.

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