

Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

Journal of South American Earth Sciences

journal homepage: www.elsevier.com/locate/jsames

Comment to “Neoproterozoic magmatic arc systems of the central Ribeira belt, SE-Brazil, in the context of the West-Gondwana pre-collisional history: A review”

Haakon Fossen^{a,*}, Vinicius T. Meira^b, Carolina Cavalcante^{c,d}, Jiří Konopásek^{d,e}, Vojtěch Janoušek^e

^a Museum of Natural History/Department of Earth Science, University of Bergen, Allégaten 41, 5007, Bergen, Norway

^b Instituto de Geociências, Universidade Estadual de Campinas, Campinas, Brazil

^c Departamento de Geologia, Universidade Federal do Paraná, Av. Cel. Francisco Heráclito dos Santos, 100, Centro Politécnico, Curitiba, PR, 81531-980, Brazil

^d Department of Geosciences, UiT – The Arctic University of Norway, Dramsveien 201, 9037, Tromsø, Norway

^e Czech Geological Survey, Klárov 3, 118 21, Praha 1, Czech Republic

ARTICLE INFO

Keywords:

Brasiliano orogeny
Ribeira belt
Intracontinental orogeny

1. Introduction

Heilbron et al. (2020) present a review of their model for the Ribeira section of the South Atlantic Neoproterozoic orogenic system (SANOS), which, together with its northward and southward continuation into the Araçuaí and Dom Feliciano belts, constitutes the Mantiqueira province on the Brazilian side of the South Atlantic Ocean. They lean mainly on geochemistry and related tectonic discrimination diagrams as they construct a ~340 m.y. long (860–520 Ma) history of multiple subduction, accretion and arc formation events. Their evolutionary history, which has become longer and more complicated over time, has recently been shown to have fundamental problems and is challenged by alternative interpretations (Meira et al., 2015, 2019a,b; Fossen et al., 2017, 2020; Cavalcante et al., 2019; Konopásek et al., 2020). Unfortunately, Heilbron et al. (2020) inadequately deal with these problems and alternative models, thereby missing the opportunity to present an open-minded and constructive discussion of the orogenic evolution of this interesting region.

The purpose of this short comment is to expose fundamental problems and implications of Heilbron et al.'s (2020) model. We mainly comment upon 1) the inconsistent and selective use of geochemical tectonic discrimination diagrams that makes the authors refuse alternative models; 2) their four additional arguments against an

intracontinental orogenic model; 3) the fundamental space problem and failures of the Heilbrons et al.'s (2020) kinematic model; 4) the chronology of the orogenic events in the central Ribeira belt that is incompatible with the timing of multiple terrane collisions implied by Heilbron et al.'s (2020) model, and 5) the geochronologic and stratigraphic constraints from the southern part of the orogenic system, which is a direct continuation of the Ribeira belt. All these data speak against the presence of a large Adamastor ocean.

2. Geochemical discrimination diagrams must be used with care

Major- and trace-element based diagrams for discrimination of geotectonic setting of igneous rocks (e.g., Pearce and Cann, 1973; Pearce and Norry, 1979; Pearce et al., 1977; Wood, 1980) have been extensively used (and abused) since they were first introduced in early 1970's. In contrast with the rather grim conclusions of Li et al. (2015), we consider such diagrams as useful projections that may often help to constrain the geodynamic setting of ancient magmatic suites, particularly of mafic composition.

Unfortunately, Heilbron et al. have not chosen a consistent set of diagrams that would facilitate systematic comparison between individual magmatic suites discussed in their work. Moreover, several of their diagrams are problematic, and interpreted in a too simplistic way,

* Corresponding author.

E-mail address: haakon.fossen@uib.no (H. Fossen).

<https://doi.org/10.1016/j.jsames.2020.103052>

Received 3 November 2020; Accepted 17 November 2020

Available online 25 November 2020

0895-9811/© 2020 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

sticking to just one of the possible interpretations and not discussing the alternatives or simply the entire spread of the data.

Nowadays the mostly abandoned diagram of Pearce et al. (1977) (see Fig. 7 in Heilbron et al., 2020) is based on the major elements Mg, Fe and Al that are fractionated by early magmatic ferromagnesian minerals (e. g., olivine, pyroxenes) and feldspars. Hence already the original authors caution against using their MgO–FeO–Al₂O₃ plot for intrusive rocks, restricting its scope solely to phenocrysts-free lavas. For this reason, this projection seems inappropriate in the present case.

The diagrams of Pearce et al. (1984), even though still popular in the granitoid community, also suffer from several shortcomings. In particular the Y + Nb vs. Rb diagram, employed also in the current work, discriminates (some of the possible) sources of granitic magmas but not necessarily the geodynamic setting of melting. For instance, syn-collisional granites are simply assumed to be exclusively strongly peraluminous, pelite-derived granites, while a variety of other sources may be involved, both metasedimentary and metaigneous. Similarly, Pearce with co-workers stressed that post-collisional granites cannot be easily discriminated, as they originate by interaction of magmas coming from variable crustal and mantle sources, depending, among other factors, on the crustal composition of the colliding plates and collision geometry (Pearce, 1996). The ambiguity associated with the discriminating power of the Y + Nb vs. Rb diagram has been documented by rigorous testing in dedicated work (Förster et al., 1997).

The high Ba–Sr contents of intermediate to acid magmatic rocks are taken by Heilbron et al. as evidence for the origin of these from subduction fluid-modified asthenospheric mantle. However, already the detailed discussion of the Ba–Rb–Sr ternary plot by El Bouseily and El Sokkary (1975) shows that such compositions are characteristic of (quartz) diorites, granodiorites and some of the granites. Indeed, one can propose that similarly low Rb/Ba and Rb/Sr ratios can also be produced by partial melting of plagioclase-rich sources, such as metagraywackes (Sylvester, 1998) or intermediate–basic metaigneous basement (e.g., Rapp and Watson, 1995). Granulitic, melt-depleted sources stripped of Rb by some earlier anatectic event represent another viable alternative.

In general, since magmas parental to individual igneous suites in variable geotectonic settings may form from variable sources at a range of P–T conditions, and further change composition through differentiation processes such as fractional crystallization/accumulation, magma mixing and/or crustal contamination, geotectonic discrimination diagrams do not give absolutely conclusive answers. This was emphasized by Konopásek et al. (2020), who concluded that the LILE enrichment and TNT (Ta, Nb, Ti) anomalies in NMORB- or Primitive Mantle normalized spider plots presented for many Neoproterozoic igneous rocks of the Mantiqueira province may represent a poor indicator of tectonic setting, in keeping with the general current knowledge that geochemical discrimination diagrams must always be used in combination with independent evidence to characterize tectonic environment (e.g., Bonin et al., 2020). Hence, when conflicting evidence appears, such as the space problem discussed below, geochemical data should not stop us from considering alternative geotectonic models. For the Ribeira belt, the space problem is extremely severe, and the alternative is a (predominantly) intracontinental model, as argued by Meira et al. (2019a, b) and Konopásek et al. (2020).

In addition to the geochemical data of igneous rocks, Heilbron et al.'s (2020) tectonic model relies on the occurrence of juvenile mafic magmatism to support their interpretation. Juvenile mafic magmatism is indeed a well-known characteristic of modern island arcs and active continental margins, both at the volcanic front and back-arc settings. However, such magmatism does not exclusively occur in these tectonic environments (see discussion in Meira et al., 2020). For example, post-collisional to late-orogenic setting with attending orogenic root delamination or rifting-related thinning could be geodynamic possibilities to account for the available geochemical and isotopic data for the Ribeira belt.

3. Their four arguments against intracontinental orogeny

The first two arguments of Heilbron et al. (2020) that add to the purely geochemical argument are the interpretation of some metasedimentary successions in the Ribeira belt as being fore-arc and back-arc basin deposits, respectively. Since this interpretation is born out of their own arc model, the argument is circular and will not be dealt with any further. The latter two points concern ultramafic pods (ophiolites) and medium to high-pressure metamorphism, and these are treated separately below.

3.1. Mafic pods and ophiolites

Well-preserved ophiolites that represent actual oceanic crust are typically considered as evidence in support of oceanic subduction. However, well-preserved ophiolites have not been found in the Mantiqueira province. Heilbron et al. (2020) mention ultramafic lenses, but their statement that “more complete ophiolitic rock assemblage is present in the Araçuaí belt” is misleading, as those weathered and poorly exposed (ultra)mafic metamorphic rocks do not present any ophiolite stratigraphy. These ultramafic lenses do not necessarily represent pieces of oceanic crust. They could for example have formed by rift-related magmatic underplating or hyperextension, and later incorporated into the orogen. This is the current interpretation of ultramafic lenses and associated metasediments in the Pyrenees, which is now understood as a modern intracontinental orogenic belt (Clerc et al., 2012; Tugend et al., 2014). As another example, mafic (metabasalt and metagabbro) and ultramafic rocks of the traditional Alpine ophiolites have been reinterpreted as representing crust/mantle transition at the base of hyperextended continental crust formed at late stages of rifting (Manatschal et al., 2006; Mohn et al., 2010). Ultramafic lenses also define a certain tectonostratigraphic level in the Scandinavian Caledonides, interpreted as exposed subcontinental mantle of hyperextended continental lithosphere and not oceanic lithosphere, and thus unrelated to the orogenic suture (Andersen et al., 2012). Hence, ultramafic and mafic rocks in orogenic belts that may appear, and even classify, as ophiolite fragments, must not be considered as unambiguous evidence of a pre-collisional ocean, let alone oceanic subduction.

3.2. P–T conditions

Heilbron et al. (2020) mention medium- to high-pressure metamorphism and evidence for a “paired metamorphic belt” in support for subduction. However, high-pressure/low-temperature metamorphism of the type characteristic for subduction is to our knowledge not documented of the Ribeira belt. Pressures from 6 to 8–9 kbar dominate the Ribeira–Araçuaí belt (e.g., Bento dos Santos et al., 2015; Cavalcante et al., 2019; Peixoto et al., 2018). In a recent comprehensive study of metamorphic conditions, Meira et al. (2019a) document peak P–T conditions at ~8 kbar and 600 °C around 620 Ma, becoming hotter under somewhat lower pressure around 570 Ma. These estimates fit a model where crustal thickening initiates before 620 Ma, followed by partial melting and crustal collapse (Cavalcante et al., 2013, 2018, 2019; Meira et al., 2019a). Hence, we do not see existing P–T data from this orogen as evidence for subduction and prolonged arc activity.

4. The space problem and their kinematic model

Heilbron et al. (2020) call for 340 million years of subduction. In 2008, Heilbron et al.'s orogenic model involved “only” 190 Ma of subduction (790–600 Ma), and they stated that “this scenario is not compatible with a paleogeography of a narrow ocean between the São Francisco–Congo and Angola paleocontinents during the Neoproterozoic”. This is a critical observation, because all models for the Ribeira belt implying subduction of an extensive oceanic domain are in conflict with the so far unquestioned connection (the “continental

bridge”) between the São Francisco and Congo cratonic foreland domains. More specifically, [Tupinambá et al. \(2012\)](#) estimated that an ocean of 1300–13,000 km width was subducted during these 190 Ma. With this subduction period being almost doubled (340 m.y.) in [Heilbron et al.’s \(2020\)](#) review, such an ocean must have been even larger, comparable in width to the Atlantic or the Pacific, according to their own reasoning. [Konopásek et al. \(2020\)](#) highlighted the fact that this represents a cardinal space problem that is incompatible with the confined setting of the Ribeira and Araçuaí belts. Together with independent evidence, they raised the question of whether or not the Adamastor ocean actually existed.

[Heilbron et al. \(2020\)](#), following [Heilbron et al. \(2008\)](#), claim that this fundamental space problem can be resolved by constructing a continental shear zone that cuts the entire Congo craton in two, from west to east and from top to bottom. Note that the term “craton” is here used rather loosely about the Congo–Tanzania–Bangweulu continental block as assembled prior to the Pan-African orogenic cycle, a block that experienced only mild and local Neoproterozoic reworking (e.g., [Collins and Pisarevsky, 2005](#)). In [Heilbron et al.’s](#) model, their hypothetical and highly speculative megashear acted as a continental transform zone that opened up a huge Neoproterozoic ocean, and then reversed to close the ocean again. This hypothetical shear zone (alternative 1 in [Fig. 1](#)) was suggested to run eastward from the Kwanza horst (Figs. 15 and 17 in [Heilbron et al., 2020](#), following [Heilbron et al., 2008](#) and [Tupinambá et al., 2012](#)), also referred to as the Malange block ([De Boorder, 1982](#)) and Malange uplift (e.g., [Hudec and Jackson, 2002](#)). The Kwanza horst ([Fig. 2](#)) is a Mesozoic horst whose location and orientation may have been controlled by older ductile basement fabrics of unknown age ([de Wit et al., 2008](#)). Older movement on the north side of this horst is sometimes referred to as dextral strike-slip, based on the change in strike of fabrics in the West Congo belt near the fault ([Fig. 2](#)). However, it is unclear whether this rotation reflects dextral movement along the Kwanza Horst lineament or simply orogenic folding; the West Congo orogenic fabrics show the opposite sense of rotation to the north, as part of a late Pan-African fold system. Hence, it is also possible to explain the map pattern as a result of orogenic folding and later (Mesozoic?) normal faulting. If the rotation is taken as evidence of dextral movement along

the horst, this deformation would be Cambrian, according to the geochronologic work by [Monié et al. \(2012\)](#), and therefore younger than the hypothetical megashear suggested by [Heilbron et al. \(2020\)](#).

The odd orientation of the Kwanza Horst may support the existence of a pre-Mesozoic basement structure along this western margin of the Congo craton. However, we find no geophysical or geologic data suggesting that it extends laterally across the entire craton as a fundamental Neoproterozoic structure. Instead, the Congo craton is almost unanimously presented as a single Neoproterozoic continental unit from the Central African belt to the Damara orogen in the south, unaffected by any dissecting Pan-African transcurrent deformation zone (e.g., [Unrug, 1993](#); [Carvalho et al., 2000](#); [Trompette, 2000](#); [Hanson, 2003](#); [Collins and Pisarevsky, 2005](#); [de Wit et al., 2008](#); [Li et al., 2008](#); [Begg et al., 2009](#); [Pérez-Gussinyé et al., 2009](#); [Evans et al., 2016](#); [Globig et al., 2016](#); [Salminen et al., 2018](#)). Such an E–W shear zone (called the Luanda shear zone by [Heilbron et al., 2008](#) and [Tupinambá et al., 2012](#)) would also have to offset the entire Congo craton, first with a sinistral sense during the opening and then with a dextral sense of shear during the closing of the oceanic domain.

The several thousand kilometers of displacement called for by [Heilbron et al. \(2020\)](#) is as large or larger as for any known continental strike-slip shear zone on this planet. It does not appear so large on [Heilbron et al.’s](#) [Fig. 17](#), because their cartoon-style figures do not show much of the oceanic crust that they call for. Their original version presented by [Heilbron et al. \(2008\)](#) shows this more clearly ([Fig. 3](#)) with Angola located completely east of their Congo craton, even though the duration of subduction (190 m.y.) was much less than the 340 m.y. presented by [Heilbron et al. \(2020\)](#). This model would also have severe implications for the eastern part of the Congo craton, where the N–S trending Mesoproterozoic Kibaran belt ([Fig. 1](#)) appears unaffected by E–W Neoproterozoic lateral movements.

We note that [Heilbron et al. \(2020\)](#) make a very brief reference to what [de Wit and Linol \(2015\)](#) name the Central Angola Mobile Belt. [Wit and Linol \(2015\)](#) consider this poorly described belt as a NW–SE trending Paleoproterozoic zone interpreted as an Eburnian (2.3–1.9 Ga) Himalaya-type collision or suture zone that includes some Archean fragments (reworked mainly around 2 Ga) and some 1.4 Ga Kibaran granites, with some evidence of Pan African deformation ([Linol pers. com., 2020](#)). The Pan-African reactivation indicated by [de Wit and Linol \(2015\)](#) appears to be limited, as we have not been able to find any description of such reactivation in the literature.

Altogether we find little or no geoscientific evidence for the existence of an enormous shear zone that completely separates the Congo craton into two parts during the Pan-African/Brasiliano orogenic history. Should it happen to exist, would it actually resolve the space problem of [Heilbron et al.’s \(2020\)](#) arc/subduction model? To evaluate this further, it is necessary to first accurately reconstruct the orogenic region to its pre-Atlantic situation ([Figs. 1 and 2](#)). The reconstruction allows us to render the CAMB alternative (“2” in [Fig. 1](#)) as kinematically unrealistic, because motion along this is incompatible with the well-documented dextral transpression in the Ribeira belt (e.g., [Vauchez et al., 1994](#)). The other proposal made by [Heilbron et al. \(2020\)](#), see their [Fig. 17](#)), indicated as “1” in [Fig. 1](#), could kinematically close an ocean to the south. However, the space problem would still exist north of the shear zone. Our reconstruction ([Fig. 2](#)) shows that a substantial part of the arc and arc-related units are located north of this hypothetical shear zone (note that [Fig. 17](#) in [Heilbron et al.](#) portrays this shear zone reaching the SF craton too far to the north). Hence such a shear zone provides no solution for the ocean subducted during the supposed 630–580 Ma arc activity in the Araçuaí belt. As demonstrated by [Fossen et al. \(2020\)](#), the arc/subduction model predicts an ocean on the order of 1000 km to have existed north of this hypothetical shear zone, which is quantitatively impossible given the undisputed confined setting of the Araçuaí–West Congo section: all of the convergence that can be produced in the Araçuaí–West Congo section is needed to invert the thin pre-orogenic rifted crust to thick orogenic crust ([Cavalcante et al., 2019](#); [Fossen et al.,](#)

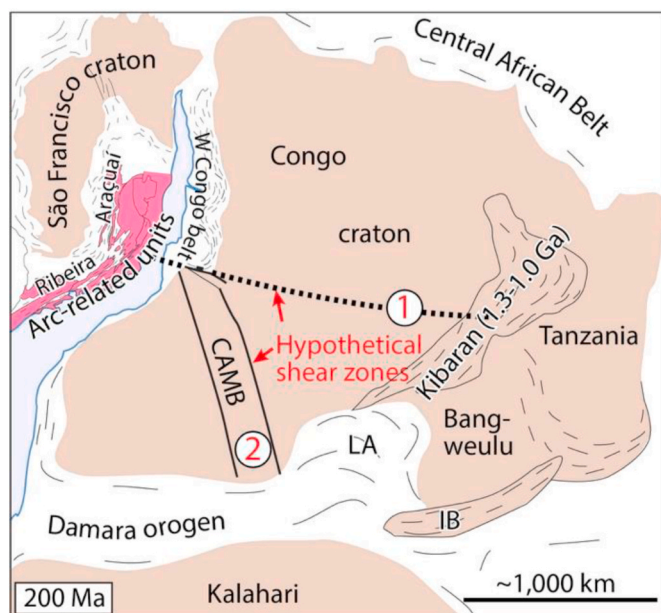


Fig. 1. Reconstruction to 200 Ma (pre-Atlantic rifting and opening) using GPlates and the [Seton et al. \(2012\)](#) model. IB, Irumide belt; LA, Lufilian arc. Arc-terranes of the arc-subduction model in the Ribeira–Araçuaí are marked in red (see [Fig. 2](#) for more details). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

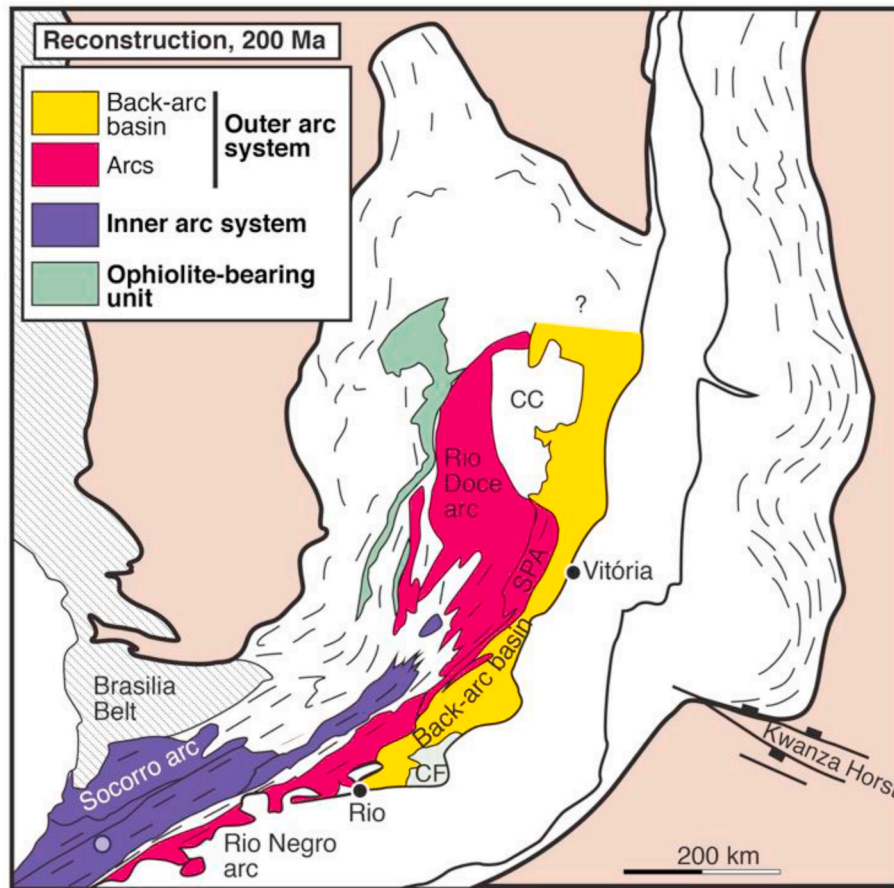


Fig. 2. Close-up of the reconstruction in Fig. 1, showing the arc systems as interpreted by Heilbron et al. (2020), extended into the Araçuaí based on Tedeschi et al. (2016).

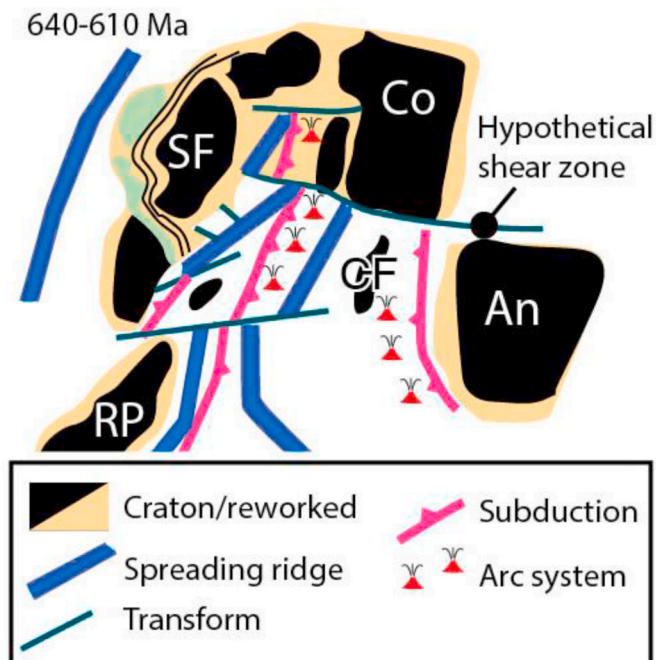


Fig. 3. Heilbron et al.'s kinematic model as redrawn from Heilbron et al. (2008) for 640–610 Ma, i.e. long after their subduction initiation at around 860 Ma. Note the enormous offset by the hypothetical shear zone. An, Angola; CF, Cabo Frio; Co, Congo; SF, RP, Rio de la Plata; São Francisco.

2020). Hence, the arc/subduction model must be replaced by an intra-continental tectonic model for the Araçuaí belt. This has fundamental consequences for the Ribeira belt, since the Rio Doce “arc” of the Araçuaí belt is part of the outer arc system of Heilbron et al. (2020) (Corrales et al., 2020).

5. Geochronologic constraints from the Ribeira belt

P-T-t-d data from metamorphic rocks from two different geological domains (Embu and Costeiro domains) in the central Ribeira belt, interpreted as two distinct terranes (Embu and Oriental terranes) in the multiple subduction model of Heilbron et al. (2020), indicate a ~80 m.y. long single and continuous orogenic event (~640–560 Ma) in both domains. This orogenic event consists of a crustal thickening stage (~640–600 Ma) followed by a late-orogenic stage (600–560 Ma) (Meira et al., 2019a, 2020). These data are incompatible with the interpretation of coeval development of two independent magmatic arc systems (Inner and Outer arc systems) earlier than 595 Ma, and late diachronous collisions from 595 to 520 Ma, as proposed by Heilbron et al. (2020).

6. Geochronologic and stratigraphic constraints from the Kaoko–Dom Feliciano–Gariep belt

Further south, the sedimentological data of Hoffman and Halverson (2008) from the Neoproterozoic sedimentary cover of the Congo Craton in Namibia show that active stretching of the pre-orogenic continental crust compatible with pre-breakup rifting ended in the period between the Sturtian and Marinoan global glaciations, i.e. between ca. 660–645 Ma (e.g. Rooney et al., 2015). Early orogenic evolution is recorded in the

relics of the hinterland domain in the Dom Feliciano Belt, which shows crustal thickening and thrust tectonics at ca. 650 Ma (Lenz et al., 2011; Martil et al., 2016; De Toni et al., 2020). Finally, orogenic flysch deposition on the African side of the orogenic system before the onset of Marinoan glaciation at ca. 645 Ma (Konopásek et al., 2017) shows that at this time, no large oceanic domain existed between the foreland domains of the Kaoko–Dom Feliciano–Gariép orogenic system. All these data suggest that there was only 10–15 m.y. available for ocean crust formation and its subsequent consumption by hypothetical subduction (Konopásek et al., 2020). This would have resulted in only a very narrow ocean, in stark contrast to the 340 m.y. of subduction and accretion proposed by Heilbron et al. (2020) for the adjoining Ribeira belt. It seems highly unlikely that the Ribeira section of a continuous orogenic system (SANOS) would be so fundamentally different from its northern (Araçuaí) and southern (Dom Feliciano) parts.

7. Conclusions

The evolutionary model presented by Heilbron et al. (2020) for the Ribeira belt, which involves a complicated 340 m.y. long history of subduction, multiple arc systems, microcontinents and collisions and final closure of a large oceanic environment as late as 520 Ma, has fundamental problems that were not sufficiently treated in their review:

- The space needed for their thousands of kilometers of oceanic environment is very difficult to accommodate.
- The suggestion to cut the Congo craton in two by a transform shear zone implies several 1000 km of displacement and would make it perhaps the largest shear zone in the world. There is no geologic or geophysical evidence for its existence, and we consider this as a hypothetical thought experiment only.
- Heilbron et al.'s (2020) "arc" environment and their Neoproterozoic Adamastor ocean continue northwards across their hypothetical shear zone and deep into the Araçuaí belt. Hence the shear zone model fails as a kinematic explanation of the arc/subduction model.
- Very limited time is available for oceanic development in the Kaoko–Dom Feliciano–Gariép belt to the south.
- Metamorphic and geochronologic data from the Ribeira belt fit intracontinental models.
- The available whole-rock geochemical data from the orogenic magmatic rocks are consistent with, but do not prove an arc/subduction tectonic setting. Such data allow for other geodynamic interpretations, including continental collision- and rift-related environments.

Any model applied to the Ribeira belt must deal with these problems and must be consistent with the tectonic evolution of adjacent parts of the orogenic system. Heilbron et al.'s (2020) complex arc/subduction model is further complicated by the unsolved and apparently unsurpassable space problem. It is therefore important that we explore simpler intracontinental orogenic models, where the voluminous magmatism is explained in other ways, rather than just complicating an existing problematic model.

Declaration of competing interest

No conflict of interest.

Acknowledgments

JK and VJ appreciate financial support by the Czech Science Foundation (grant no. 18-24281S). VM acknowledges Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq - Brazil) for financial support (grant no. 404767/2016-8).

References

- Andersen, T.B., Corfu, F., Labrousse, L., Osmundsen, P.T., 2012. Evidence for hyperextension along the pre-Caledonian margin of Baltica. *J. Geol. Soc.* 169, 601–612.
- Begg, G.C., Griffin, W.L., Natapov, L.M., O'Reilly, S.Y., Grand, S.P., O'Neill, C.J., Hronsky, J.M.A., Djomani, Y.P., Swain, C.J., Deen, T., Bowden, P., 2009. The lithospheric architecture of Africa: seismic tomography, mantle petrology, and tectonic evolution. *Geosphere* 5, 23–50.
- Bento dos Santos, T.M., Tassinari, C.C.G., Fonseca, P.E., 2015. Diachronic collision, slab break-off and long-term high thermal flux in the Brasiliano–Pan-African orogeny: implications for the geodynamic evolution of the Mantiqueira Province. *Precambrian Res.* 260, 1–22.
- Bonin, B., Janoušek, V., Moyen, J.-F., 2020. Chemical Variation, Modal Composition and Classification of Granitoids. Geological Society, London. Special Publications 491.
- Carvalho, H.d., Tassinari, C., Alves, P.H., Guimarães, I.P., Simões, L.S.A., 2000. Geochronological review of the Precambrian in western Angola: links with Brazil. *J. Afr. Earth Sci.* 31, 383–402.
- Cavalcante, G.C.G., Egydio-Silva, M., Vauchez, A., Camps, P., Oliveira, E., 2013. Strain distribution across a partially molten middle crust: insights from the AMS mapping of the Carlos Chagas Anatexite, Araçuaí belt (East Brazil). *J. Struct. Geol.* 55, 79–100.
- Cavalcante, C., Fossen, H., de Almeida, R.P., Hollanda, M.H.B.M., Egydio-Silva, M., 2019. Reviewing the puzzling intracontinental termination of the Araçuaí–West Congo orogenic belt and its implications for orogenic development. *Precambrian Res.* 322, 85–98.
- Cavalcante, C., Hollanda, M.H.B.M., Vauchez, A., Kawata, M., 2018. How long can the middle crust remain partially molten during orogeny? *Geology* 46, 839–842.
- Clerc, C., Lagabriele, Y., Neumaier, M., Reynaud, J.-Y., Saint Blanquat, M., 2012. Exhumation of subcontinental mantle rocks: evidence from ultramafic-bearing clastic deposits nearby the Lherz peridotite body, French Pyrenees. *Bull. Soc. géol. France* 183, 443–459.
- Collins, A.S., Pisarevsky, S.A., 2005. Amalgamating eastern Gondwana: the evolution of the circum-Indian orogens. *Earth Sci. Rev.* 71, 229–270.
- Corrales, F.F.P., Dussin, I.A., Heilbron, M., Bruno, H., Bersan, S., Valeriano, C.M., Pedrosa-Soares, A.C., Tedeschi, M., 2020. Coeval high Ba–Sr arc-related and OIB Neoproterozoic rocks linking pre-collisional magmatism of the Ribeira and Araçuaí orogenic belts, SE-Brazil. *Precambrian Res.* 337.
- De Boorder, H., 1982. Deep-reaching fracture zones in the crystalline basement surrounding the West Congo system and their control of mineralization in Angola and Gabon. *Geoexploration* 20, 259–273.
- De Toni, G.B., Bitencourt, M.F., Konopásek, J., Martini, A., de Andrade, P.H.S., Florisbal, L.M., de Campos, R.S., 2020. Transpressive strain partitioning between the major gercino shear zone and the tijuca fold belt, Dom Feliciano belt, Santa Catarina, Brazil. *J. Struct. Geol.* 136, 104058.
- de Wit, M.J., Linol, B., 2015. Precambrian basement of the Congo basin and its Flanking terrains. In: de Wit, M.J., Guillocheau, F., de Wit, M.C.J. (Eds.), *Geology and Resource Potential of the Congo Basin*. Springer, pp. 19–37. <https://doi.org/10.1007/978-3-642-29482-2>.
- de Wit, M.J., Stankiewicz, J., Reeves, C., 2008. Restoring Pan-African-Brasiliano connections: more Gondwana control, less Trans-Atlantic corruption, 294. Geological Society, London, Special Publications, pp. 399–412.
- El Bouseily, A.M., El Sokkary, A.A., 1975. The relation between Rb, Ba and Sr in granitic rocks. *Chem. Geol.* 16, 207–219.
- Evans, D.A.D., Trindade, R.I.F., Cotelani, E.L., D'Agrella-Filho, M.S., Heaman, L.M., Oliveira, E.P., Söderlund, U., Ernst, R.E., Smirnov, A.V., Salminen, J.M., 2016. Return to Rodinia? Moderate to high palaeolatitude of the São Francisco/Congo craton at 920 Ma. *Geol. Soc. Spec. Publ.* 424, 167–190.
- Förster, H.-J., Tischendorf, G., Trumbull, R.B., 1997. An evaluation of the Rb vs. (Y + Nb) discrimination diagram to infer tectonic setting of silicic igneous rocks. *Lithos* 40, 261–293.
- Fossen, H., Cavalcante, G.C., de Almeida, R.P., 2017. Hot versus cold orogenic behavior: comparing the Araçuaí–west Congo and the caledonian orogens. *Tectonics* 36. <https://doi.org/10.1002/2017tc004743>.
- Fossen, H., Cavalcante, C., Konopásek, J., Meira, V.T., de Paes Almeida, R., Hollanda, M.H.B.M., Trompette, R., 2020. A critical discussion of the subduction-collision model for the Neoproterozoic Araçuaí–West Congo orogen. *Precambrian Res.* 343, 105715.
- Globig, J., Fernández, M., Torne, M., Vergés, J., Robert, A., Faccenna, C., 2016. New insights into the crust and lithospheric mantle structure of Africa from elevation, geoid, and thermal analysis. *J. Geophys. Res.: Solid Earth* 121, 5389–5424.
- Hanson, R.E., 2003. Proterozoic geochronology and tectonic evolution of southern Africa. *Geol. Soc. Lond. Spec. Publ.* 206, 427–463.
- Heilbron, M., Valeriano, C.M., Tassinari, C.C.G., Almeida, J., Tupinamba, M., Siga, O., Trouw, R., 2008. Correlation of Neoproterozoic terranes between the Ribeira Belt, SE Brazil and its African counterpart: comparative tectonic evolution and open questions. *Geol. Soc. Lond. Spec. Publ.* 294, 211–237.
- Heilbron, M., de Morisson Valeriano, C., Peixoto, C., Tupinambá, M., Neubauer, F., Dussin, I., Corrales, F., Bruno, H., Lobato, M., Horta de Almeida, J.C., Guilherme do Eirado Silva, L., 2020. Neoproterozoic magmatic arc systems of the central Ribeira belt, SE-Brazil, in the context of the West-Gondwana pre-collisional history: a review. *J. S. Am. Earth Sci.* 103.
- Hoffman, P.F., Halverson, G.P., 2008. Otavi group of the western northern platform, the eastern Kaoko zone and the western northern margin zone. In: Miller, R.McG. (Ed.), *The Geology of Namibia*, vol. 2. Geol. Surv. Namibia, Windhoek, 13–69–13–136.

- Hudec, M.R., Jackson, M.P.A., 2002. Structural segmentation, inversion, and salt tectonics on a passive margin: evolution of the Inner Kwanza Basin, Angola. *Geol. Soc. Am. Bull.* 114, 1222–1244.
- Konopásek, J., Cavalcante, C., Fossen, H., Janoušek, V., 2020. Adamastor – an ocean that never existed? *Earth Sci. Rev.* 205, 103201.
- Konopásek, J., Hoffmann, K.H., Sláma, J., Košler, J., 2017. The onset of flysch sedimentation in the Kaoko belt (NW Namibia) – implications for the pre-collisional evolution of the kaoko–Dom Feliciano–garipe orogen. *Precambrian Res.* 298, 220–234.
- Lenz, C., Fernandes, L.A.D., McNaughton, N.J., Porcher, C.C., Masquelin, H., 2011. U–Pb SHRIMP ages for the cerro bori orthogneisses, Dom Feliciano belt in Uruguay: evidences of a ~800 Ma magmatic and ~650 Ma metamorphic event. *Precambrian Res.* 185, 149–163.
- Li, C., Arndt, N.T., Tang, Q., Ripley, E.M., 2015. Trace element indiscrimination diagrams. *Lithos* 232, 76–83.
- Li, Z.X., Bogdanova, S.V., Collins, A.S., Davidson, A., De Waele, B., Ernst, R.E., Fitzsimons, I.C.W., Fuck, R.A., Gladkochub, D.P., Jacobs, J., Karlstrom, K.E., Lu, S., Natapov, L.M., Pease, V., Pisarevsky, S.A., Thrane, K., Vernikovsky, V., 2008. Assembly, configuration, and break-up history of Rodinia: a synthesis. *Precambrian Res.* 160, 179–210.
- Manatschal, G., Engström, A., Desmurs, L., Schaltegger, U., Cosca, M., Müntener, O., Bernoulli, D., 2006. What is the tectono-metamorphic evolution of continental break-up: the example of the Tasna Ocean–Continent Transition. *J. Struct. Geol.* 28, 1849–1869.
- Martil, M.M.D., Bitencourt, M.F., Armstrong, R., Nardi, L.V.S., Pimentel, M.M., Schmitt, R.S., Florisbal, L.M., Chemale Jr., F., 2016. Cryogenian granulitic orthogneisses of the Várzea do Capivarita Complex thrust pile and implications for the timing of magmatic arc activity and continental collision in the southern Mantiqueira Province, Brazil. In: Martil, M.M.D. (Ed.), *O magmatismo de arco continental pré-colisional (790 Ma) e a reconstrução espaço-temporal do regime transpressivo (650 Ma) no complexo Várzea do Capivarita, sul da província Mantiqueira*. Unpublished PhD. thesis. Federal University of Rio Grande do Sul, Porto Alegre, pp. 73–112.
- Meira, V.T., Garcia-Casco, A., Juliani, C., Almeida, R.P., Schorscher, J.H.D., 2015. The role of intracontinental deformation in supercontinent assembly: insights from the Ribeira Belt, Southeastern Brazil (Neoproterozoic West Gondwana). *Terra. Nova* 27, 206–217.
- Meira, V.T., Garcia-Casco, A., Hyppolito, T., Juliani, C., Schorscher, J.H.D., 2019a. 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. *Tectonics* 38, 3182–3209.
- Meira, V.T., Garcia-Casco, A., Juliani, C., Schorscher, J.H.D., 2019b. Late tonian within-plate mafic magmatism and ediacaran partial melting and magmatism in the Costeiro domain, central Ribeira belt, Brazil. *Precambrian Res.* 334.
- Meira, V.T., Garcia-Casco, A., Hyppolito, T., Juliani, C., Schorscher, J.H.D., 2020. 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”. *Tectonics* 39. <https://doi.org/10.1029/2020TC006307> e2020TC006307.
- Mohn, G., Manatschal, G., Müntener, O., Beltrando, M., Masini, E., 2010. Unravelling the interaction between tectonic and sedimentary processes during lithospheric thinning in the Alpine Tethys margins. *Int. J. Earth Sci.* 99, 75–101.
- Monié, P., Bosch, D., Bruguier, O., Vauchez, A., Rolland, Y., Nsungani, P., Buta Neto, A., 2012. The late neoproterozoic/early palaeozoic evolution of the West Congo belt of NW Angola: geochronological (U–Pb and Ar–Ar) and petrostructural constraints. *Terra. Nova* 24, 238–247.
- Pearce, J.A., 1996. Sources and settings of granitic rocks. *Episodes* 19, 120–125.
- Pearce, J.A., Cann, J.R., 1973. Tectonic setting of basic volcanic rocks determined using trace element analyses. *Earth Planet Sci. Lett.* 19, 290–300.
- Pearce, J.A., Norry, M.J., 1979. Petrogenetic implications of Ti, Zr, Y, and Nb variations in volcanic rocks. *Contrib. Mineral. Petrol.* 69, 33–47.
- Pearce, J.A., Harris, N., Tindle, A.G., 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *J. Petrol.* 25, 956–983.
- Pearce, T.H., Gorman, B.E., Birkett, T.C., 1977. The relationship between major element geochemistry and tectonic environment of basic and intermediate volcanic rocks. *Earth Planet Sci. Lett.* 36, 121–132.
- Peixoto, E., Alkmim, F.F., Pedrosa-Soares, A., Lana, C., Chaves, A.O., 2018. Metamorphic record of collision and collapse in the Ediacaran–Cambrian Araçuaí orogen, SE–Brazil: insights from P–T pseudosections and monazite dating. *J. Metamorph. Geol.* 36, 147–172.
- Pérez-Gussinyé, M., Metois, M., Fernández, M., Vergés, J., Fulla, J., Lowry, A.R., 2009. Effective elastic thickness of Africa and its relationship to other proxies for lithospheric structure and surface tectonics. *Earth Planet Sci. Lett.* 287, 152–167.
- Rapp, Watson, 1995. Dehydration melting of metabasalt at 8–32 kbar: implications for continental growth and crust–mantle recycling. *Journal of Petrology* 36, 891–931.
- Rooney, A.D., Strauss, J.V., Brandon, A.D., Macdonald, F.A., 2015. A Cryogenian chronology: two long-lasting synchronous Neoproterozoic glaciations. *Geology* 43, 459–462.
- Salminen, J., Hanson, R., Evans, D.A.D., Gong, Z., Larson, T., Walker, O., Gumsley, A., Soderlund, U., Ernst, R., 2018. Direct Mesoproterozoic connection of the Congo and Kalahari cratons in proto-Africa: strange attractors across supercontinental cycles. *Geology* 46, 1011–1014.
- Seton, M., Müller, R.D., Zahirovic, S., Gaina, C., Torsvik, T., Shephard, G., Talsma, A., Gurnis, M., Turner, M., Maus, S., Chandler, M., 2012. Global continental and ocean basin reconstructions since 200 Ma. *Earth Sci. Rev.* 113, 212–270.
- Sylvester, P.J., 1998. Post-collisional strongly peraluminous granites. *Lithos* 45, 29–44.
- Tedeschi, M., Novo, T., Pedrosa-Soares, A.C., Dussin, I.A., Tassinari, C.C.G., Silva, L.C., Goncalves, L., Alkmim, F.F., Lana, C., Figueiredo, C., Dantas, E., Medeiros, S., Campos, C.D., Corrales, F., Heilbron, M., 2016. The Ediacaran Rio Doce magmatic arc revisited (Araçuaí–Ribeira orogenic system, SE Brazil). *J. S. Am. Earth Sci.* 68, 167–186.
- Trompette, R., 2000. Gondwana evolution; its assembly at around 600Ma. *C. R. Acad. Sci. Paris, Sciences de la Terre et des planètes* 330, 305–315.
- Tugend, J., Manatschal, G., Kuznir, N.J., Masini, E., Mohn, G., Thonon, I., 2014. Formation and deformation of hyperextended rift systems: insights from rift domain mapping in the Bay of Biscay–Pyrenees. *Tectonics* 33, 1239–1276.
- Tupinambá, M., Heilbron, M., Valeriano, C., Júnior, R.P., de Dios, F.B., Machado, N., Silva, L.G.d.E., de Almeida, J.C.H., 2012. Juvenile contribution of the neoproterozoic Rio negro magmatic arc (Ribeira belt, Brazil): implications for western Gondwana amalgamation. *Gondwana Res.* 21, 422–438.
- Unrug, R., 1993. The supercontinent cycle and Gondwanaland assembly: component cratons and the timing of suturing events. *J. Geodyn.* 16, 215–240.
- Vauchez, A., Tommasi, A., Egidio-Silva, M., 1994. Self-indentation of a heterogeneous continental lithosphere. *Geology* 22, 967–970.
- Wood, D.A., 1980. The application of a Th–Hf–Ta diagram to problems of tectonomagmatic classification and to establishing the nature of crustal contamination of basaltic lavas of the British Tertiary volcanic province. *Earth Planet Sci. Lett.* 50, 11–30.