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A critical discussion of the subduction-collision model for the Neoproterozoic Araçuaí-West Congo orogen

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ABSTRACT

The Neoproterozoic Araçuaí-West Congo orogen in Brazil and Congo represents a branch of the Brasiliano/Pan-African orogenic system that is considered to terminate northward into a confined cratonic environment defined by the horseshoe-shaped pre-Atlantic São Francisco-Congo craton. The prevailing interpretation is that this orogen formed as a result of 50 m.y. of subduction leading to a classical continent–continent collision. This subduction-collision model hinges on interpretation of 630–580 Ma granitoids in the core of the orogen as being arc-related, and of locally exposed mafic and ultramafic metamorphic rocks as being ophiolitic. We show that when tested beyond geochemical signature, the model has fundamental problems that cannot be accounted for. In particular, there is an insurmountable oceanic space problem in this confined setting that is overlooked in most of the current literature. There are also problems with subduction initiation, lack of unambiguous evidence for oceanic crust, no trace of any high-P metamorphism and the abrupt termination of an ocean with no realistic way to transfer the large amount of oceanic opening displacement and subsequent convergence required by the model. We conclude that the prevailing subduction-collision model cannot possibly work and argue that the existing data are more consistent with hot intracontinental orogeny. We stress the importance of building tectonic models on more than one type of data, making realistic restorations and palinspastic reconstructions, and taking into account modern geotectonic knowledge.

1. Introduction

It is generally accepted that the Neoproterozoic Araçuaí orogen in Brazil and its African counterpart, the West Congo orogen (Fig. 1), are an unusual example of termination of an orogenic belt into a cratonic environment (e.g., Porada, 1989; Brito Neves and Cordani, 1991; Pedrosa-Soares et al., 1998; Alkmim et al., 2006; De Wit et al., 2008; Gray et al., 2008; Stampfli et al., 2013; Barbosa and Barbosa, 2017; Degler et al., 2018). A major Tonian-Cryogenian rift system was shortened by convergent movements between the São Francisco and Congo cratons during the Brasiliano-Pan African orogeny (Porada, 1979, 1989), expressed by westward thrusting onto the São Francisco craton and eastward thrusting onto the Congo craton (Fig. 2). As the geosynclinal theory (Almeida et al., 1981) was replaced by modern plate tectonics (Porada, 1979), the idea of a proto-South Atlantic ocean (Adamastor ocean) south of the São Francisco craton was born (Porada, 1979; Hartnady et al., 1985). The Adamastor ocean was then extended northwards through the Ribeira (Heilbron and Machado, 2003; Heilbron et al., 2008) and into the Araçuaí orogen (Pedrosa-Soares et al., 1998).

Several workers have considered the amount of oceanic crust to be very limited if not absent in the Araçuaí-W Congo part of the orogenic system (e.g., Torquato and Cordani, 1981; Porada, 1989; Brito Neves and Cordani, 1991; Trompette, 1994, 1997; Kröner and Cordani, 2003; Meira et al., 2015a; Fossen et al., 2017; Cavalcante et al., 2019), consistent with its confined setting. The intracontinental (ensialic) model that these authors call for is simply that of extensive rift-related crustal thinning and basin formation, followed by convergent movements between the African (Congo craton) and Brazilian (São Francisco craton) sides. This model requires the formation of a wide Neoproterozoic rift system, possibly hyperextended, that was shortened to form the Araçuaí-West Congo orogen in the Ediacaran (Cavalcante et al., 2019).

Others favor a subduction-collision model involving extensive subduction of oceanic crust and related arc activity in the Araçuaí-West Congo orogen that ended with wholesale collisional orogenesis (e.g., Pedrosa-Soares et al., 1992, 1998; Amaral et al., 2020). In a key paper

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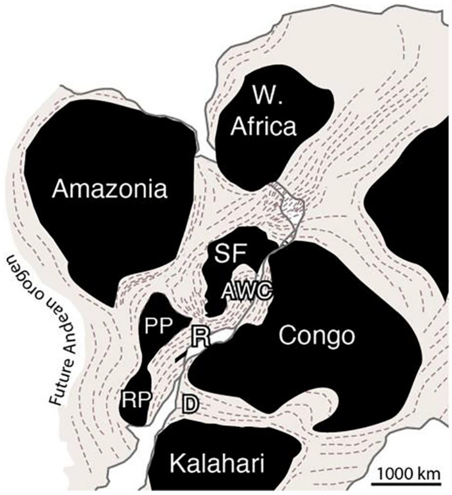

Fig. 1. The configuration of cratons (black) of W Gondwana and surrounding Neoproterozoic mobile belts. The Araçuaí-West Congo orogen (AWC) defines an embayment between the São Francisco (SF) and Congo cratons, and is generally described as a (semi)confined orogen. The challenge of the published subduction-collision model for this orogen is how to account for a ~1000 km wide ocean into this embayment and then eliminate this space during the Brasiliano/Pan-African orogeny. R: Ribeira belt, D: Damar belt, PP: Paranapanema craton, RP: Rio de la Plata craton.

by Pedrosa-Soares et al. (1998), outcrops of amphibolite and ultramafic rocks were interpreted as altered fragments of oceanic crust formed at ca. 816 Ma. In the same paper, large volumes of calc-alkaline granitoids in the internal part of the orogen were interpreted to represent a volcanic arc formed above an east-dipping subduction zone that was active from ca. 630 to 580 Ma. Since then, a large number of papers have been presented within the framework of this subduction-collision model (e.g., Pedrosa-Soares et al., 2001, 2011; Alkmim et al., 2006, 2017; Gonçalves et al., 2014, 2016, 2017; Gradim et al., 2014; Kuchenbecker et al., 2015; Peixoto et al., 2015; Richter et al., 2016; Tedeschi et al., 2016; Degler et al., 2017; Melo et al., 2017; Cutts et al., 2018; Novo et al., 2018; Serrano et al., 2018; Amaral et al., 2020; Corrales et al., 2020). The subduction-collision model is mainly based on tectonic discrimination diagrams that show that the geochemistry of granitoid rocks is consistent with arc magmatism. The purpose of this paper is to point out and discuss what we see as fundamentally problematic issues with the subduction-collision model that now dominates the literature, and demonstrate through reconstructions and kinematic considerations that this model is fundamentally incompatible with a confined orogenic setting, urging future workers to consider alternative models for this part of the Brasiliano/Pan-African orogenic system. As an alternative model, we suggest a hot intracontinental orogenic model that better explains the total body of data currently available from this interesting branch of the Brasiliano–Pan-African orogenic system.

2. The subduction-collision model and its geochemical foundation

The main stages of the subduction-collision model for the Araçuaí orogen (Pedrosa-Soares et al., 1998) (Fig. 3) are:

1) Formation of a rift system from ca. 940 Ma that developed into an ocean;
2) Oceanic spreading going on at 645 ± 10 Ma according to Amaral et al. (2020), who also suggest that oceanic spreading started around or after 676 ± 5 Ma;
3) Construction of a magmatic arc complex on the Congo craton continental margin in response to subduction of oceanic crust from ca. 630 to 580 Ma (Fig. 3a);
4) Closure of the ocean by continental collision, around 580 Ma (Fig. 3b);
5) Crustal thickening (rift inversion or "collision") from ca. 580 Ma (Fig. 3c).

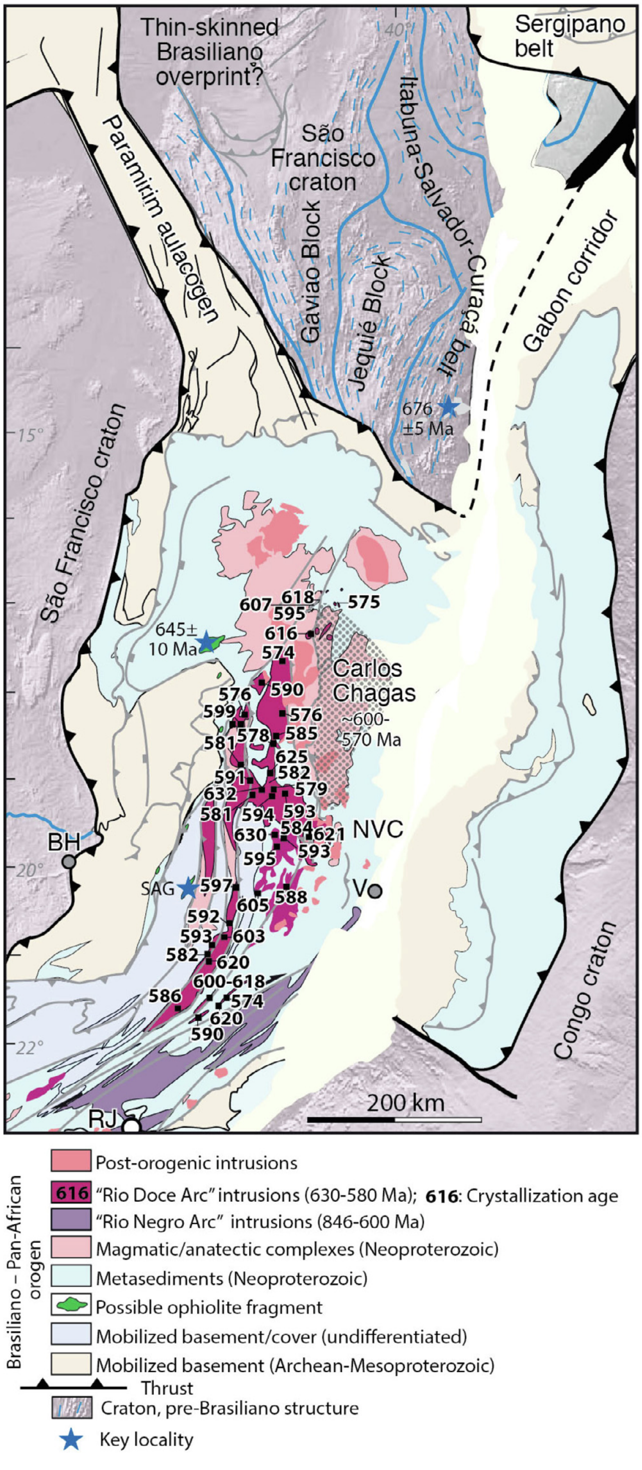

Fig. 2. Map of the Araçuaí-West Congo orogen and the northernmost part of the Ribeira belt (S of 21°N). Stars indicate localities discussed in the text. Crystallization ages (632–574 Ma) are U-Pb ages reported from the so-called pre-collisional "Rio Doce Arc" intrusions (as compiled by Tedeschi et al., 2016) (SAG: Santo Antônio do Grama locality). The hot syn-orogenic Carlos Chagas anatectic domain and its range of crystallization ages (~600–570 Ma; Cavalcante et al., 2018) are shown.

Constrained by geochronologic data, geochemical signature is the

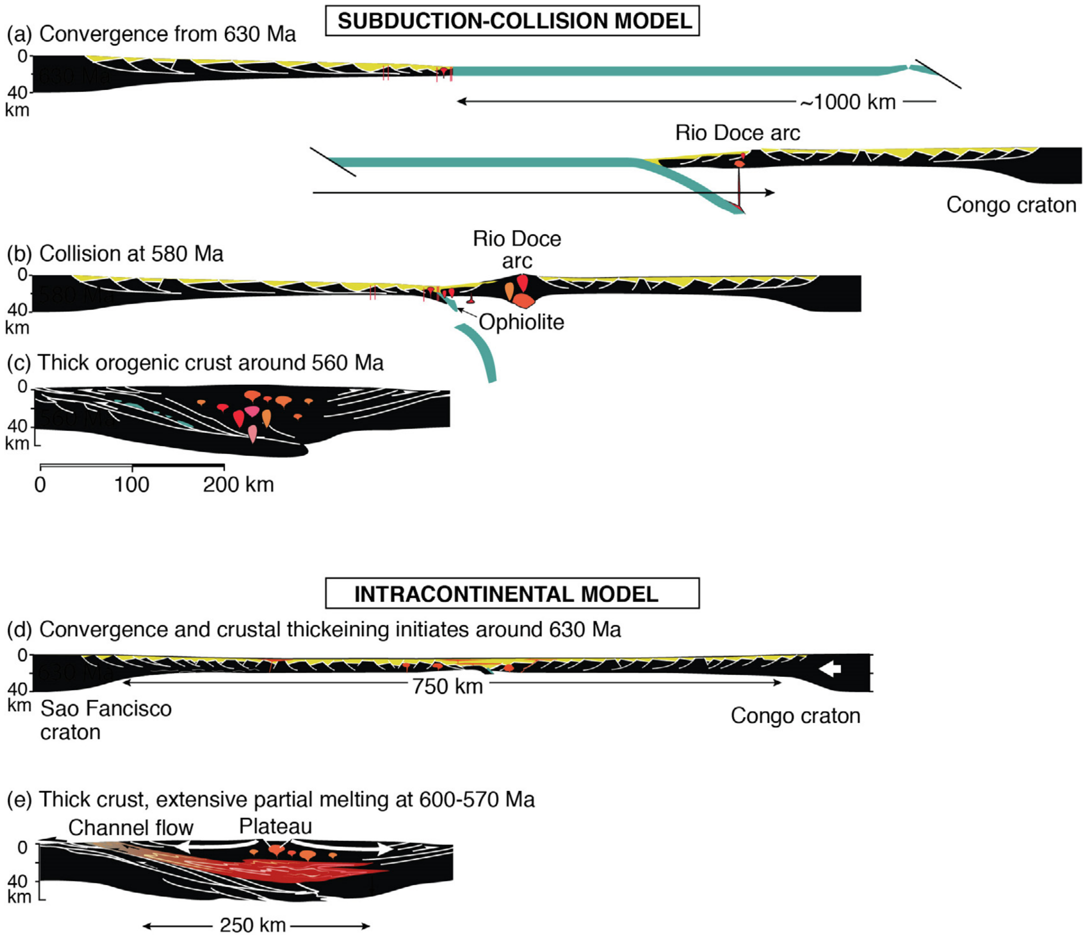

Fig. 3. The two different models discussed in the text. (a)–(c) shows the subduction-collision model, where arc development on the Congo continental margin occurs in response to oceanic subduction. This model requires a roughly 1000 km wide ocean to have existed at the onset of convergence. (d)-(e) shows a hot intracontinental orogeny model detailed in Cavalcante et al. (2018, 2019). The subduction-collision model implies around 1500 km of total convergence, which is incompatible with the confined orogenic setting, while the intracontinental model involves only ~500 km of convergence and is possible to combine with a semi-confined setting. No vertical exaggeration; note that (a) is split into two segments.

main argument put forward to suggest 50 m.y. of arc formation and related subduction of oceanic crust in the Araçuaí orogen. Geochemical data as presented by Pedrosa-Soares et al. (2001, 2011), Gonçalves et al. (2014, 2017), Gradim et al. (2014), Tedeschi et al. (2016), and Novo et al. (2018) appear to be consistent with arc magmatism on a continental margin between ca. 630 and 580 Ma. However, it is now generally agreed that tectonic discrimination diagrams should never be used in isolation, but always together with independent evidence (e.g., Bonin et al., 2020). This is particularly so with granitic rocks; certain geochemical data from mafic rocks can give safer indicators of tectonic regime (e.g., Mantle and Collins, 2008), although modification of the mantle during previous subduction events, or contamination by continental crust or lithosphere in continental-plate environments can cause significant variations (e.g., Konopásek et al., 2018; Xia and Li, 2019).

Indeed, geochemical signature is a prime indicator of melt source or chemical reservoir and not necessarily a fixed indication of tectonic setting. Hence, a given geochemical dataset can be interpreted in different ways (e.g., de Sigoyer et al., 2014; Couzinié et al., 2016, Moyen et al., 2017; Bonin et al., 2020). Since independent evidence speaks strongly against the widely published subduction-collision model for the Araçuaí orogen, these data need to be reevaluated in the context of the complete current body of knowledge. In particular, any tectonic interpretation should realistically consider the space problem involved in the confined setting of this orogen.

3. The orogenic space problem

The Araçuaí orogen is referred to as a “horseshoe-shaped confined orogen” (Amaral et al., 2020, following Pedrosa-Soares et al., 2001, 2008; Alkmim et al., 2006, 2017; Gonçalves et al., 2014) with unbroken cratonic crust in the west, north (the so-called continental bridge) and east (Degler et al., 2018 and references therein) (Fig. 1). The idea of an unbroken bridge between the São Francisco and Congo cratons relates largely to the absence of documented Neoproterozoic deformation on the Brazilian side where the youngest documented deformation is Paleoproterozoic (Barbosa & Barbosa, 2017). The Atlantic margin is narrow across the bridge, following the trend of the Itabuna-Salvador-Curaçá belt and its internal Paleoproterozoic structure (Fig. 2). The African margin has a wider part of no or poor crystalline bedrock exposure, and it may be possible to fit a close to 200 km wide orogenic branch along the Atlantic margin (the Gabon corridor in Fig. 2). This orogenic “corridor” adds the kinematic flexibility required to form the Brasiliano–Pan-African orogeny (Fossen et al., 2018; Cavalcante et al., 2019). However, the corridor is not wide enough to involve more than ~ 200 km of convergence at the most (Cavalcante et al., 2019), in agreement with paleomagnetic data (D’Agrella Filho et al., 1990, 2004; Renne et al., 1990). The other corridor transecting the craton, the inverted Paraminim aulacogen, involves considerably less shortening, judging from structural descriptions by Cruz and Alkmim (2006). Furthermore, any strike-slip motion on these corridors must also be limited, considering that they abut against Brasiliano-age orogenic belts to the north.

Obviously, this confined situation only allows for limited divergent (rift-related) and convergent (orogenic) tectonic movements. This was made clear in the so-called *nutcracker model* presented by Alkmim et al. (2006), but the implications of this model are not taken into consideration in papers that advocate or build on the subduction-collision model. For instance, Amaral et al. (2020) state that their results "provide robust evidence for the acting of typical Phanerozoic plate tectonics processes in a singular type of orogen (the confined orogen), ruling out models of solely intracontinental evolution, and shedding light in [*sic*] Precambrian orogenic processes", while the overwhelming space problem is not considered.

The space problem was discussed by Fossen et al. (2017) and in more detail by Cavalcante et al. (2019), and mainly concerns the ~ 50 m.y. of east-directed subduction strongly advocated in numerous recent papers (e.g., Pedrosa-Soares et al., 1992, 1998, 2001, 2011; Gonçalves et al., 2014, 2016, 2017; Gradim et al., 2014; Tedeschi et al., 2016; Alkmim et al., 2017; Amaral et al., 2020). This period of subduction would have consumed an ocean on the order of 1000 km wide, using a relatively slow subduction rate of 2 cm/y (Fig. 3), which is completely incompatible with the confined orogenic model. Furthermore, in addition to the shortening represented by consumption of oceanic crust, we know that the Araçuaí orogeny inverted the thinned crust of a continental rift system to a more than 60 km thick orogenic crust over a wide area. This inversion must have involved approximately 500 km of convergence between the Brazilian and African sides (Cavalcante et al., 2019), which is by itself in excess of what the nutcracker model of Alkmim et al. (2006) can produce, but possible if the bridge is "loosened" along the Gabon corridor (Fig. 2) (the softened nutcracker model of Cavalcante et al., 2019). Arguments in favor of a semi-confined setting are strong, as argued by Alkmim et al. (2006), thus the width of any oceanic crust in this system would have had to be extremely limited.

Calculating the size of the ocean implied by the subduction-collision model is somewhat more complicated if the central mid-ocean ridge (MOR) was still active during subduction. The complications affect the first stage of the subduction history, during which new oceanic crust forms during subduction. If the spreading rate equals the subduction rate, the size of the ocean remains constant during this period, while the MOR is moving toward the subduction zone. In the Araçuaí case, however, the system as a whole must have been convergent to initiate the subduction zone, close the ocean and form the orogen. Overall convergent settings can also produce a scenario involving concomitant back-arc spreading (upper-plate retreat; e.g., Heuret and Lallemand, 2005; Vanderhaeghe and Duchene, 2010), and thus two oceans. This would imply the opening of a new (back-arc) ocean on the African margin, of which there is no evidence. Hence, any subduction-collision model must involve a single-ocean model with a subduction rate that must have been higher than the contemporaneous spreading rate.

To quantify the effect of syn-convergent spreading, consider the situation where convergence between the São Francisco and Congo cratons generates a subduction zone along the Congo margin at 630 Ma (Fig. 4a). If we assume a spreading rate of 2 cm/y and a subduction rate of 3 cm/y, then over the first 25 m.y. until the MOR is subducted (Fig. 4a-b), we would have an effective convergence rate of 1 cm/y and an overall shortening of the system of 250 km. For the last 25 m.y. of subduction, there would be no active MOR, and thus no formation of new oceanic crust, and subduction would close the basin at 580 Ma according to Amaral et al. (2020). Using the same 3 cm/y subduction rate, we find that 750 km of ocean would have been subducted during the last 25 m.y. of arc activity (605–580 Ma), and we can calculate the width of the original ocean at ca. 1000 km. Different spreading and subduction rates would give different estimates, but for realistic rates, the estimated initial width of the ocean will be at least 750 km, which creates a major space problem in this confined setting.

In order to further illustrate the space problem generated by the subduction-collision model, we consider the map of the Araçuaí orogen (Fig. 5a, from Amaral et al., 2020) together with the most recent reconstruction of the situation during the suggested ocean floor spreading (Fig. 5b, from Alkmim et al., 2017). The reconstruction has moved the São Francisco craton away from Congo to give space to a wide ocean that propagated northward. There is no explanation of how this widening is accommodated, but the way it is presented requires significant stretching of the continental bridge (e.g. Fig. 2 in Richter et al., 2016). Furthermore, the subduction-collision model implies that the oceanic crust in this central part of the orogen was very wide, but abruptly disappears northwards (Fig. 5c) over a much shorter distance than what is seen for any modern and well-constrained paleo-ocean termination (Fig. 5e-f).

The newest and most detailed discussion of the "pre-collisional ocean" is provided by Amaral et al. (2020), who obtained a 645 ± 10 Ma age from a meta-plagiogranite vein that they claim to indicate "an epoch of oceanic crust generation in the Macaúbas basin". However, the single age presented indicates the time of intrusion of this particular magmatic vein, not an epoch. Their epoch-statement may relate to the 15 m.y. between this age and the initiation of orogenic magmatism (subduction according to their model) at ~ 630 Ma. That leaves a minimum of 15 m.y. of ocean crust generation before their Rio Doce arc is established. Amaral et al. further regard the amphibolites and ultramafic metamorphic rocks to represent "some of the youngest, hot and most buoyant oceanic crust formed in the northern Macaúbas basin", even though we show in Fig. 4 how their subduction-collision model probably would produce "hot oceanic crust" for another 40 m.y. until 605 Ma. They then regard the 676 ± 5 Ma age of a granite in the São Francisco basement to the north (Teixeira et al., 1997; see Fig. 2 for location) as a maximum age of their oceanic spreading, apparently rejecting the ca. 816 Ma age for ocean crust formation reported by Pedrosa-Soares et al. (1998). Hence, their model now involves up to 46 m.y. of ocean crust formation prior to their continent–continent collision. 46 million years would be consistent with the formation of an approximately 1000 km wide ocean.

4. Problems related to subduction initiation and MOR subduction

The subduction initiation itself requires attention, and since this subject to our knowledge is not mentioned in the Araçuaí-West Congo literature, we will also focus on this issue. In light of our present understanding of subduction initiation, it is not clear to us how a subduction zone would form in an ocean of the kind envisaged by for instance Gonçalves et al. (2016), Richter et al. (2016), Alkmim et al. (2017), and Amaral et al. (2020). From what we know from nature and numerical modeling, a long and deep lithospheric weakness seems to be required for both induced and spontaneous subduction to initiate (Stern and Gerya, 2018). In the more or less orthogonally opening ocean predicted by the nutcracker model of Alkmim et al. (2006), the mid-ocean ridge (MOR) and its transform faults would be the only lithospheric structures capable of subduction initiation. However, subduction-initiation along a MOR results in an oceanic arc, and not the continental arc situation called for by Pedrosa-Soares et al. (1998, 2001) and several later authors.

Another factor that is thought to promote subduction zone initiation is the presence of old and dense oceanic crust, i.e. a wide ocean (e.g., Doglioni et al., 2007). Initiation of a subduction zone along the Congo continental margin would create the subduction required for the subduction-collision model, producing an arc on the continental Congo margin (Fig. 4a-b). However, the dense oceanic crust that could have led to such initiation implies a large ocean of a size that is impossible to open and close within the (semi)confined setting of the Araçuaí-West Congo orogen. Interestingly, no clear example of passive margin collapse has been documented, although it can probably happen along a transform or shear margin (Stern and Gerya, 2018). Again, the more or less orthogonal opening of any ocean in the Araçuaí-West Congo belt is

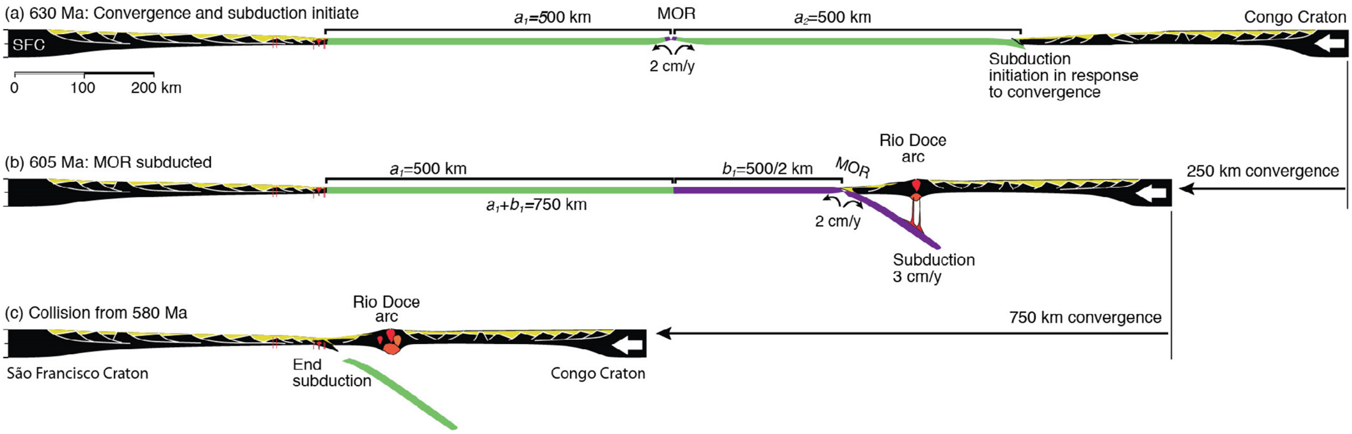

Fig. 4. Illustration of the oceanic development implied by the subduction-collision model, for the case of active seafloor spreading during subduction (no vertical exaggeration). In a convergent setting, the subduction rate (constant at 3 cm/y in this example) must exceed the spreading rate (2 cm/y). The evolution is then calculated based on 50 m.y. of subduction. (a) Onset of subduction. (b) Mid-ocean ridge (MOR) reaching the subduction zone. Oceanic crust formed from the onset of subduction to the subduction of the MOR is marked in violet, older oceanic crust in green. At this point (605 Ma), half of the ocean would be subducted. From then on, no new oceanic crust forms, and the ocean closes at 580 Ma (e.g., Amaral et al., 2020). A ca. 1000 km wide ocean (a) is created for the specified spreading/subduction rates. As a minimum estimate, ultra-slow spreading (1 cm/y) and slow subduction (2 cm/y) gives a 750 km wide ocean, while spreading at 2 cm/y and subduction at 4 cm/y gives a 1500 km wide ocean. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

unlikely to have formed a shear margin of the length and orientation required for subduction initiation. Any model that involves subduction and related arc formation in the Araçuaí-West Congo orogen should take subduction initiation into account.

In addition to the problem of subduction initiation, subduction of a MOR is part of the subduction-collision model (e.g., Alkmim et al., 2006, 2017; Gradim et al., 2014). The motivation for this interpretation is the need for a subduction-related heat source to explain extensive melting and magmatism in what is considered to be a back-arc environment. Metamorphism and magmatism in the upper plate can be caused by MOR subduction (e.g., Uyeda and Miyashiro, 1974), but generally in the forearc rather than in the back-arc. However, the MOR subduction model is unlikely for the following reason: if subduction initiated along the Congo continental margin, as postulated by the nutcracker model (Alkmim et al., 2006; Richter et al., 2016), the MOR would be oriented roughly parallel to the subduction zone. Hence, a trench-parallel ridge subduction scenario is used by advocates of the subduction-collision model to explain positive thermal anomalies in the "back-arc setting" of the Araçuaí-West Congo orogen (e.g., Gradim et al., 2014). However, geodynamic thermo-mechanical numerical models show that any attempt to subduct a young and buoyant MOR lithosphere in such a setting would most likely fail. Instead, slab detachment would occur, and subduction will terminate (Burkett and Billen, 2009, 2010; Quevedo et al., 2013). That would correspond to the situation shown in Fig. 4b, at a point when half of the ocean still remains. A critical angle of around 60° between the MOR axis and the trench seems to control whether a slab will detach to form a window or keep the subduction active (Quevedo et al., 2013); a low angle could produce a transform system similar to the current San Andreas system, for which there is no evidence. In any event, a MOR subduction model would not be able to explain more than a fraction of the extensive time interval of melting and magmatism in the core of the Araçuaí belt.

5. A southward propagating ocean pinned in the north?

In an attempt to put the ophiolite interpretation into a larger context, Amaral et al. (2020) make use of an unpublished ~ 600 Ma age (Queiroga, 2010) from an amphibolite locality far south in the Araçuaí orogen (Santo Antônio do Grama *ortho*-amphibolites or SAG in Fig. 2) as evidence of younger oceanic crust. This interpretation introduces another problem, because at 600 Ma, their Rio Doce arc and related subduction had already been going on for 30 m.y., and we are getting close to the inferred timing of collision (580 Ma). In this setting, at a time when the mid-ocean ridge would have been subducted, new oceanic crust could only form in the back-arc environment, east of the arc itself. In fact, the majority of preserved ophiolites in the world are related to back-arc processes (Furnes et al., 2014). However, in the Araçuaí orogen there are no indications of such supra-subduction ophiolites, and no hint of possible ophiolitic rocks within, or east of, the so-called Rio Doce arc. Furthermore, the SAG is located on the "wrong" (west) side of their suture. Hence there is a conceptual problem with the model, given the age of the mafic rocks and their structural setting.

In an attempt to resolve this problem, Amaral et al. (2020) conclude that "the oceanic opening in the Macaúbas basin would start from north to south". This idea is opposite to the previously published model, which suggests northward propagation of the ocean (Fig. 5b; Alkmim et al., 2017). The model becomes even more problematic into the Ribeira belt, where oceanic crust is believed to have formed much earlier. More specifically, the major Rio Negro complex (or "arc"), which shares similarities with the Rio Doce "arc" in the Araçuaí orogen, is now interpreted by some as an arc complex that was active from 790 to 600 (Tupinambá et al., 2012) or 840 to 605 Ma (Heilbron et al., 2017; Peixoto et al., 2017). At this scale, it seems clear that the ocean, if it ever existed, would have propagated from the south. We note that the suggested 235 m.y. of subduction of oceanic crust in the Ribeira belt implies an enormous pre-collisional ocean (Heilbron and Machado, 2003). Its width was estimated to several thousands of kilometers by Tupinambá et al. (2012), using the same line of argument that we used above for the width of a theoretical Araçuaí ocean. The space problem is, in other words, overwhelming also in the Ribeira part of the orogenic system, which will not be discussed further here (see Meira et al., 2019, for an alternative interpretation). We conclude that the model involving unidirectional southward propagation of an ocean in the Araçuaí region would be a most unusual and unlikely scenario. We also emphasize that these problems arise as a consequence of interpreting the amphibolitic and associated ultramafic rocks in the Araçuaí orogen as ophiolitic and interpreting the two ages (645 and 600 Ma) as times of ocean floor spreading.

Regardless of propagation directions, the ocean as portrayed by Amaral et al. (2020) must have been very wide all the way to the latitude of the Ribeirão da Folha site, because the associated Rio Doce "arc" to the east shows long activity also in its northern part (see ages

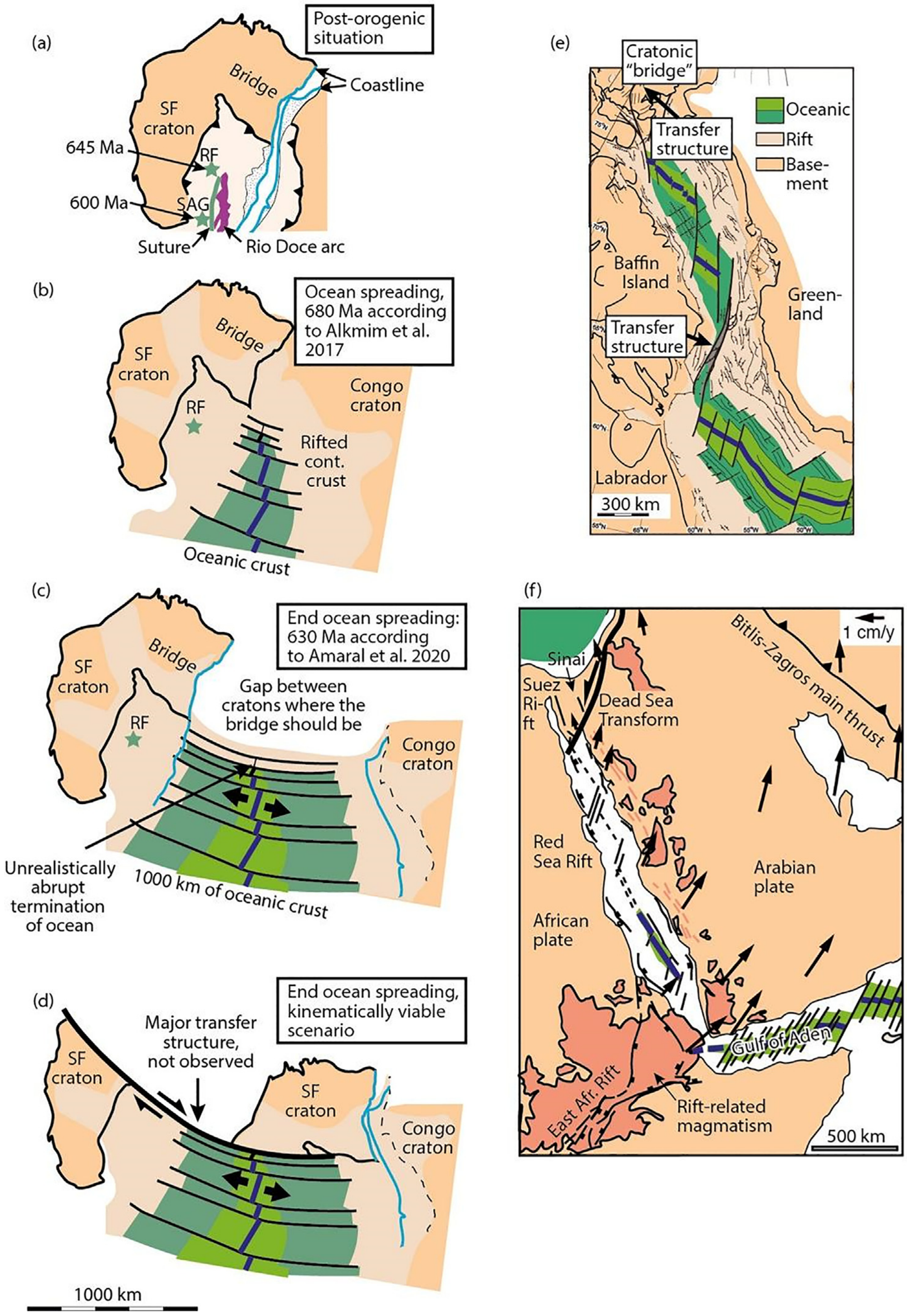

Fig. 5. Illustration of the space problem, kinematic challenges and unrealistic changes in ocean width associated with the subduction-collision model. (a) the São Francisco – Congo cratons in the Paleozoic, before the opening of the South Atlantic Ocean. The "Bridge" is generally considered to have been unbroken throughout the Proterozoic and Paleozoic. (b) The formation of oceanic crust, as envisaged by Alkmim et al. (2017). (c) Insertion of a 1000 km wide ocean to illustrate the consequence of 50 m.y. of subduction. In this scenario, the bridge would be torn apart and the continents separated by hundreds of kilometers, which we know was not the case. Also note the unrealistically abrupt termination of the oceanic domain, very different from terminations observed for example in the Labrador-Baffin Bay area (e) and the Gulf of Aden-Red Sea area (f). (d) shows a theoretical example of how this could be solved by adding a huge transfer zone. (e) shows natural examples of two such oblique transfer zones (Labrador Sea and Baffin Bay, from Oakey and Chalmers, 2012). (f) shows a change in orientation of the Gulf of Aden system to the younger Red Sea Rift, and the termination of the system against the Dead Sea transform (based on Bosworth et al., 2005). Note that the continental margins as drawn along the ocean in (b) are much too narrow to produce the thick and wide Araçuaí orogenic crust, meaning that the space problem is even bigger than what is shown here. RF – Ribeirão da Folha locality, SAG – Santo Antônio do Grama locality. All figures are presented at the same scale. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

shown in Fig. 2). Both modern (Fig. 5e-f) and reconstructed (e.g., Heine et al., 2013) examples of ocean floor propagation through continental crust show much narrower oceans with long and well-developed rifts ahead of the termination point. We have illustrated (Fig. 5c) the abrupt termination of the ocean in the Araçuaí region based on constraints given by Amaral et al. (2020), and the figure shows in principle how the ~ 1000 km wide ocean must terminate over just a couple of hundred kilometers. This is kinematically impossible unless a major transfer structure exists that can transfer the displacement out of the continental embayment (Fig. 5d). Such a transfer structure could also be oblique, as in the Labrador-Baffin Bay example of Fig. 5e, or like the less advanced Dead Sea transform that formed when the Suez rift terminated against strong Mediterranean oceanic crust, failing to break the continental bridge between Africa and Sinai. In the Dead Sea case, a future Red Sea ocean will terminate abruptly against the Dead Sea transform, and the transform segment will become a transform passive margin (Bosworth et al., 2005). Another example is the Gulf of Aden propagation, where oceanic crust terminates against the East African Rift and displacement is taken up by the Red Sea rift (Fig. 5f). In our last hypothetical illustration (Fig. 5d) of the Araçuaí orogen, a strike-slip transfer or transform structure cuts across the São Francisco craton and displaces its southern part westward by a distance corresponding to the width of the ocean. The existence of such a transfer structure is highly unlikely, judging from published maps and literature, even though a schematic attempt to introduce such a NW-trending structure was made (and later apparently abandoned) by Pedrosa-Soares et al. (1992).

6. The absence of high-P rocks

Subduction of oceanic crust that leads to continent–continent collision usually results in orogenic belts with high-pressure and sometimes ultrahigh-pressure rocks that relate to either subduction complexes (metamorphosed oceanic lithosphere) or continental complexes subducted to high-pressure conditions. Such high-P rocks are reported from most orogens involving subduction (Dewey and Bird, 1970; Ernst, 1973; Miyashiro, 1973; Jolivet et al., 2003; Liou et al., 2004; Ernst, 2005; Guillot et al., 2009), particularly from the circum-Pacific belt (for example the Franciscan Complex) and *peri*-Caribbean systems (e.g., García-Casco et al., 2006; Wakabayashi and Dumitru, 2007), various types of ophiolites and associated rocks from the collisional Alpine-Himalayan system (e.g., Butler et al. 2013; Cottle et al., 2015), and a huge (ultra)high pressure subducted basement domain in the Caledonides (e.g., Kylander-Clark et al., 2009). High-pressure rocks are particularly common in ophiolitic and other subducted units derived from the down-going (subducting) plate, i.e. the environment envisaged by Peixoto et al. (2015) and Amaral et al. (2020). However, they are not found in any part of the Araçuaí-West Congo orogen or in its continuation to the south (the Ribeira belt; Meira et al., 2019). Even in the domains interpreted as accretionary wedges, no relicts of high pressure/low temperature metamorphism have been reported (Peixoto et al., 2015; Amaral et al., 2020). Although not conclusive by itself, the apparent absence of high-P mineral assemblages does not support a subduction-collision model for the Araçuaí-West Congo orogen.

7. Could the "ophiolite" magmatism not be rift-related, and "arc-like" magmatism be related to delamination during intracontinental orogeny?

Pedrosa-Soares et al. (1998) and later authors portray occurrences of ultramafic rocks, amphibolite and now a plagiogranite vein (Amaral et al., 2020) as evidence for ocean floor spreading. However, the occurrences of these ultramafic and mafic rocks are of limited extent and may alternatively represent rift-related magmatism, or break-up related magmatism during development of a wide rift that never resulted in mature oceanic crust. Noteworthy, rift-related tholeiitic rocks of MORB affinity also occur in older parts of the pre-orogenic Neoproterozoic rift basin (Macaúbas Group and its related West Congolian Group in the West Congo belt; Kampunzu et al., 1991). One could perhaps compare the situation at the onset of convergence with that of the Red Sea, where a very thin strip of oceanic crust is developing in the southern part (Fig. 5f). In this case rifted subcontinental mantle is overlain by basaltic lava, intruded by gabbroic bodies and dikes, and covered by sediments. With all these components in place, accretion of this terrane during convergence could qualify as a subduction-unrelated ophiolite (Dilek and Furnes, 2014). Such an ophiolite would record the transition from rifting to break-up, and no wide oceanic basin would have developed. Geochemically these settings produce MORB-type compositions but show large variations in multielement patterns and geochemical discrimination diagrams such as Th/Yb versus Ta/Yb (Dilek and Furnes, 2014). We would welcome a discussion of rift-related origin of these magmatic rocks, like the one about the Kaoko-Dom Feliciano-Gariep orogenic system further south (Konopásek et al., 2018). Furthermore, the "pre-collisional" I-type calc-alkaline granitoids and mafic rocks interpreted as arc-related magmatism by Pedrosa-Soares et al. (1998) and later authors could be envisaged as a bimodal magmatism derived from delamination processes associated with intracontinental shortening, as shown by Gorczyk and Vogt (2015).

8. The formation of excessive melt around 600 Ma: hot orogeny

The Araçuaí orogen is a hot orogen with widespread magmatism and partial melting (Vauchez et al., 2007, 2019). Cavalcante et al. (2013, 2014, 2016, 2018) showed that huge volumes of anatectic melt ("Carlos Chagas" in Fig. 2) formed by partial melting of continental crust, and used AMS measurements, temperature estimates and microfabric data to demonstrate widespread melt-present deformation consistent with mid-crustal channel flow toward the São Francisco foreland. Temperature estimates coupled with precise age determinations demonstrated melt crystallization from 597 to 572 Ma (Cavalcante et al., 2018). Hence peak crustal temperatures in the Araçuaí orogen were reached by 600 Ma and followed by very slow cooling.

The high temperature and extensive melting of the middle crust can be interpreted as a result of crustal thickening (orogeny) and related crustal heating (Sandiford and McLaren, 2002; McKenzie and Priestley, 2016). Crustal thickening must then have initiated more than 20 m.y. before 600 Ma, which is the time it takes for thickened crust to heat to melting temperatures that can lead to channel flow tectonic behavior (Vanderhaeghe, 2009; Jamieson et al., 2011; Horton et al., 2016; Cavalcante et al., 2018, 2019). This model does not require any subduction of oceanic crust and explains large volumes of anatexites and anatectic granites formed at ca. 600–570 Ma and thus eliminates the problem of putting a vast ocean into a confined continental environment. Amaral et al. (2020) imprecisely claim that "Widespread anatexis on [*sic*] paragneiss complexes, during the collisional stage of the Araçuaí orogen, produced huge volumes of peraluminous granites with ages ranging from c. 585 to c. 540 Ma". Cavalcante et al. (2018) already demonstrated that anatexis happened at peak regional temperature before 597 Ma (the oldest age so far of melt crystallization in the anatexites), which is at odds with the subduction-collision model.

9. Concluding remarks

We conclude that the tectonic model for the Araçuaí orogen presented in multiple papers over the last two decades from Pedrosa-Soares et al. (1998) to Amaral et al. (2020) is facing insurmountable challenges, particularly when tested against kinematic constraints imposed by the confined orogenic model. There is a pressing need to actively look for and test new models that can better explain the available body of data from this orogen. In particular, we suggest that intracontinental models (Trompette, 1994, 1997, 2000) should be (re)considered.

One such model is the intracontinental hot orogen model that has progressively evolved through several recent contributions (Vauchez et al., 2007; Petitgirard et al., 2009; Mondou et al., 2012; Cavalcante et al., 2013, 2014, 2018, 2019; Fossen et al., 2017). This alternative model is appealing because it solves the fundamental problems produced by the subduction/collision model. It explains the timing of peak temperature, heating in response to crustal thickening, large-scale melting of middle crust during the pre-collisional stage of the subduction-collision model, and most importantly, complies with kinematic constraints related to a semi-confined orogenic setting.

Similar ideas are being developed for the Ribeira belt (Meira et al., 2015a, 2015b, 2019), and a space problem associated with a major subduction-collision model has been identified also in the Kaoko-Dom Feliciano-Gariep orogenic system (Konopásek et al., 2017). Hence, the entire Mantiqueira orogenic system should be critically reconsidered with respect to orogenic models (Konopásek et al., 2019) and we hope that current and future researchers engaged in understanding this fascinating orogenic system will agree that real scientific progress can only be made through critical multidisciplinary and collaborative efforts.

Declaration of Competing Interest

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

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