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Special Section:
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Key Points:
- Profound temperature control on orogenic evolution and tectonic style is demonstrated by comparing two thermally different orogens
- The cold Caledonian collision produced ultradeep continental subduction, and huge thrust nappes separated by high-strain mylonite zones
- The hot Araçuaí-West Congo orogen produced a symmetrical profile with molten crust between a collapsing plateau over and a flat root

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Hot Versus Cold Orogenic Behavior: Comparing the Araçuaí-West Congo and the Caledonian Orogens

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Abstract Observations and modeling show that temperature controls crustal rheology and therefore also the orogenic evolution of continent-continent collision zones and the associated tectonic style. In order to explore the effect of temperature in a natural environment, we compare eroded sections through the unusually cold lower Paleozoic North Atlantic Caledonian (Scandian) collision zone and the very hot Brasiliano/Pan-African Araçuaí-West Congo orogen. A cold and stiff subducting Caledonian continental margin was able to subduct as a rather coherent unit to ultrahigh-pressure conditions, twice as deep as the Pan-African/Brasiliano crust that was quickly heated and softened and got involved in partial melting. Furthermore, the Caledonian collision developed large coherent thrust sheets that were transported hundreds of kilometers toward the foreland. This was never achieved in the hot Araçuaí-West Congo orogen, where much of the tectonic stress was absorbed by the partially molten central part of the orogen through magmatic state deformation. Major mylonite zones (thrusts) such as those seen in the Caledonides are therefore less common in the Araçuaí-West Congo orogen. Further, the deep continental subduction in the Caledonides developed a strongly asymmetric collision zone, with rapid variations in pressure and temperature. In contrast, the Araçuaí-West Congo orogen soon developed into a more symmetric geometry due to its easily flowing hot crust, with a relatively flat base and a corresponding plateau in its upper part. Deformation of the cold Caledonian crust was controlled by plate-tectonic stress, while gravitational forces more strongly influenced the hot Brasiliano/Pan-African example.

1. Introduction

Continent-continent collisions create orogenic belts with a variety of sizes, basement behavior, metamorphic structure, and tectonic style, depending on a series of external and internal variables. Such factors include the size of any precollisional ocean and its arc/microcontinent constituents, the width, shape, compositions, preexisting inheritance, orientations and strength of continental margins, kinematics, rate and duration of convergence, mantle heat flow, and the internal heat produced in the orogen and affect the resulting sizes and shapes of the orogenic wedge, structural style (degree of basement involvement, folding versus thrusting, amount of nappe translations, steep versus low-angle structures, and plateau formation), significance of strike-slip shearing, degree and style of extensional collapse, depth of subduction, and metamorphic structure. Hence, orogeny is a complicated process where the end result depends on a number of interacting variables whose combined effect may be difficult to predict. More and more of these effects can be controlled and their effect explored through numerical modeling, within the limitations set by the code, computing power and setup. Such models are giving valuable information about the first-order effects of specific conditions and processes, such as variations in crustal rheology, crust-mantle coupling and thermal evolution (e.g., Burov et al., 2014; Duretz & Gerya, 2013; Erdős et al., 2014; Jamieson et al., 2010; Rey and Müller, 2010). However, natural orogenesis is inherently more complicated than what can be simulated by current numerical methods, and comparative studies of natural orogenic belts can provide additional information about factors controlling orogenic evolution.

In this work we focus on the thermal aspects of continent collisions by comparing two orogenic belts of similar size and not so different ages, namely, the Pan-African/Brasiliano Araçuaí-Ribeira-West Congo orogen of southeastern Brazil and the south Scandinavian Caledonides. Temperature is addressed because we believe it to be one of the most important factors controlling orogenic evolution. These two orogens were chosen

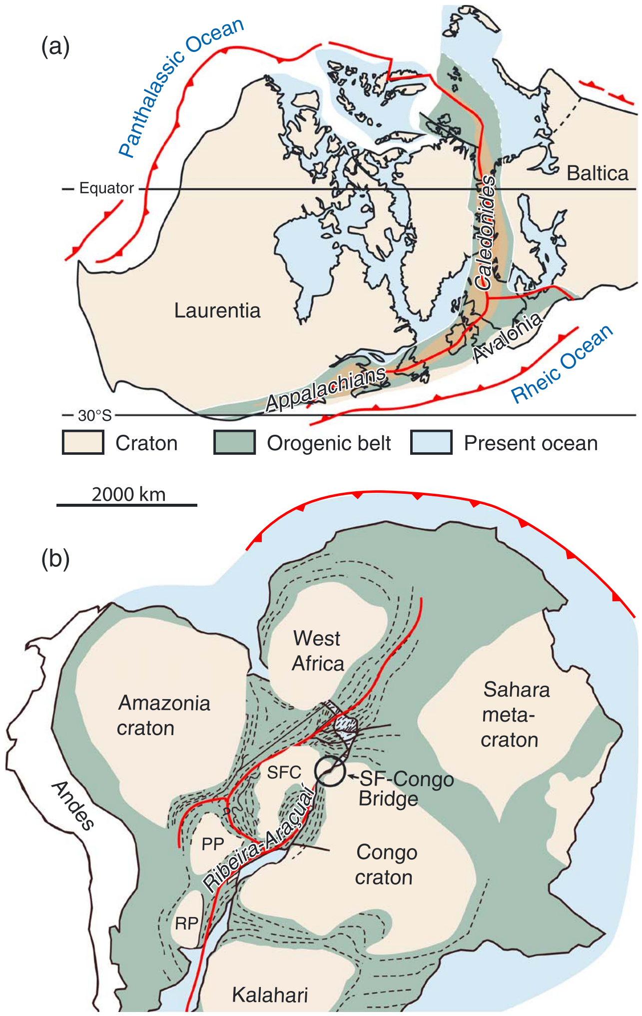

Figure 1. General setting at ~420 Ma of (a) the Caledonian-Appalachian belt (based on Torsvik et al., 2012) and (b) Brasiliano-Pan-African belts of West Gondwana. PP = Paranapanema Craton, RP = Rio de La Plata craton, SFC = São Francisco craton. The two maps are drawn at the same approximate scale.

because they represent two extremes in terms of thermal evolution: The former being an example of an unusually hot orogen, and the Caledonides being unusually cold for its size. In the following we describe their fundamental differences in geometry and tectonic style and discuss how they may be explained chiefly in terms of differences in thermal evolution.

2. General Framework of the Two Orogens

Restoration of the two orogenic belts to the pre-Atlantic (Pangea) situation (Figure 1) shows that the Araçuaí-West Congo and Caledonian belts are comparable in terms of width and length and that both belong to extensive orogenic systems that involved the interaction between several continents: most importantly the São Fancisco and Congo for the former and the Laurentia and Baltica for the Caledonides. The Caledonides are up to 900 km wide at the latitudes of southern Scandinavia (closer to 700 km if Devonian extension is accounted for), decreasing to 500–600 km across northern Scandinavia and across the British Isles (Figures 1a, 2, and 3). The Araçuaí-West Congo section of the Brasiliano system is ~650 km wide (up to 75 km more if the weak thin-skinned deformation of the Ediacaran Bambui Group covering the São Francisco craton is included; Reis & Alkmim, 2015), narrowing southward into the transpressive Ribeira belt (Figure 4).

Both the Caledonides and the Araçuaí-West Congo orogen are generally thought to involve subduction of one continental margin under the other. In the Caledonides the Baltican margin (Scandinavian side) was subducted, generating ultrahigh-P metamorphic conditions for the deepest part (Dobrzhinetskaya et al., 1995; Krogh et al., 2011; Wain et al., 2001). In the Araçuaí-West Congo case the São Francisco (Brazilian) margin is the one considered to be subducted according to most published models (e.g., Alkmim et al., 2006; Vauchez et al., 2007). However, unlike the Caledonides (Figure 2b) no paleopressure gradient has been found to support this model, which is based on the interpretation of precollisional island arc-evolution on the rifted margin of the Congo craton (Gradim et al., 2014, and references therein). At the collisional stage, however, the Araçuaí-West Congo orogen appears to be fairly symmetric (Figures 5 and 6) with low-temperature marginal belts surrounding a wide and hot internal part. The Caledonian orogen also portrays a retrowedge of considerable size (Figures 2 and 3), but when taking the peak Caledonian pressure and temperature structure into account it is clear that its collisional geometry was markedly asymmetric.

In the Caledonides, the Baltican margin of Scandinavia interacted with the Laurentian margin of Greenland, and the orogenic belt branches into the Appalachian belt to the southwest and the less prominent Polish Caledonides to the southeast, with the Avalon microcontinent located to the south (Figure 1). Prior to the main collisional stage Baltica and Avalonia were surrounded by oceans as they moved toward Laurentia (Torsvik et al., 2012). In contrast, the Araçuaí branch of the Brasiliano system, which continues southward as the Ribeira and eventually as the Dom Feliciano belts into Uruguay (Figure 4), appears to terminate or split up northward into the São Francisco craton, which, prior to the Cretaceous rifting, is generally interpreted to have been connected to the larger Congo craton on the African side by what is generally known as the São Francisco-Congo cratonic bridge (Figure 1) (e.g., Alkmim et al., 2006; Pedrosa-Soares et al., 2001; Porada, 1989). This apparent northward termination of the orogenic system, creating what has been referred to as a "confined orogen" (Pedrosa-Soares et al., 2001), represents an incompletely understood geometric and kinematic situation that is different from the Caledonian one and puts important constraints on the evolution of the northern part of the Araçuaí-West Congo orogenic system.

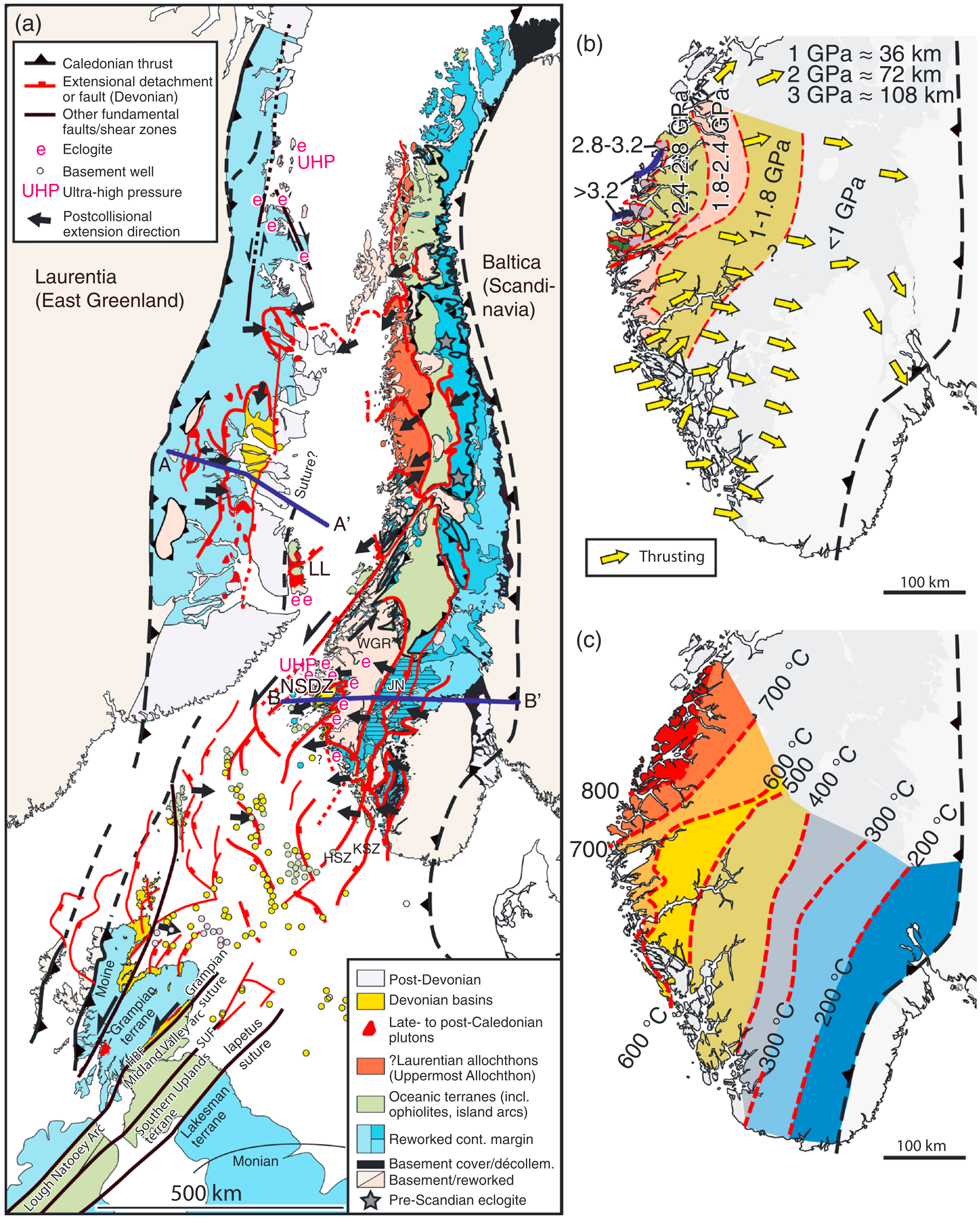

Figure 2. (a) Map showing the Caledonian orogen (Late Devonian restoration) with the Laurentian part (Greenland) restored relative to Baltica (Scandinavia). (b) Pressure, kinematics, and (c) temperature conditions near top basement during peak metamorphic conditions are shown. The circles represent well information. Based mostly on maps and data presented by Higgins and Leslie (2008), Fossen (2000, 2010), Hacker et al. (2010), and Fossen et al. (2016). HBF = Highland Boundary Fault; HSZ = Hardangerfjord Shear Zone; JN = Jotun Nappe; KSZ = Karmøy Shear Zone; LL = Liverpool Land; NSDZ = Nordfjord-Sogn detachment zone; SUF = Southern Uplands Fault; WGR = Western Gneiss Region.

3. The Araçuaí-West Congo Orogen

The Araçuaí-West Congo orogen is the northern part of the extensive Mantiqueira Province, which developed along the eastern margin of South America from Uruguay to central Brazil during the assembly of West Gondwana (e.g., Almeida et al., 1973; Bento dos Santos, Tassinari, & Fonseca, 2015, and references therein)

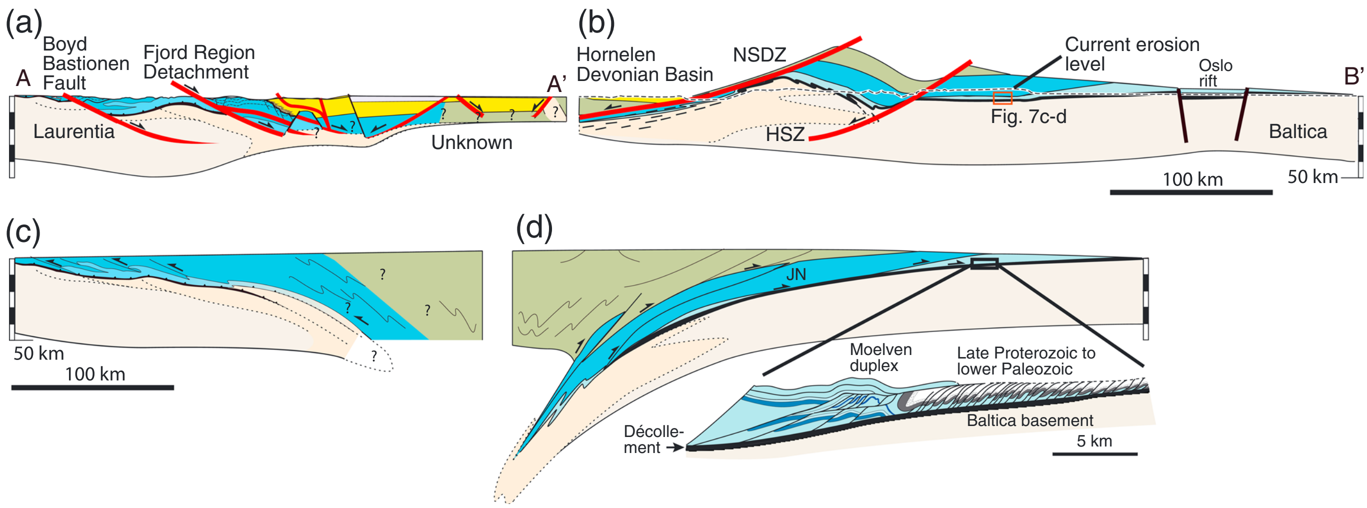

Figure 3. (a–d) Profiles across the south Scandinavian Caledonides, as indicated in Figure 2. Greenland part (Figure 3a) based on Higgins et al. (2004) and Andresen, Rehnström, and Holte (2007). Greenland Moho from Mjelde et al. (2016). Inset shows the tectonic style in the thin-skinned foreland part of the orogen, based on Morley (1986).

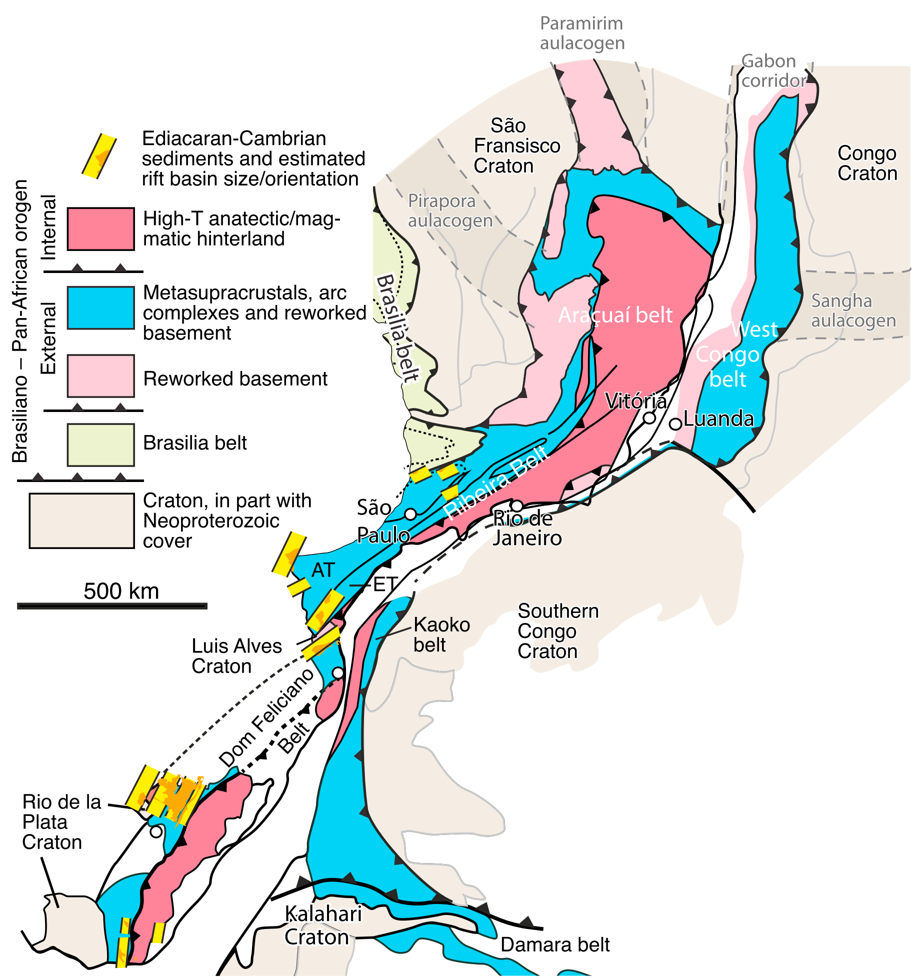

Figure 4. Tectonic map of the Mantiqueira (Araçuaí-Ribeira-Dom Feliciano) orogenic system. Based mainly on Heilbron et al. (2008), Tack et al. (2001), Pedrosa-Soares et al. (2008), and Almeida et al. (2012). AT = Andrelândia terrane; ET = Embu Terrane.

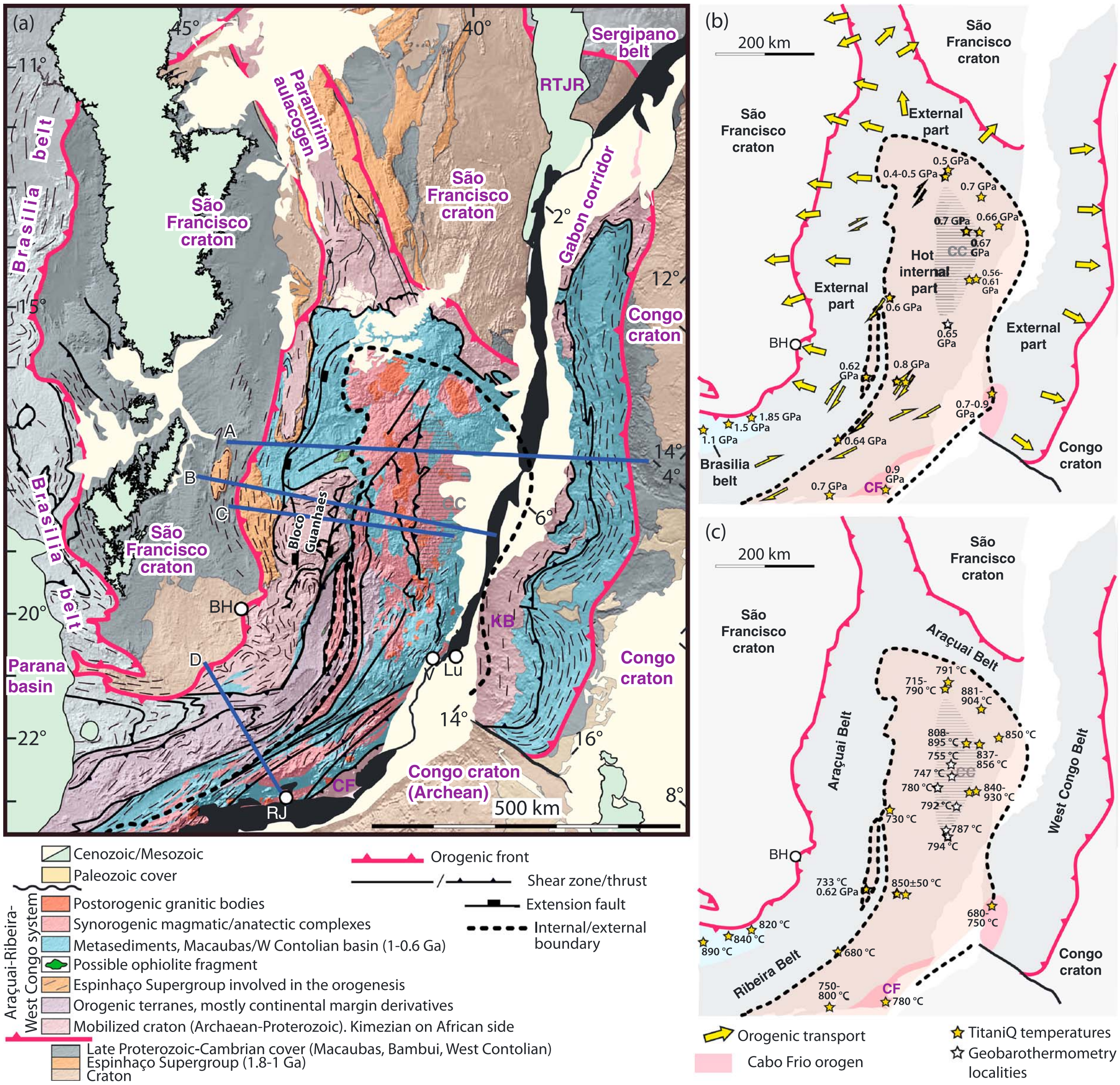

Figure 5. (a) Geologic map of the Araçuaí and northern Ribeira belt, with Congo restored with respect to a fixed Brazilian side. Based on maps from the Geological Survey of Brazil (CPRM), and references cited in Figure 4. KB = Kimezian bassement; RTJR = Recôncavo-Tucano-Jatoba rift; BH = Belo Horizonte; CC = Carlos Chagas anatectic domain; CF = Cabo Frio; Lu = Luanda; RJ = Rio de Janeiro; SP = São Paulo; V = Vitoria. (b) Kinematic and geobarometric data. Minimum deformation temperatures for the Carlos Chagas domain from TitaniQ geothermometry and peak metamorphic mineral paragenesis. TitaniQ temperatures from Cavalcante et al. (2014). Geobarothermometric data from Garcia et al. (2003), Schmitt et al. (2004) Munhá et al. (2005), Belém (2006), Petitgirard et al. (2009), Uhlein et al. (2009), Bento dos Santos et al. (2011), Gradim et al. (2014), Moraes et al. (2015), and Degler et al. (2017). Kinematic data mainly from Alkmim et al. (2006).

(Figure 4). Altogether this province shows a complicated and long-lived orogenic evolution, with an increasingly complex history of precollisional terrane accretion southward from the Araçuai, through the Ribeira and into the Dom Feliciano belt. The entire orogenic province does, however, have in common a magmatic internal part with evidence of very high temperatures maintained over a long period of time. The total orogenic evolution along the Mantiqueira Province spans a couple of hundred million years, varies along strike in terms of timing of events and kinematics, with extensive arc development and subsequent continent collision that generally seems to get younger southward (e.g., Gray et al., 2008). In this contribution we will focus on the northern part of the Mantiqueira Province, mainly the Brasiliano Araçuai belt and its Pan-African counterpart known as the West Congo belt.

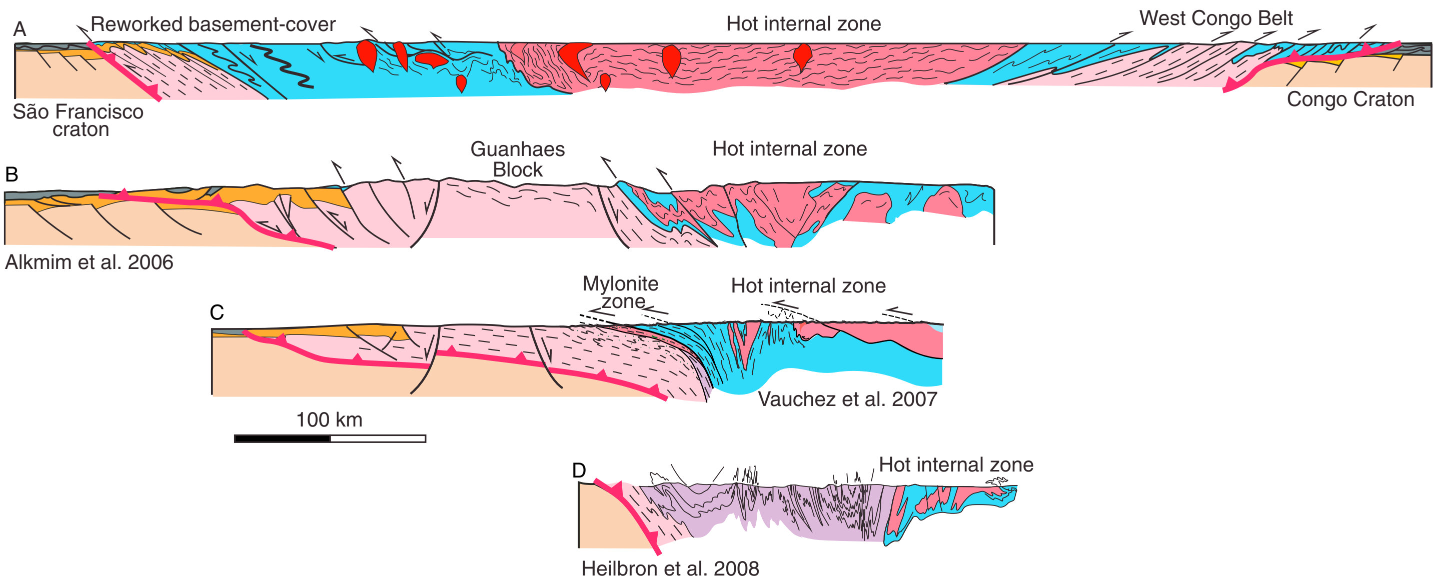

Figure 6. Cross sections through the Araçui-West Congo orogenic belt. Locations and legend are shown in Figure 4. Based on Tack et al. (2001), Alkmim et al. (2006), Vauchez et al. (2007), Pedrosa-Soares et al. (2008), Heilbron et al. (2008), and own interpretations. See Figure 4 for legend and location.

3.1. The External (Foreland) Part

The Araçuaí-West Congo orogen is primarily the result of collisions against the western margin of the São Francisco margin in the late Proterozoic (forming the Brasilia belt) and is composed of an *external* (foreland) *fold-and-thrust belt* and a wide and hot *internal domain* (hinterland) dominated by partial melting and magmatism and, into the Ribeira section to the south, transcurrent shear zones (Alkmim et al., 2017; Hasui & Oliveira, 1984; Heilbron et al., 2017; Pedrosa-Soares et al., 2001; Trompette, 1994; Vauchez et al., 2007; Vauchez et al., 1994) (Figure 5). The external belt is thin-skinned (not involving basement) only in its most marginal part (less than, and locally much less than 100 km wide). Inward the basement becomes involved, with rejuvenation of preorogenic rift structures (Alkmim et al., 2017) (Figures 6a and 6b). The external fold-and-thrust belt and its structural grain trends N-S in both Brazil and Congo (from Vitoria/Luanda and northward; Figure 5), curving east-southeastward around latitude 15°S toward the present Brazilian coastline, but with a northward extension into and across the craton along the reactivated Paramirim aulacogen (Figure 5) (Cruz & Alkmim, 2017). This modified aulacogen represents a long-lived pre-Brasiliano extensional rift basin that was inverted (shortened) during the Brasiliano orogenic evolution, but also with evidence of extensional and transcurrent kinematics interpreted as late or postorogenic (Cruz et al., 2015). The amount of late Proterozoic shortening across this aulacogen decreases northward, but the structure clearly crosscuts the entire São Francisco craton. Hence, it represents an orogenic structure that transects the São Francisco craton and provided flexibility to the craton during the orogenic evolution.

On the African side, the corresponding West Congo fold-and-thrust belt extends several hundred kilometers farther northward along the coast than its Brazilian counterpart, as shown in Figures 4 and 5. This ~150 km wide north trending corridor separates the São Francisco and Congo cratons, here informally referred to as the Gabon corridor (Figure 4). This corridor is best interpreted as a reactivated aulacogen related to the Early Neoproterozoic (Tonian) rifting along the African margin, similar to the Paraminim aulacogen to the west. This rifting event is known as the Zadinian-Mayumbian event, interpreted in the context of dextral transtension farther south along the Mantiqueira Province (Gresse, 1995; Tack et al., 2001). The width and structural pattern indicated from the map (Figure 5) suggest that this corridor experienced considerably more orogenic shortening than the Paramirim aulacogen.

South of Luanda along the Congo margin, the fold-and-thrust belt is abruptly aborted by a major zone of E-W trending transcurrent structures with dextral sense of displacement (Figure 5b). The tectonic history and eastward extension of this basement structure into the craton is not well known, but it has the appearance of being a reactivated pre-Pan-African structure. Its profound effect on the West Congo belt suggests that it may represent a cratonic segment boundary that accommodated differential cratonic movements between the northern and southern parts of the Congo craton.

From the southern Araçuaí and into the entire Ribeira belt, a series of elongated tectonic units of magmatic and gneissic metamorphic rocks occur, separated by mostly dextral shear zones. These map-scale units have been interpreted as terranes of continental margin and arc-related signature in the context of repeated margin accretion, although the way that they have been defined and interpreted has changed over the last couple of decades (Heilbron et al., 2008). Their presence and signatures suggest a more complicated history of collisions and lateral movements than the orogenic evolution of the Araçuaí belt to the north.

Except for local postorogenic extensional reactivation (Marshak et al., 2006), the general kinematics of the entire external belt is everywhere top-to-the-foreland (Figures 5b and 7a), that is, eastward onto the Congo craton for the West Congo belt, and toward the São Francisco craton for the Brazilian part. The metamorphic conditions change progressively from nonmetamorphic or very low grade along the craton (Figure 7a) to amphibolite facies close to the internal hinterland domain, and to granulite facies conditions within the internal domain (e.g., Pedrosa-Soares et al., 2001).

3.2. The Hot Internal Part

The internal hinterland domain, roughly enclosed by the thick dashed line in Figure 5, is exposed on the Brazilian side of the Atlantic; Neoproterozoic intrusions do not appear to be present in the Kimezian mobilized basement (Tack et al., 2001), although late Pan-African leucocratic veins have been described from the southernmost part of the West Congo belt (Monié et al., 2012). This domain defines the high-temperature core of the orogen and includes vast amounts of magmatic and anatectic rocks (Figure 7b) that range in crystallization age from 630 to 480 Ma (e.g., Nalini et al., 2000; Pedrosa-Soares et al., 2011; Petitgirard et al., 2009; Silva et al., 2005), formed in or emplaced into a very hot environment. The transition into the internal hot part of the orogen is gradual and is here set where the peak orogenic temperature exceeds 700°C. In the central Araçuaí belt, mylonitic rocks (including paragneisses with evidence of partial melting) of amphibolite facies mark this transition, indicating basement involvement during foreland-directed thrusting (Vauchez et al., 2007). Temperatures of 730°C and pressures of 0.6 GPa have been reported from this outer part of the hot internal orogen, which also shows evidence of partial melting (Petitgirard et al., 2009).

In most of the internal part temperatures were higher during deformation and peak metamorphism, up to 850°C and locally even higher (Figure 5b). This has been documented by a variety of geothermometers applied to stable mineral parageneses in granulites and migmatites of the orogen, as discussed in detail by Moraes et al. (2015), who found temperature values around 850°C in the northern part of the hot internal domain. This is consistent with other results, which generally show peak metamorphic temperatures in excess of 750°C for this domain, as illustrated in Figure 4c (Belém, 2006; Dias et al., 2016; Gradim et al., 2014; Gonçalves et al., 2016; Moraes et al., 2015; Munhá et al., 2005; Uhlein et al., 2009). A rather well-studied portion of this internal hot part of the orogen is the Carlos Chagas anatectic domain (CC in Figure 5), where vast amounts of crustal melt have been produced and deformed in the nonsolid state at midcrustal levels during the orogeny (Cavalcante et al., 2013, 2014). In this anatectic domain, the temperature at the time of crystallization of quartz from melt, that is, the last stage of crystallization, has been constrained independently by means of titanium-in-quartz (TitaniQ) geothermometry (Cavalcante et al., 2014). The results showed temperatures ranging from 750 to 800°C, consistent with metamorphic peak temperatures above 800°C. Furthermore, high ($>$30%) portions of melt was shown to be present at these temperatures, based on conservative P-T values and the chemical compositions of the anatexites (Cavalcante et al., 2014). Interestingly, similar temperatures are reported from the Ribeira belt in Rio de Janeiro (Bento dos Santos et al., 2011; Kuhn, 2004) and from the southeasternmost Brasilia Belt (Garcia et al., 2003).

Several estimates of paleopressures associated with the metamorphic peak in the internal part of the orogen have been presented in the literature, generally varying between 0.5 and 0.7 GPa. (Belém, 2006; Dias et al., 2016; Gradim et al., 2014; Gonçalves et al., 2016; Moraes et al., 2015; Munhá et al., 2005; Petitgirard et al., 2009; Uhlein et al., 2009). The highest pressure (0.8 GPa) for the main Araçuaí-West Congo orogeny was found in the southernmost part of the Araçuaí belt (Bento dos Santos et al., 2011). The pressure estimates throughout the internal part of the orogen are thus very uniform and indicate that the present erosion level through the hot internal part of the orogen was buried at 20–25 km depth, that is, midcrustal levels. When considering the

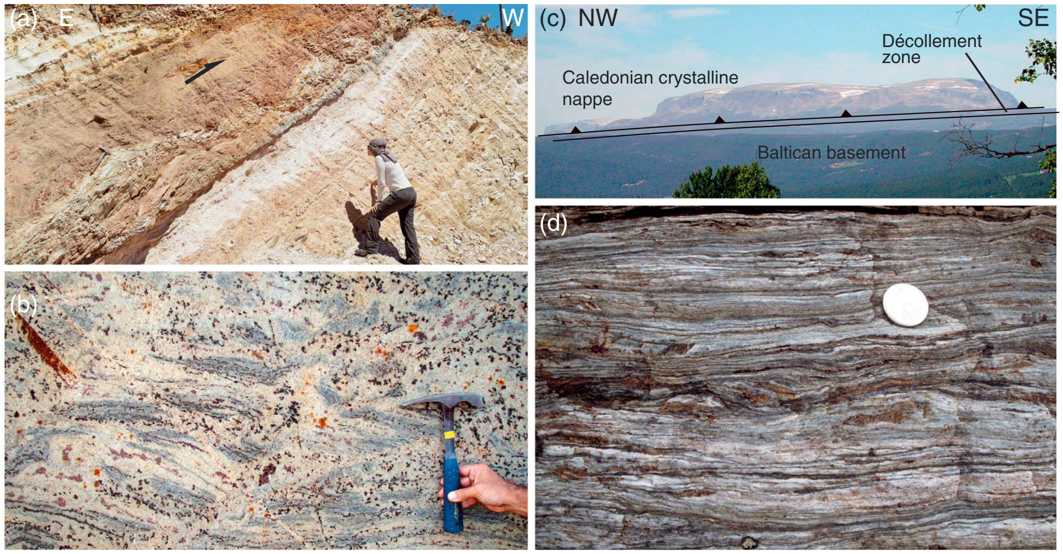

Figure 7. Photos of some characteristic rocks and settings from the (a and b) Araçui-West Congo and (c and d) Caledonian orogens. Very low-grade silisiclastic sediments of the São Francisco craton with top-to-the-craton sense of thrusting (Serra do Cipó) (Figure 7a). Migmatite from the Carlos Chagas anatectic domain, showing the presence of granitic melt (leucosome) (Figure 7b). Lower part of the basal thrust and lower part of the orogenic wedge (Jotun Nappe correlative) in south Norway (Haugastøl area) (Figure 7c). Mylonitic sole of the Jotun Nappe (Aurlandsdalen) (Figure 7d). The coin is 2.5 cm in diameter.

present crustal thickness of ~40 km (Assumpção et al., 2017), this implies a fairly uniform crustal thickness of 60–65 km across the hot internal part of the orogen at the time of peak Araçuaí-West Congo metamorphism.

Altogether, the thermal and pressure data suggest very high temperatures at midcrustal depths. Geochronologic results suggest that the internal domain was hot for a long time, cooling at <3°/Myr until 500 Ma (Petitgirard et al., 2009), and cooling through the Ar/Ar retention temperature for biotite around 470 Ma in both the eastern (Munha et al., 2005) and western (Petitgirard et al., 2009) parts of the hot internal orogenic domain. Magmatism and partial melting dominate the main orogenic period from close to 630 until 560 Ma, with magmatism continuing until ~480 Ma. Pedrosa-Soares et al. (2011) grouped the magmatic/anatectic rocks of the Araçuaí hinterland into precollisional (630–585), syncollisional (585–530 Ma), and postcollisional (530–480 Ma) granitoids. The precollisional rocks were interpreted as a long-lived arc system (Pedrosa-Soares et al., 2011; Tedeschi et al., 2016) that was active from 630 to 585 Ma (Pedrosa-Soares et al., 2011) or 630 to 580 Ma (Gonçalves et al., 2016). This model implies 45–50 Myr of subduction of oceanic crust, which would accumulate precollisional shortening on the order of 1000 km between the São Fancisco and West Congo margins even for slow subduction rates (~2 cm/yr). Clearly, such an amount of convergence is incompatible with the constraints imposed by any version of the “confined” or “nutcracker” orogenic model presented by Alkmim et al. (2006), even if the São Francisco-Congo craton is significantly softened by throughgoing structures such as the Paramirim aulacogen and the and Gabon corridor. The magmatism and partial melting, which occur in a continental setting with predominantly crustal magmatic sources (Gonçalves et al., 2017), is better understood as a characteristic feature of a long-lived hot orogenic setting, as proposed by Vauchez et al. (2007), Petitgirard et al. (2009) and Cavalcante et al. (2013, 2014), and discussed more closely below.

3.3. Boundary Conditions and Orogenic Evolution

The kinematic evolution of the Araçuaí-West Congo belt is constrained by several cratonic elements that are considered to have been connected prior to the orogeny. However, the elements were dissected by preorogenic aulacogens and possibly other transecting structures that added mobility to the continental system during the mostly east-west orogenic shortening. Alkmim et al. (2006) argues that these cratonic elements were connected as a single, yet flexible continent, and suggested a nutcracker-style kinematic mechanism for the orogeny. A modified version of this model is shown in Figure 8, where two structures, the

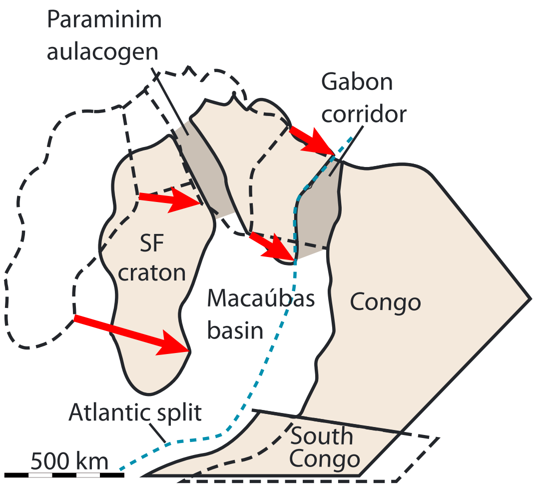

Figure 8. Schematic evolution of the Araçuaí orogen, showing progressive closing of the preorogenic Macaúbas basin. The red arrows indicate displacement vectors; the green arrows suggest the overall "nutcracker" kinematics. The model is modified from the nutcracker model of Alkmim et al. (2006) by considering the Gabon corridor (modified aulacogen), which allows for more convergence (on the order of 500 km).

Paramirim aulacogen and the Gabon corridor, are considered to provide most of the mobility of the São Francisco-Congo craton during the orogenesis. The convergence associated with these two structures is, based on their width and internal structure, unlikely to have been much more than 200 km. However, additional shortening can have been provided by rotation of the São Francisco craton, together producing a total shortening on the order of 500 km, as illustrated in Figure 8. Most of this shortening is needed to thicken the continental crust to 65 km during the Late Proterozoic orogenic convergence, meaning that any subduction-related arc development prior to crustal thickening must have been very limited.

The most attractive interpretation of the evolution of this hot orogen involves extensive partial melting of the middle crust in response to orogenic crustal thickening (Cavalcante et al., 2013, 2014; Vauchez et al., 2007). Recent dating of melt crystallization in the anatectic domain (Hollanda et al., 2014) suggests that significant crustal thickening and melting of the middle crust were already ongoing at 600 Ma. Observations from other orogens as well as theoretical calculations show that it takes in the order of 20–25 Ma to establish a large middle-crustal anatectic domain (Hodges et al., 2006; Jamieson et al., 2011; Nelson et al., 1996), which implies that crustal thickening in the Araçuaí-West Congo orogen probably started at 630–620 Ma. In other words, the oceanic crust under the preorogenic Macaúbas basin (the Adamastor ocean; Dalziel, 1997) may have been very limited or even absent in the Araçuaí-West Congo part of the Mantiqueira province (Meira et al., 2015).

Detailed field and anisotropy of magnetic susceptibility mapping of magmatic deformation fabrics (Cavalcante et al., 2013) together with representative temperature and viscosity estimates from the anatectic part of the Araçuaí orogen (Cavalcante et al., 2014) show a middle-crustal flow pattern consistent with influence of both tectonic and gravitational forces. In this setting, the upper crust would likely collapse and spread gravitationally over the very weak middle crust, while the external part of the orogen would experience transport (thrusting) toward the surrounding cratons, in agreement with the kinematics shown in Figure 5b. This model also explains the presence of a system of middle Ediacaran-early Cambrian rifts in the upper crust, preserved in the southern part of the Ribeira and Dom Feliciano belts (Figure 4) (Almeida et al., 2010, 2012). A situation similar to that of the current Tibetan Plateau may be envisaged, where orogenic spreading occurs over a partially molten (fluid) middle crust during orogenic convergence, driving thrusting in the foreland (e.g., Hodges, 2006; Royden et al., 2008). Such spreading of the hot internal part of the orogen may also explain the short distance that is seen several places between the hot hinterland and the orogenic front.

Timing of thrusting in the external part of the Araçuaí-West Congo is not very well constrained, especially not the early (main) stages. As for the later stages, preliminary geochronologic data from the southernmost part of the West Congo belt suggest high-temperature and slightly higher (~1 GPa) pressure orogenic activity as late as 540 Ma, with possible additional activity around 490 Ma (Monié et al., 2012) (Figures 5b and 5c). This late activity may be related the late (~540 Ma) collision of the Cabo Frio terrane with the main Ribeira belt (Schmitt et al., 2004; 2016) and the associated closure of a pre-540 Ma basin south of the Araçuaí orogen. This event, marked as the Cabo Frio orogen in Figures 5b and 5c, is also suggested to last until ~490 Ma based on U-Pb dating of metamorphic minerals (Schmitt et al., 2016). In the Araçuaí part of the orogen, late orogenic activity is indicated by thrusting of a sedimentary unit (Três Marias Formation) that contains 558 Ma old detrital zircons (Kuchenbecker et al., 2015). Furthermore, the age of the youngest synkinematic intrusive body dated in the Araçuaí belt is ~530 Ma (the Ibituruna syenite; Petitgirard et al., 2009), whereas the oldest post-kinematic granites in the Araçuaí-West Congo orogen is ~520 Ma (Noce et al., 2000). If collision initiated at ~625 Ma, this would imply ~100 Ma of orogenic shortening, possibly even more if the youngest ages reported by Monié et al. (2012) from the southernmost West Congo belt are considered. Continuous convergence over such a long interval seems unlikely, particularly since significant crustal thickening must have occurred at a relatively early stage. Pedrosa-Soares et al. (2001) report magmatic quiescence from 570 to 535 Ma, which may possibly indicate reduced (or no) convergence for this post peak-metamorphic period of very slow cooling (Petitgirard et al., 2009). Late (~540 Ma) orogenic activity may also be explained as a consequence of the collision of Amazonia against west margin of the São Francisco craton (e.g., Valeriano et al., 2008) or of late orogenic activity farther south along the Mantiqeira Province (Monié et al., 2012). However, the main orogenic thickening and partial melting in the Araçuaí-West Congo orogen occurred at an earlier stage, around or shortly after 600 Ma.

4. The Caledonides

Cross sections through the external parts of the Caledonides (Figure 3d) show a classical foreland fold-and-thrust belt that is considerably wider than that of the Araçuaí belt. This belt is found on both sides of the orogen but is better developed on the Scandinavian side. Toward the hinterland, the lowest continental thrust nappes are overridden by successively more far-transported allochthonous units inferred to represent imbricated fragments of the pre-collisional Baltoscandian and Laurentian margins. The Precambrian basement is better exposed on the Scandinavian side due to its deeper erosion level, where it gradually becomes more reworked toward the hinterland. Correspondingly, the Caledonian P-T conditions increase toward the coastal areas (Figures 2d and 2e), where early Devonian eclogites, locally associated with coesite and microdiamonds (Dobrzhinetskaya et al., 1995), developed under an orogenic stack of allochthonous units during the continental subduction and eduction. A large number of ophiolite fragments are preserved in the upper allochthonous units (oceanic terrane in Figures 2a–2c) on the Scandinavian side of the collision zone. Eclogitized crust is also found locally in the hinterland of the SE Greenland margin (Liverpool Land; LL in Figure 2a) and is explained as a fragment of the Baltican margin that ended up on the Greenland side after the opening of the North Atlantic Ocean (Augland, Andresen, & Corfu, 2010). The general structure on both margins is that of laterally extensive thrust sheets separated by distinct mylonite zones (Figures 7c and 7d).

Island arc complexes of Ordovician age are preserved in the upper allochthon (oceanic) units and show an evolution from ~500 to 430 Ma (Dunning & Pedersen, 1988; Fossen & Austrheim, 1988; Scheiber et al., 2016). From 430 to 425 Ma, continent-continent collision is assumed to have occurred over a time span of ~20 Myr (the Scandian event or orogeny), with (ultra)high-pressure metamorphic conditions in the deepest part of the western basement around 420–400 Ma (Krogh et al., 2011; Kylander-Clark et al., 2007; Kylander-Clark et al., 2008; Terry et al., 2000a; Walsh et al., 2007). Evidence of early orogenic activity, possibly representing collision between the Baltican margin and a microcontinent or arc complex, is found within some of the nappes north of the area focused on in this work (i.e., area covered by Figures 2b and 2c). In the Seve nappe in central Sweden, an Ordovician (~450 Ma) (ultra)high-pressure event (Jämtlandian) is recorded in eclogites (Brueckner & Van Roermund, 2007; Janák et al., 2013; Smith, 1984). Farther north, indications of early Ordovician (Finmarkian) subduction along the Baltoscandian outer margin at 490–470 Ma are found (Essex et al., 1997). These events may be related to early and apparently hotter collisions involving arc complexes and microcontinents and suggest that an orogenic wedge started to develop before the main continent-continent collision around 425 Ma (the Scandian collisional event), which is the focus of our comparison.

In both the Greenland and Scandinavian parts of the Caledonian belt, collisional structures were strongly reworked by extensional and transtensional deformation shortly after the collision ended at around 405 Ma (Fossen & Dunlap, 1998). The extension reactivated Caledonian thrusts, notably the weak and low-angle basal thrust (décollement zone) in the southern Scandinavian Caledonides, and the effect was that of continental eduction (reversal of the subduction kinematics) of the Baltican margin together with vertical gravitational ascent of the deeply subducted margin (Andersen et al., 1991; Fossen, 1992, 2000, 2010). Secondarily, a regional set of extensional shear zones formed, of which the largest ones offset the entire orogenic wedge (Figure 3). Offsets on the order of 50–100 km have been estimated for the most extensive of these Devonian shear zones (Nordfjord-Sogn detachment zone) (Andersen and Jamtveit, 1990; Fossen, 2000; Norton, 1987), which show thicknesses of up to 5–6 km. Similar extensional structures developed on the Greenland side of the belt (Figure 2b), together with Devonian hanging wall basins (Higgins and Leslie, 2008; Gilotti & McClelland, 2008).

Particularly impressive Devonian continental supradetachment basins developed in the hanging wall of the Nordfjord-Sogn detachment zone (Figure 2c), showing up to 25–30 km of stratigraphic thickness (Séranne & Séguret, 1987; Vetti & Fossen, 2012). During the early to middle Devonian extension, the most deeply (ultra-high pressure) subducted portion of the Baltican margin experienced more or less isothermal decompression until lower crustal or midcrustal levels were reached, and then rapid cooling toward the frictional-plastic transition at rates of 30–90°C/ Myr (Root et al., 2005; Walsh et al., 2013). The less deeply subducted part of Baltica experienced cooling throughout the extensional history, and the entire basement region exposed in S Norway cooled through the Ar/Ar retention temperature of muscovite around 400–380 Ma (Walsh et al., 2013). Neither the extreme pressures nor rapid exhumation documented for the Norwegian Caledonides are seen in the Greenland counterpart, reflecting the asymmetry of the Caledonian collision zone prior to extension.

5. Amount of Convergence

The amount of convergence (shortening) involved during the Caledonian continent-continent collision constrained by nappe restorations, where nappes of continental margin affinity (e.g., the Jotun Nappe; JN in Figure 2) show evidence of up to 400 km of displacement toward the foreland (Hossack & Cooper, 1986). Furthermore, outboard terranes of the Iapetus oceanic environment were thrust more than 500 km onto Baltica, according to Gee (1978) and Gee, Andréasson, and Krill (2017). Adding the estimated 200–400 km of nappe translations in the retrowedge (Greenland) (Higgins et al., 2004) yields a total shortening of continental crust across the Caledonian orogen on the order of 600–900 km (e.g., Gee, 1978; Gee et al., 2008). The generally accepted model involving subduction of the edge of the Baltican margin to ~150 km depth during the continent-continent collision (>3.5 GPa; Smith & Godard, 2013) is consistent with these estimates of horizontal shortening.

The amount of shortening across the Araçuaí-West Congo belt is more difficult to estimate. Foreland thrust-and-fold belts typical for large orogenic belts exist on both the South American and African sides, with marginal metasedimentary sequences overridden by thrust nappes involving fragments of the continental margins. From sections across the orogen (Figure 6; Tack et al., 2001), the external fold-and-thrust belt shortening appears to be limited to tens of kilometers. The internal domain (hinterland) is represented by high-T conditions characterized by anatectic units and granitoid intrusive bodies, and the amount of shortening across this zone is difficult to estimate. P-T data suggest thickening of the crust to ~65 km in the internal part of the orogen (Cavalcante et al., 2014), which would require at least tripling of the thinned continental margins and shortening on the order of 400–500 hundred kilometers. This rough estimate of orogenic shortening is lower than for the Caledonides and is consistent with the simple kinematic model shown in Figure 8. It is also consistent with the absence of major Caledonian-style continental thrust sheets moved hundreds of kilometers toward the foreland, as discussed below.

6. Differences in Structural Style and Rheology

The difference in structural style between the Caledonides and the Araçuaí-West Congo orogen is noticeable, from the outcrop scale to the scale of the orogen (Figure 9). The Caledonian orogen involves laterally extensive nappe units with up to several hundred kilometers of displacement. This tectonic style has produced a layered tectonostratigraphic structure where nappes are stacked on top of each other, forming the Caledonian orogenic prowedge on top of the subducting Baltican basement, and a somewhat smaller retro-wedge on the Laurentian margin in East Greenland (Figure 2). Most of these Caledonian nappes experienced relatively low-pressure and low-temperature metamorphism (mostly greenschist facies for the oceanic terranes and greenchist to lower amphibolite facies metamorphism for the continental margin units), and the relatively low temperatures kept the crystalline continental rocks strong during the collision. Low-grade metamorphic conditions also mean that most continental thrust nappes must have been ripped off the Baltican continental margin at relatively shallow depths or represent microcontinents that never went down the subduction channel (e.g., Andersen et al., 2012). The cold and rigid nature of these sheets enabled many of them to travel hundreds of kilometers toward the foreland without being internally dismembered.

The major Jotun Nappe in the South Norway Caledonides is probably the best example of this style of thrusting. A more than 200 km long, 100 km wide, and >5–6 km thick remnant is preserved from erosion but may

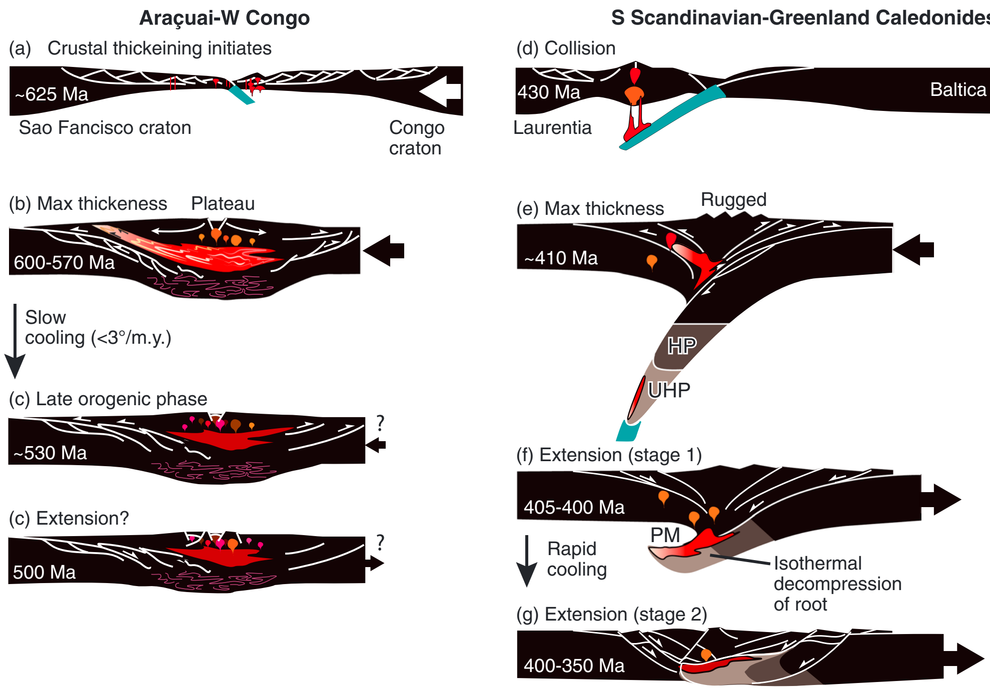

Figure 9. Schematic cross-sectional illustrations of the evolution of the Araçuaí-West Congo part of the Brasiliano orogenic system and the North Atlantic Caledonides.

have been considerably larger if correlated with similar allochthonous units along the west coast. The Jotun Nappe consists of Proterozoic continental crust with large parts that are only weakly affected by Caledonian deformation; most of the shear strain is localized to a mylonite zone along its base. Much of the Jotun Nappe, and particularly the portions of the nappe that are rich in feldspar (anorthositic, gabbroic rocks), show very little evidence of Caledonian strain, in spite of being transported >360 km to the southeast (Hossack et al., 1985). This can be explained by the fact that temperatures (Fauconnier et al., 2014) were generally too low to effectively activate plastic deformation of feldspar (≲450°C). For comparison, the strain in the Jotun Nappe related to the hotter Sveconorvegian (1.25–0.9 Ga) orogeny is much more pervasive than the Caledonian overprint (Lundmark et al., 2007).

The Araçuaí-West Congo orogen does not expose extensive Caledonian-style thrust sheets with hundreds of kilometers of displacement (Figure 6). The most prominent mylonite zone described in the literature is the >5 kilometer thick low-angle top-to-W zone east of the Bloco Guanhães (Lat 18–20°S in Figure 4, as marked in Figure 6c) (Mondou et al., 2012; Vauchez et al., 2007). This zone separates the external foreland part of the orogen along the sheared eastern margin of the São Francisco craton from the internal anatectic/magmatic hinterland. The displacement associated with this mylonite zone is unknown. However, if we assume that the mylonitic fabrics commonly require shear strains close to 10 (e.g., Fossen & Rykkelid, 1990; Simpson, 1983) a total displacement of roughly 50 km can be calculated, suggesting that the displacement across this mylonite zone is at least on the order of several tens of kilometers. However, this mylonite zone does not carry rigid thrust nappes but appears to be related to foreland-directed flow of the hot internal part of the orogen.

The fact that the hot internal part of the Araçuaí-West Congo orogen shows little or no evidence of localization of strain into major thrusts or shear zones can be explained by the high amount of melt present in this hot part of the orogen. The formation of melt networks with as little as 7% melt dramatically weakens the crust from the outcrop to the crustal scale (e.g., Rosenberg & Handy, 2005; Vanderhaeghe & Teyssier, 2001), with a decrease in strength experimentally estimated to 2–3 orders of magnitude (Rushmer, 1996). Most of the hot internal part of the orogen shows evidence of melt in excess of this number, and some parts show the presence of >30% melt during deformation (Cavalcante et al., 2013), which would make this part of the crust behave more like a fluid (Vanderhaeghe, 2009). Hence, the middle crust of the internal part of the orogen can be considered to have been very weak during peak metamorphic conditions. Under such conditions strain is taken up by the melt and therefore widely distributed in the middle crust, provided that a large portion of the middle crust contains melt (Cavalcante et al., 2013, 2014, 2016; Vauchez et al., 2007). The lack of, or very weak, crystal preferred orientation of quartz is diagnostic for deformation of partially molten rocks, even where a strong mesoscopic foliation is defined by biotite and feldspar (Cavalcante et al., 2016). This diagnostic lack of crystallographic fabric contrasts with the well-defined crystallographic preferred orientations produced during solid-state deformation in the high- to ultrahigh-pressure subducted Baltican crust (Barth et al., 2010) and the Caledonian orogenic wedge (e.g., Fossen, 1993).

The generally weak and mostly nonsolid state fabrics in the anatectic rocks of the hinterland show a variably oriented but mostly low-angle foliation and gently plunging lineation that varies in orientation from orogen perpendicular (E-W) to orogen-parallel (N-S) (Cavalcante et al., 2013). Together with temperature and viscosity estimates during peak temperature deformation (Cavalcante et al., 2014, 2016), this dispersed fabric pattern is consistent with a combination of gravity-driven deformation in addition to tectonically driven flow in this part of the orogen (Cavalcante et al., 2013, 2014). Overall transport toward the foreland is indicated by the mylonitic zone along its margins (see above), suggesting large-scale spreading of the hot internal part of the orogen. Hence, structural observations confirm the interpretation of the Araçuaí-West Congo as a hot orogen with a very weak and partly molten middle crust that is unstably trapped between the elevated upper crust and the crustal root, and consequently flowing laterally as strength was lost due to partial melting. This scenario is similar to that envisioned for the currently collapsing Tibetan plateau and several older orogenic belts (e.g., Dewey, 1988; Jamieson & Beaumont, 2011). The soft rheologic behavior of the internal part of the orogen is completely melt controlled—a situation that is completely different from the localization of strain into major thrusts in the Caledonides.

Rheology differences also pertain to the cratonic basement involved. The Baltican basement is well exposed from the foreland to the hinterland in the South Norway Caledonides and is significantly affected by ductile Paleozoic deformation only in its hinterland part. Even in that part, much of the ductile deformation and related metamorphism appear to have formed during postcollisional divergence (Fossen et al., 2014). As shown from the paleopressures summarized in Figure 2, the continental Baltican margin was subducted to depths of up to 150 km, meaning that it remained coupled to its underlying mantle until reaching this depth. Such a behavior requires a very strong crust. A relatively cold lithospheric environment at this time, possibly together with a dry lower crust and lack of fluids, could explain its strong rheology. Temperature estimates along the top of the subducted Baltican margin (Fauconnier et al., 2014) confirm such a cold orogenic environment. In contrast, there is no evidence of deep subduction of any part of the Araçuaí-West Congo crust during the orogenic history, although the possibility exists that pressure data from early continental subduction have not been preserved or discovered. Available geobarometric data show rather constant paleopressures around 0.6 MPa across the hot internal zone, suggesting a uniformly thickened internal part of the orogen. Such a symmetric geometry is characteristic for hot orogens with a very weak and easily flowing orogenic crust (e.g., Chen et al., 2017).

7. Why So Hot? Why So Cold?

Great differences in thermal development of the Caledonian and Araçuaí-West Congo orogens resulted in significant differences in rheology and strength, which again gave rise to two extremely different orogens in terms of tectonic style and orogen geometry. This raises the question why the Araçuaí-West Congo orogen was so hot and the Caledonides so cold.

In the Araçuaí-West Congo orogen, the high temperatures, slow cooling, and excessive amount of melt in the hinterland (Figure 9b) require a heat source capable of maintaining a high temperature for a long time, more specifically to keep the temperature above 700°C from 600 to 480 Ma. This represents an unsolved question in the literature on the Araçuaí-West Congo orogen, although vague references to radiogenic heat release from subducted metasediments and mantle upwelling, including subduction of a spreading ridge, slab break-off, and upwelling of asthenospheric mantle, have been made (Bento dos Santos et al., 2015; Gradim et al., 2014; Tedeschi et al., 2016).

While a mantle heat source related to upwelling of astenospheric mantle is possible, crustal heat production from radioactive elements (U, Th, and K) can be very significant in thickened continental crust that involve metamorphism of sedimentary rocks over several tens of millions of years (Jamieson & Beaumont, 2013) and should be considered as an important, if not the most important, heat source in the Araçuaí-West

Congo orogen. The preorogenic basin between the São Fancisco craton and the Congo craton was very wide (more than the 600 km represented by the orogenic belt), containing large volumes of fertile (pelitic) sedimentary rocks to be involved in the orogeny. Radiogenic decay during burial of these sedimentary rocks is likely to have produced a great amount of heat over an extended period of time, based on general calculations (e.g., Faccenda, Gerya, & Chakraborty, 2008; Jamieson et al., 1998; Sandiford & McLaren, 2002). In general, such heat production in large continent-continent collision zones leads to temperatures >700°C in the middle crust after ~20 Myr of collision, which will then turn the collision zone into a large hot orogen with increasing amounts of melt (Jamieson et al., 2011; Jamieson & Beaumont, 2013). This is the scenario suggested for the Himalayan orogen (Zhang et al., 2004) where the present crustal thickness is at least doubled, midcrustal to lower crustal temperatures are well above 700°C (Klemperer, 2006), and where melting started at ~30 Ma, 20–25 Myr after the collision, and is still ongoing (Jamieson et al., 2011). Similar models have been proposed for the Grenvillan and Variscan orogens (Jamieson et al., 2010; Maierová et al., 2016), and all of these hot orogens show evidence of lateral flow of midcrustal material under a stronger upper crustal lid that rifted during the slow gravity-driven orogenic spreading (slow syncollisional collapse; Figure 9b), that is, the model favored for the Araçuaí-West Congo orogen (Cavalcante et al., 2013, 2014). However, some of the magmatism during the orogenic cycle has a mantle source, suggesting an additional deeper thermal contribution, particularly during the postorogenic stage (Pedrosa-Soares et al., 2011, and references therein).

The Scandinavian Caledonides are unusually cold for their size (most cold orogens are small; Jamieson and Beaumont, 2013), and the main reasons for this may be a short-lived collision with relatively rapid subduction and exhumation of a strong crust. In terms of subduction rates, some 500 km of Baltican crust from the foreland to the hinterland was involved in the Caledonian continental subduction, which happened over 20–25 Myr (from 430–425 to 405 Ma). This yields an average continental subduction rate of ~1 cm/yr or a sinking (burial) rate of 0.75 cm/yr using the simple subduction geometry reconstructed by Fossen (2000). This is somewhat slower than the Himalayan sinking rate of 1.1–1.4 cm/yr estimated by Kaneko et al. (2003), which buried continental rocks to 100 km over 7–9 Myr Furthermore, it is much slower than the precollisional convergence rate extracted from paleomagnetic data (8–10 cm/yr; Torsvik et al., 1996), suggesting that convergence dramatically slowed down during the Caledonian collision, similar to the Himalayan case (Molnar and Tapponnier, 1975). Precise dating of UHP eclogites from the Caledonides by Krogh et al. (2011) shows that UHP conditions were reached already at 415 Ma. This implies that subduction to >100 km happened over 10–15 Myr, which gives a sinking rate close to that of the Himalayas for this first part of the collision. This scenario was also modeled numerically by Butler et al. (2015), who obtained very realistic results for a convergence rate of 2.5 cm/yr (and a stiff Baltican margin). Hence, the subduction or convergence rate seems to have been rather normal for the Caledonian collision, and the cold conditions cannot be explained by unusual high continental subduction rates.

For the Himalayan case, melting and related weakening sufficient enough to cause regional crustal flow were achieved after ~25 Myr of continental subduction, even though evidence exists that partial melting initiated significantly earlier (e.g., Carosi et al., 2015; King et al., 2011). This stage was never reached within the short collisional timeframe of the Caledonides. Instead, most of the melting observed in the subducted Baltican margin occurred during isothermal decompression during the following exhumation history, and only in the deeply subducted parts of the Baltican margin (Gordon et al., 2013; Labrousse et al., 2011). If the Caledonian collision had continued for a longer period of time, then we would expect a transition into a hotter orogen with more extensive partial melting, spreading, and plateau development, that is, more similar to the Himalayan and the Araçuaí-West Congo examples. While the partial melting that did occur in the deepest parts of the orogen may have contributed to the exhumation process (Gordon et al., 2013; Labrousse et al., 2011), the termination of the collision and onset of divergent movements was more likely controlled by external plate-kinematic conditions. Structural and kinematic mapping shows that there was a shift to a period of (minor) plate divergence in the Early Devonian (Fossen & Dunlap, 1998), and the most likely reason for this change is Early-Middle Devonian northward motion of the Avalonian-Cadomian blocks, marked as Avalonia in Figure 1. Rey et al. (1997) related this northward movement to early Variscan movements, that is, Godwana pushing northward. Kroner and Romer (2013) suggests that this northward push was mainly imposed by the extended continental margin of the Gondwana plate called the Armorican spur, north of the West African craton as it collided with the Midland Valley microcraton. In this specific scenario, the Armorican spur represented an indenter that started to split the Laurentian and Baltican plates apart. This

Table 1
Table Comparing Characteristic Features of the Araçuai-West Congo and Caledonide Orogens

Araçuaí-West Congo	Caledonides
Continents loosely connected before orogeny	Continents unconnected before orogeny
Symmetric profile	Asymmetric profile
Minor thrust sheets, pervasive deformation	Large thrust sheets, major thrusts, and strong strain localization
Narrow thin-skinned external part	Wide thin-skinned external part
Scarce evidence of oceanic crust	Abundant evidence of oceanic crust
Large hot orogen; abundant melting	Large cold orogen, very limited melting
Shallowly subducted continental margin: 0.6–0.7 GPa throughout the hinterland	Deeply subducted continental margin: >3.2 GPa in the deepest exposed parts
Max T achieved relatively early (~600 Ma)	Max T achieved during early post-orogenic exhumation (~405–400 Ma)
Gravity-driven spreading over partially molten middle crust with plateau development	No extensive weak and spreading middle crust, no large plateau development
Long collisional history (50–100 Ma)	Short collisional history (20–25 Myr)
Very slow cooling (<5°C/Myr)	Rapid cooling of subducted margin (up to 30–90°C/Myr)
Limited amounts of postorogenic extension	Large amounts of postorogenic extension

northward push model also explains the northward waning effect illustrated in Fossen, 2010, his Figure 10). Hence, the Caledonides never reached the hot orogenic stage because of changes in plate kinematics. The Araçuaí-West Congo orogen did, probably because orogenic activity in the Brasília belt to the west imposed compressional stress on the Araçuaí-West Congo orogen over a long period of time (from ~630 to 530 Ma) (Fuck et al., 2017; Valeriano, 2017).

Studies of active subduction systems indicate a difference between east and west dipping slabs. In general, west directed slabs are faster, deeper, and steeper than east directed ones. They also show a shallower basal décollement, among other things (Carminati & Doglioni, 2012; Doglioni & Panza, 2015). These characteristic features, exemplified by the Alpine versus the Apenninic belt (Carminati & Doglioni, 2012), fit well with the west dipping Caledonian collisional subduction system, as discussed above. Similarly, evidence from the Araçuaí-West Congo orogen suggests a much shallower, low-P/high-T system that is unlikely to have been very fast, that is, in agreement with a typical east facing asymmetric collisional system. This difference between east and west facing systems is related to an asymmetric mantle flow pattern, with a general westward drift of the plates relatively to the underlying asthenosphere (Crespi et al., 2007) due mainly to the rotation of the Earth. Most likely this effect existed also during the formation of the Brasiliano-Pan-African and Caledonian systems and is mentioned here as a factor that may have enhanced the differences between the two orogenic systems discussed here.

8. Consequences for Later Reactivation (Rifting)

Very different crusts are produced in the hot and cold orogenic cases described in this work. The cold Caledonides ended up with a large number of fundamental thrusts and shear zones with strong internal fabrics. Such structures and fabrics can potentially be reactivated during later deformation, and, depending on their orientations, influence the way that later rifts develop. In the Caledonides, the 300–500 km wide North Sea rift system formed on top of the orogen some 150 million years after its cessation. A significant influence of Caledonian thrusts and ductile extensional shear zones on the evolution of this wide rift system has been documented in several recent papers, even if their orientations are not optimal for reactivation (Fazlikhani et al., 2017; Fossen et al., 2016; Phillips et al., 2016). In general, a wide distribution of orogenic structures that weaken the crust may be one of several factors contributing to the formation of wide rift systems.

A hot orogenic belt like the Araçuaí-West Congo, formed by mostly orthogonal convergence, lacks large and mechanically weak shear zones that can be reactivated with a favorable orientation: most structures in such gravity-influenced orogens are subhorizontal or nonplanar. Hence, the rifted margins on the Araçuaí-West Congo orogen show new-formed rift faults with few or no reactivated orogenic structures. Reactivated structures along the east Brazilian rifted margin are steeper strike-slip-dominated orogenic structures, particularly related to the Ribeira belt to the south (Fetter, 2009) or the Borborema Province to the north (e.g., Destro et al., 1994).

9. Conclusions

A comparison between the unusually cold Caledonian and hot Araçuaí-West Congo orogens illustrates fundamental differences in terms of architecture, geometry, and evolution that to a large extent can be explained in terms of thermal, and consequently rheological, differences (Table 1). Cold Caledonian conditions makes for strong (highly viscous) rheology, particularly in crust of continental composition. This resulted in (1) large thrust nappes with up to several hundreds of kilometers of transport, (2) strong localization of strain into large thrusts, (3) deep continental subduction and (ultra)high pressure metamorphism, (4) asymmetric profile, and (5) rapid exhumation and cooling.

The hot Araçuaí-West Congo orogen produced the following characteristic features that for the most parts can be attributed to its hot nature: (1) smaller thrust nappes with shorter transport, (2), large and weak internal hot domain, (3) extensive partial melting, (4) distributed strain, (5) symmetric profile with flat base and top (plateau), (6) synorogenic gravity collapse over weak molten crust, and (7) slow cooling.

These observations are qualitatively consistent with modeling results showing that weak crust allows for wider and more distributed deformation and symmetric profile, whereas strong crust tends to result in underthrusting (continental subduction) and asymmetric orogens (Chen et al., 2017; Faccenda et al., 2008). The most fundamental change appears to happen when partial melting become widespread. Fertile radiogenic sediments are thought to have been an important heat source in the Araçuaí-West Congo and similar settings, causing initial melting of the middle crust after some 20 Myr If significant amounts of sediments are involved, such heating can keep the middle crust molten for a long time, as was the case for the Araçuaí-West Congo orogen. The Caledonian collisional history, on the other hand, was too short for this thermal effect to become important, as the convergence was aborted and replaced by divergence after 20–25 Myr This comparison of two end-member orogens highlights the most fundamental controls that temperature is expected to have on the evolution of large-scale orogenic belts.

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