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Connecting the Araçuaí and Ribeira belts (SE – Brazil): Progressive transition from contractional to transpressive strain regime during the Brasiliano orogeny

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ABSTRACT

Whether the Araçuaí and the Ribeira Neoproterozoic belts in southeast Brazil represent a continuous or two distinct orogenic belts is still a debated question. We compile existing geologic and geophysical data and argue that the two belts, in spite of differences in tectonic style and kinematics, should be considered as part of an orogenic continuity that formed during the mostly Late Proterozoic Brasiliano orogenic evolution. Structural mapping supported by Anisotropy of Magnetic Susceptibility data shows that the transition between the two belts is gradual, with a progressive change from a NE-trending subvertical foliation and subhorizontal stretching lineation in the Ribeira belt to gently dipping and less pronounced fabrics in the Araçuaí belt. The lineation progressively changes northward from NE to E-W, suggesting a transition from overall transcurrent to thrust kinematics, and the solid-state finite strain seems to get progressively higher into the Ribeira belt. Differences in tectonic style are explained by the southward termination of the rigid São Francisco craton, which caused oblique collision and lateral escape, as supported by numerical modeling. Shear-wave splitting measurements suggest that the transcurrent deformation in the Ribeira belt affected the entire lithosphere. In the transitional zone, the seismic anisotropy pattern is more complex and the delay time between the fast and slow shear-waves is smaller. These observations, together with a similar record of magmatism and timing of orogenic events and P-T conditions during peak metamorphism strongly support continuity between the Araçuaí and the Ribeira belts. This model is a "quasi-facsimile" of the Paleoproterozoic deformation that occurred in the Great Slave Lake area in Canada.

1. Introduction

Many orogens show evidence of transcurrent deformation along sections of the belt, often coeval with a large amount of magmatism and peak metamorphic conditions. Transcurrent deformation is, in most cases, associated with strain at the plate margins being partitioned into simple shear and pure shear components (e.g. Fitch, 1972; Sanderson and Marchini, 1984; Oldow et al., 1990; Fossen and Tikoff, 1993; Tikoff and Teyssier, 1994; Dewey et al., 1998). Several factors may explain the development of such transpressional deformation. The plate convergence vector, and thus the far-field forces, may be oblique to the plate boundaries, as is the case in Indonesia (e.g., Philippon and Corti, 2016), and strain will be partitioned to accommodate the obliquity. Alternatively, heterogeneities and anisotropy in the colliding plate margins may generate transpressional tectonics even when the convergence is normal to the plate boundaries (e.g., Tommasi and Vauchez, 2015 and references therein).

The Mantiqueira Province, as defined by Almeida et al. (1981), is the orogenic system along the Brazilian coast that extends from the southern border of the eastern São Francisco craton (16° S) to Uruguay (33ºS). It constitutes a more than 3000 km long NNE-trending Neoproterozoic orogenic system that recorded a protracted sequence of orogenic events related to the assembly of West Gondwana, and comprises, from north to south, the Araçuaí, Ribeira, and Dom Feliciano orogens (Fig. 1). In this contribution we explore the transition between two contiguous orogenic segments: the Araçuaí belt, which is

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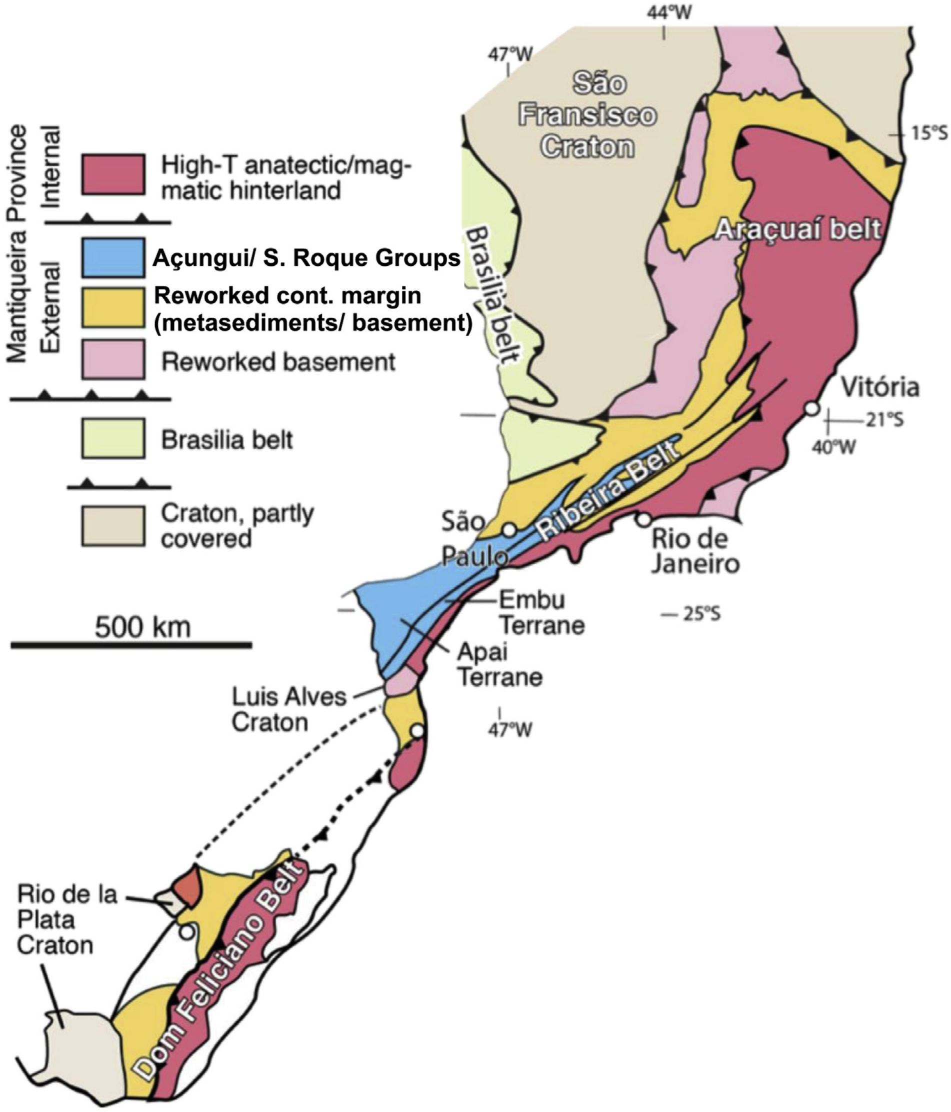


Fig. 1. Schematic map of the Mantiqueira Province and its main subdivisions. Modified from Heilbron et al. (2004).

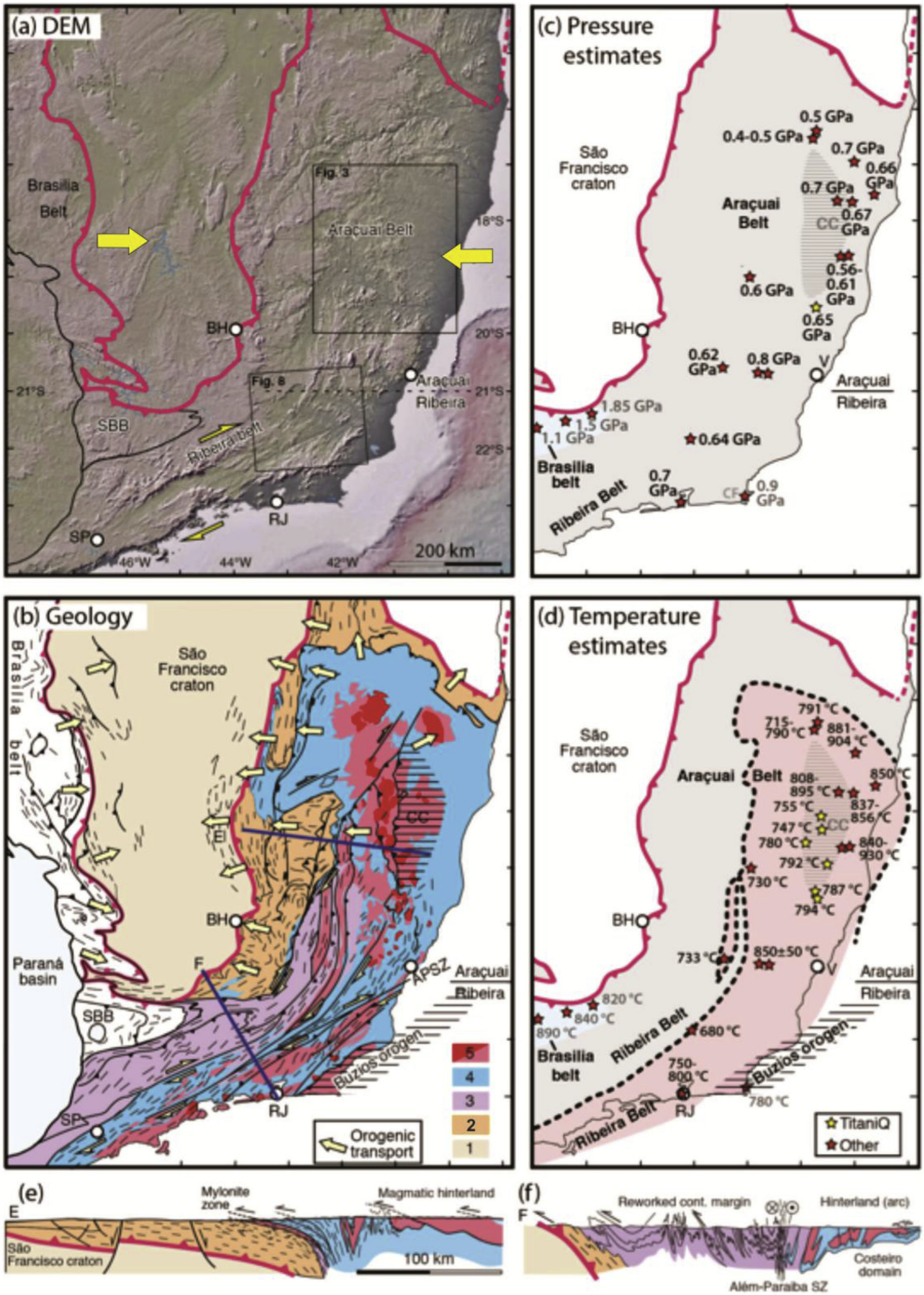
characterized by orogen-normal shortening, and the Ribeira belt in which transpressional tectonics dominates. These two Brasiliano/Pan-African belts form a domain of orogenic deformation and magmatism from 17ºS to beyond 25ºS along the east coast of Brazil (Fig. 1).

Initially no distinction was made between these two belts, and the entire mobile belt was called Ribeira (Hasui et al., 1975). Then, Almeida (1977) introduced a division of the northern part of the orogen, which bounds the São Francisco craton, with the Araçuaí belt representing the westernmost metasedimentary rocks of the orogen and the Ribeira belt representing its eastern, internal domain. This distinction was mostly grounded on contrasted rock assemblages and geochemical characteristics, the boundary between the two belts was oriented ~ NS parallel to the carton's eastern limit (e.g. Brueckner et al., 2000). Later on, the entire orogenic domain, East of the São Francisco craton, from 15ºS to 21ºS, has been considered as the Araçuaí belt (e.g., Trompette, 1994; Vauchez et al., 1994; Pedrosa-Soares et al., 2001, 2008; Heilbron et al., 2004). Regardless, both the Araçuaí and Ribeira orogenic belts are generally considered to have formed at convergent plate boundaries between ~630 and 520 Ma during the Neoproterozoic Brasiliano or Pan-African convergence between the São Francisco and Congo cratons.

The Ribeira and Araçuaí belts display contrasting structural characteristics:

- In the Ribeira belt, steep lithospheric-scale orogen-parallel transcurrent shear zones associated with orogen-normal thrusting dominate the well-developed regional fabric, typical of a transpressional belt (Hasui and Oliveira, 1984; Trompette, 1994; Vauchez et al., 1994; Cunningham et al., 1998). Orogen-normal shortening possibly started slightly before the formation of transcurrent shear zones, but transcurrent shearing in the main shear zones occurred under peak metamorphic conditions (granulitic facies in the northern part of the Ribeira belt) similar to the pressure and temperature conditions of shortening tectonics (Egydio-Silva et al., 2002). In addition, the northwestern boundary of the shear-zone displays a gradual transition between transcurrent shearing and orogen-normal shortening. Combination of coeval orogen-parallel shearing and orogen-normal shortening, i.e., transpression, is also predicted in this part of the belt by numerical models (Vauchez et al., 1994) due to accommodation of the southward termination of the stiff São Francisco craton.

- Regional tectonics of the Araçuaí belt is dominated by westward thrusting of allochthonous units toward the São Francisco craton, and only subsidiary orogen-parallel transport. This contrast with the transpressive style of the Ribeira belt, together with the northward rotation of the orogenic fabric from NE to ~ NS has raised the question whether the Araçuaí and Ribeira Neoproterozoic belts represent a continuous orogen or two distinct orogenic belts. A boundary between



(caption on next page)

Fig. 2. a) Shaded relief map with yellow arrows indicating convergence direction during the orogeny. B) Simplified geologic map of the Araçuaí-Ribeira orogenic system. 1: São Francisco craton, 2: Mobilized cratonic rocks, 3: Tectonic terranes of mostly continental margin origin, 4: Metasedimentary rocks, migmatitic in the hinterland, 5: granitic intrusions and anatexites. c) Pressure estimates (peak conditions). d) Temperature data. RJ: Rio de Janeiro; SP: São Paulo; BH: Belo Horizonte; SBB: Southern Brasilia Belt; CC: Carlos Chagas anatexite; APSZ: Alem Paraiba shear zone; V: Vitoria. e-f) Cross-sections as indicated in (b), in part from Vauchez et al. (2007) and Heilbron et al. (2008). TitaniQ temperatures represent minimum crystallization temperatures of quartz from Cavalcante et al. (2014). Other geobarothermometric data are from Garcia and Campos Neto (2003), Schmitt et al. (2004), Munhá et al. (2005), Belém (2006), Petitgirard et al. (2009), Uhlein et al. (2009), Bento dos Santos et al. (2010), Gradim et al. (2014), Moraes et al. (2015), and Degler et al. (2017). Modified from Fossen et al. (2017). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

these two domains was suggested at the 21ºS parallel, i.e., about the termination of the São Francisco craton (e.g., Pedrosa-Soares and Wiedemann-Leonardos, 2000; Heilbron et al., 2004 and references therein). However, such an ~ EW frontier between the two belts is not supported by recent geological and geophysical results. Instead, a gradual change in strain regime between these two belts agrees better with numerical modeling, mapping of foliation and lineation using the anisotropy of magnetic susceptibility (AMS) and seismic anisotropy measurements (Vauchez et al., 1994; Heintz et al., 2003; Egydio-Silva et al., 2005; Assumpção et al., 2006).

This paper aims to discuss the transition between the Araçuaí and Ribeira belts in the light of current geochronologic and structural data, numerical modeling and seismic anisotropy. We also discuss to what extent the structural differences are due to one single collision, or if the two belts experienced different orogenic histories.

2. Geologic setting

The Araçuaí and Ribeira orogenic segments (Fig. 2) are located in the northeastern and central parts of the Mantiqueira Province, respectively. Other Neoproterozoic Brasiliano belts, such as the Dom Feliciano belt in southern Brazil and Brasilia orogen south and west of the São Francisco craton, are somewhat older than the Araçuaí and Ribeira orogens, although with an overlap in age (Babinski et al., 1996; Silva et al., 2005; Philipp et al., 2016). The metamorphic peak in the Southern Brasilia belt at ca. 650-630 Ma (zircons U-Pb ages) is thought to coincide with the main collisional stage, while 600-580 Ma K/Ar mica ages are related to final cooling of the orogen (Valeriano et al., 2016). The peak event corresponds to the final collisional stage of the Dom Feliciano belt, which also has an older arc-related orogenic history (Fernandes et al., 1992; Philipp et al., 2016), while the Ribeira and Araçuaí belts are generally considered to have formed by convergent movements mainly in the interval (620–550 Ma; Valeriano et al., 2016; Heilbron et al., 2017). In these orogenic segments, the assumed pre-collisional stage of arc building is still poorly understood. For instance, recent geochronologic (Hollanda et al., 2014) and tectonic (Mondou et al., 2012) data rather suggest that, in the Araçuaí belt, the tonalitic-granodioritic magmatism, regarded as representing the pre-collisional arc magmatism (e.g., Tedeschi et al., 2016 and references therein) was syn-collisional.

2.1. *Araçuaí belt*

The Araçuaí belt displays a mostly ~ N-S structural trend and shows a progressive increase in metamorphic condition from the low-grade foreland to a high temperature –low-pressure hinterland. Its internal part has, to a first order, been described in terms of several domains of contrasting lithologic and tectonic characteristics (Fig. 3): a HT mylonitic zone separating the hot internal anatectic and plutonic core of the orogen from the metasedimentary cover of the craton (Oliveira et al., 2000; Vauchez et al., 2007) (Fig. 3).

The Mylonitic Unit (Fig. 3) is composed of mylonitic metasediments that display evidence of westward thrusting under high-temperature and low-pressure conditions (800-730 °C, 0.6 GPa) associated with leucocratic sills intrusion due to synkinematic partial melting dated at 577 ± 9 Ma (U-Pb on zircon, Petitgirard et al., 2009, Fig. 4a–b).

The Plutonic Unit (Figs. 3 and 4c-d) is dominated by high-temperature metasedimentary rocks intruded by synkinematic tonalitic and granodioritic bodies, dated at ~580 Ma and subsidiary granitic bodies emplaced during successive magmatic events until ~510 Ma (U-Pb on zircon, Mondou et al., 2012; Xavier, 2017). In this unit Mondou et al. (2012) documented a complex structural pattern, associated with belt-normal thrusting and subsidiary belt-parallel transcurrent motions (Fig. 5).

The Anatectic Unit comprises a thick (> 10 km) layer of diatexites, metatexites and anatectic granites (Carlos Chagas anatexite) associated with migmatitic granulite (Nova Venécia complex, to the north) and migmatitic kinzigite (Paraiba do Sul complex, to the south). This unit achieved its current migmatitic/magmatic aspects mainly as the result of partial melting of metasedimentary rocks at ~600-572 Ma (U-Pb on zircon and monazite (Vauchez et al., 2007; Hollanda et al., 2014; Kawata, 2014). The kinematic and geometric pattern in this domain is characterized by a predominantly subhorizontal migmatitic foliation, which bears a lineation showing a variation in orientation suggesting 3D deformation in the magmatic stage (Cavalcante et al., 2013, Fig. 4e–f), i.e. quite different from the well-structured Ribeira belt (see below).

Ti-in-Quartz thermometry data suggest that temperatures > 800 °C were reached during the melting event (Cavalcante et al., 2014), and deformation mostly occurred in the magmatic state as supported by the preservation of a well-oriented magmatic fabric and scarce evidence of weak to moderate solid-state reworking (Mondou et al., 2012; Cavalcante et al., 2013). The anatexites are intruded by charnockite and biotite-granite from a late to post-tectonic magmatic event lasting from ~540 to 480 Ma (e.g. Sollner et al., 1991; Noce et al., 2000; Magalhães, 2010; Mondou et al., 2012; Toledo, 2015; Xavier, 2017).

2.2. *Ribeira belt*

The Ribeira belt (Fig. 1) was initially defined as a folded system that extend along the eastern coast of Brazil from the south of Bahia at ~16° S until Uruguai at ~35° S (Hasui et al., 1975). Currently, the Ribeira belt encompass the tectonic units in the southeastern Brazil (Fig. 6) characterized by a major NE-SW strike-slip system of anastomosing transcurrent shear zones that deform the Paleoproterozoic basement, the Mesoproterozoic and Neoproterozoic metasedimentary sequences, and large volumes of syn-orogenic Neoproterozoic granitic plutons, juxtaposing different tectonic blocks or terranes that were reworked during the Brasiliano orogeny (Campanha and Sadowski (1999; Campos Neto, 2000; Janasi et al., 2001, 2009; Heilbron et al., 2008; Valeriano et al., 2016). The shear zones separate domains of thrusted and folded rock units (Fig. 2f), consistent with large-scale partitioning of transpressional deformation into orogen-parallel and orogen-normal components. Several attempts have been made to define the deformed rocks of the Ribeira belt into a system of different tectonic units or terranes, of which Fig. 6 is only one example and represents an early view of the main tectonics units in southeastern Brazil (e.g., Campanha and Sadowski, 1999; Heilbron et al., 2008, 2017; Basei et al., 2010; Trouw et al., 2013; Bento dos Santos et al., 2015; Valeriano et al. (2016). In this work, we have avoided interpretation of the various domains defined in the Ribeira belt since many discordant ones have been already published and due to insufficient geochronologic, geochemical and

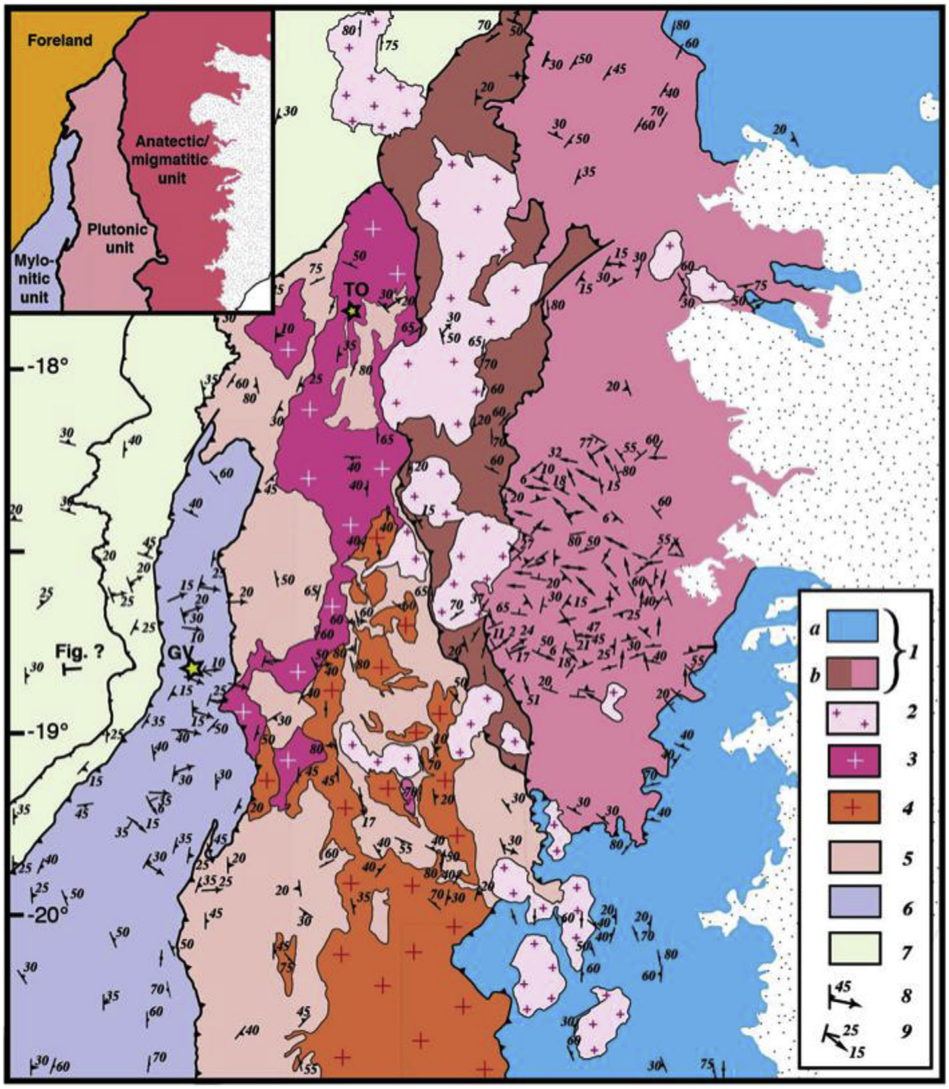


Fig. 3. Simplified map of the Araçuaí belt showing the main tectonic domains (inset), lithologic units and fabric orientation. 1: diatexites, metatexites and anatectic granites (a) associated with migmatitic granulite and migmatitic kinzigite (b). 2: Late-orogenic granite and charnockite. 3: São Vitor tonalite. 4: Galiléia batholith. 5: High-T metasedimentary rocks. 6: metasedimentary and metaigneous mylonites. 7: Mobilized São Francisco crust. GV = Governador Valadares; TO = Teofilo Otoni. 8: Magnetic foliation and magnetic lineation. 9: Foliation and stretching lineation observed in the field. Based on Vauchez et al. (2007), Mondou et al. (2012) and Cavalcante et al. (2013).

lithologic data, more work is needed to properly define theses units and understand their relations.

An interesting characteristic of the Ribeira belt is the general increase in metamorphic grade from south to north. Campanha and Sadowski (1999) describe the southern portion of the Ribeira belt as being characterized by a large volume of metasedimentary rocks of low metamorphic grade (Açungui Supergroup), migmatites and gneisses of the basement (Atuba Complex). Metavolcanosedimentary rocks, orthogneisses and large volume of granitic rocks (Embú and Costeiro Complexes) characterize the central sector of the belt. High temperature paragneisses, migmatites, charnockite and granitic rocks (the Paraiba do Sul and Juiz de Fora domains) more similar to the rocks and metamorphic condition in the Araçuaí belt (Fig. 6) compose the northern region. Also rocks of the Cabo Frio domain (Fig. 2) underwent high-grade metamorphism, but this terrane is related to a younger collisional event dated at 540-490 Ma (Schmitt et al., 2004, 2016), and Monié et al. (2012) suggested that it is correlated with the southernmost part of the West-Congo orogenic belt (This Cambrian collisional event, called the Buzios orogeny by Schmitt et al. (2004), has tentatively been explained in terms of a lineament on the African side of the orogenic system (Luanda shear zone) separating a northern and southern part of the Congo craton (Heilbron et al., 2008; Tupinambá et al., 2012). This model, however, does not explain the similar young deformation ages in the southernmost West Congo Belt (Monié et al., 2012). Regardless, the Cabo Frio orogen is significantly younger than the main Ribeira-Araçuaí orogeny, and should be treated separately.

3. Geochronologic and thermal similarities between the Ribeira and Araçuaí belts

The geochronologic data available for Ribeira and Araçuaí belts, which can be separated into peak metamorphic and crystallization ages, are quite similar (Fig. 7). Pedrosa-Soares et al. (2001) consider that a continental magmatic arc was built in the core of the Araçuaí belt at ca. 625-590 Ma, and that the collision between the South American and African proto-continents occurred at 591-575 Ma. However, coupling U/Pb dating of zircon and structural analysis (Vauchez et al., 2007; Petitgirard et al., 2009; Mondou et al., 2012; Hollanda et al., 2014) substantiate that the extensive tonalitic/granodioritic magmatism was synchronous with high-temperature deformation and partial melting of the middle/lower crust active between at least 600 and 570 Ma in response to crustal thickening and cannot represent a pre-collisional magmatic arc (Vauchez et al., 2007; Mondou et al., 2012; Fossen et al., 2017). Older ages, like 625-600 Ma, are uncommon in the tonalite-granodiorite batholith and need to be confirmed. Most published ages are younger than 590 Ma and thus contemporaneous of the synkinematic high temperature metamorphism. Several syn-to post-collisional magmatic pulses follow the orogenic magmatic peak until ~520-500 Ma (e.g. Noce et al., 2000; Xavier, 2017). This magmatic evolution and its relationship with deformation and metamorphism are grossly coeval

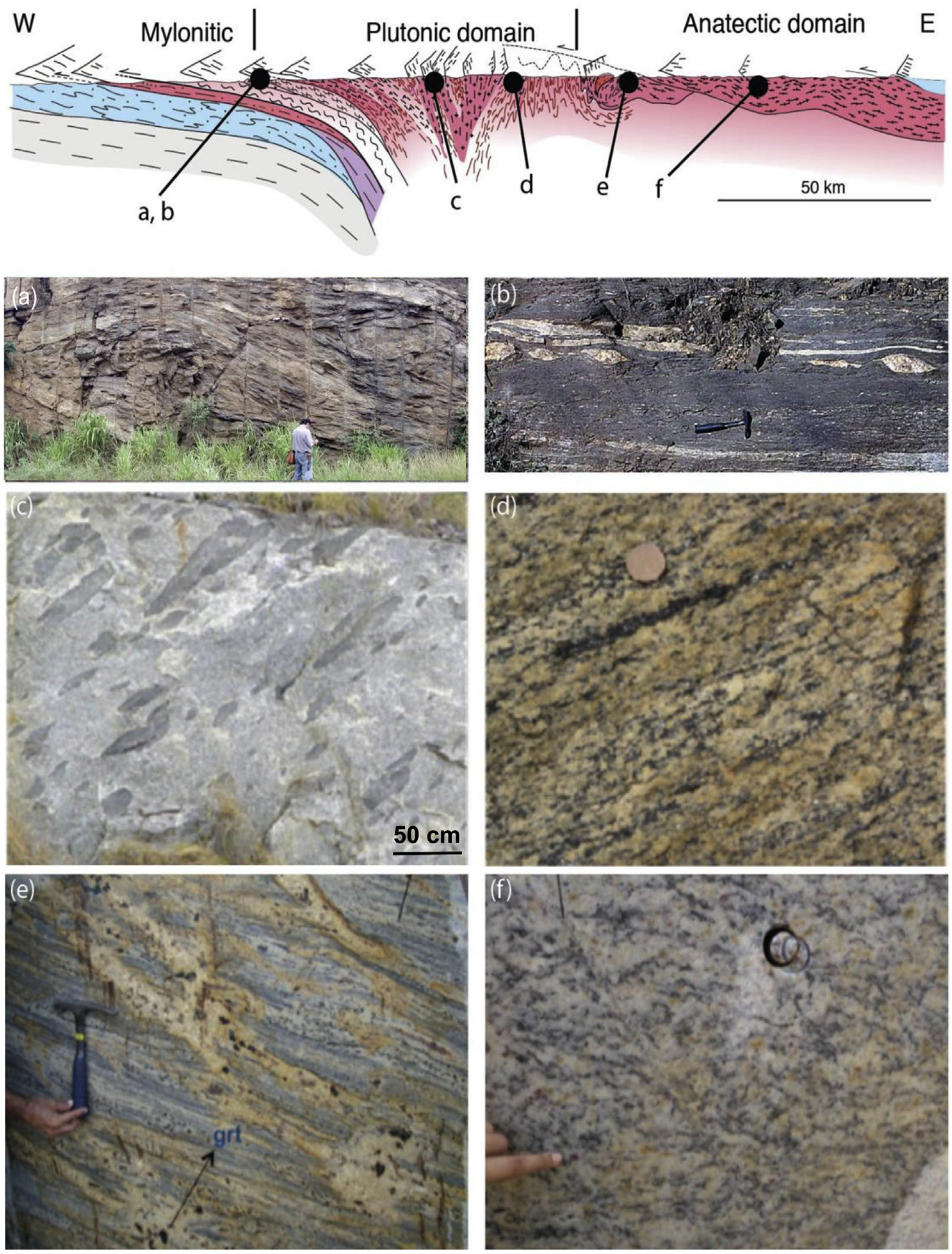


Fig. 4. Schematic cross-section across the Araçuaí orogen (After Vauchez et al., 2007; see Fig. 2 for location) and photos of characteristic lithologies. a-b) The Mylonitic unit, showing kinematic transport to the west. From Mondou et al. (2012); c-d) The Plutonic unit represented by the Galiléia tonalite (c) and an example of strong preferred orientation of elongated mafic enclaves within the tonalite (d); Migmatitic structures (e) and anatexite (f) of the Carlos Chagas Anatectic unit.

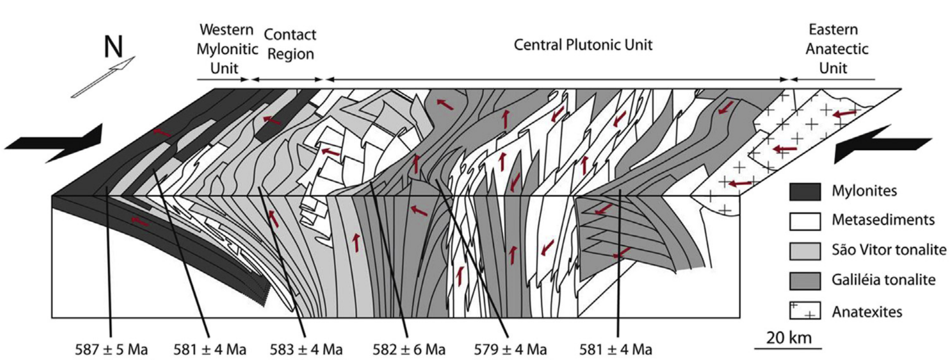


Fig. 5. 3D diagram exhibiting the complex structural pattern of the Plutonic Unit. Dips are extrapolated downward. Red arrows represent the local direction of crustal flow. Plutonic crystallization ages obtained in the different structural subregions are indicated. See Mondou et al. (2012) for details. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

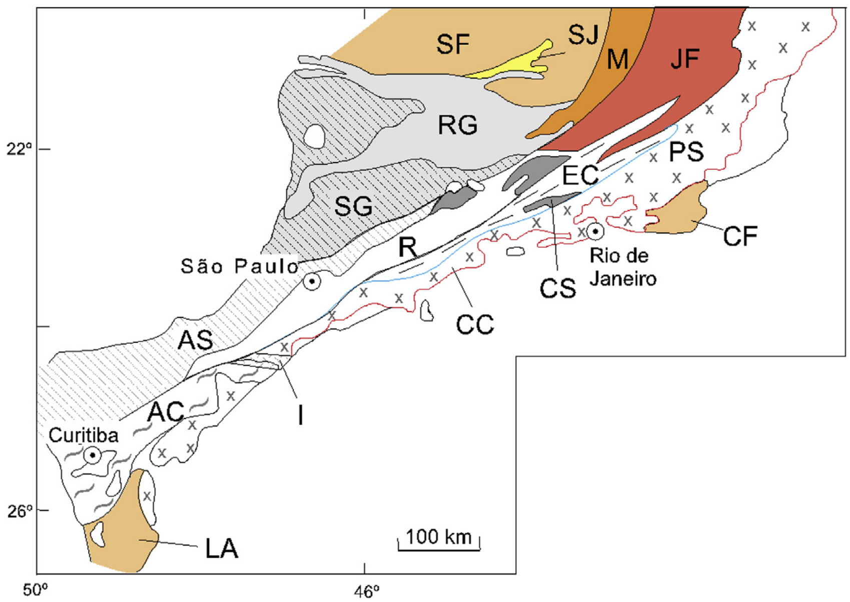


Fig. 6. The main tectonic units of southeastern Brazil. Cratonic fragments or blocks: (LA) Luís Alves, (I) Itatins; (SF) São Francisco. Mesoproterozoic to Neoproterozoic fold belts: (RG) Alto Rio Grande, (R) Ribeira, (AS) Assungui Group, (CC) Costeiro Complex and (SG) Socorro-Guaxupé Nappe. Archean and Paleoproterozoic high-grade rocks, reworked in Brasiliano: (AC) Atuba Complex, (M) Mantiqueira Complex, (SF) Juiz de Fora Complex, (EC) Embu Complex, (PS) Paraíba do Sul Complex, (SJ) São Jõao de Rei Group. Ediacaran to Cambrian rocks: (CF) Cabo Frio terrane. Cenozoic sediments (CS). Modified from Campanha and Sadowski (1999) and Valeriano et al. (2016).

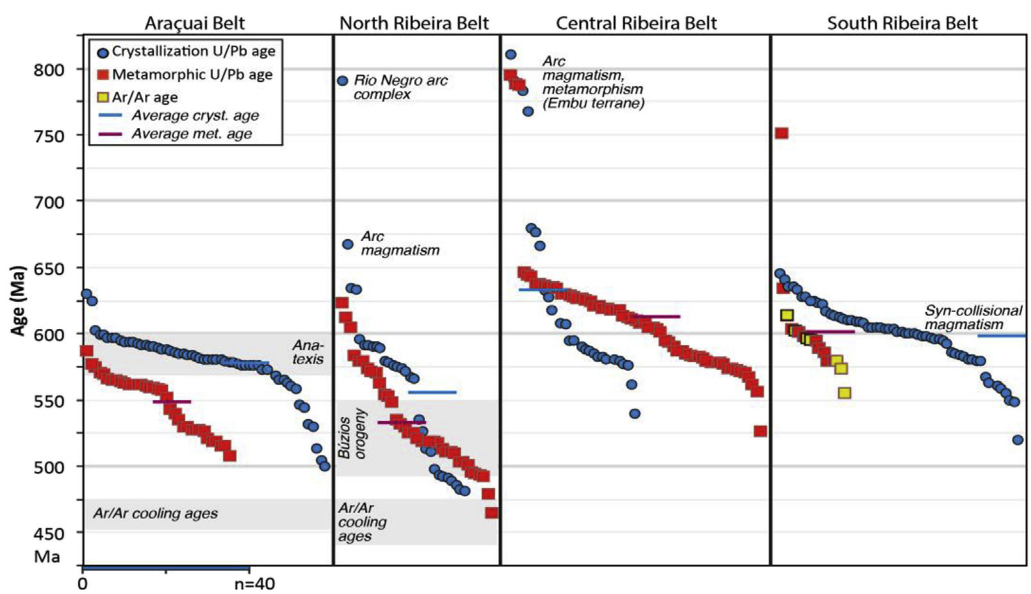


Fig. 7. Compilation of published ages (mostly U/Pb) from the Araçuaí belt and the northern, central and southern parts of the Ribeira belt. Crystallization ages represent magmatic crystallization, including crystallization of leucosomes in anatexites. The Ribeira belt contains a few older ages that might suggest components of early arc formation. Based on data compiled by Meira et al. (2015) and, with additional data from the Araçuaí belt by Hollanda et al. (2014) and Melo et al. (2017a, b) and summarized by Bento dos Santos et al. (2015).

with the tectonic evolution of the central part of the Ribeira belt during the Brasiliano orogenic development.

Bento dos Santos et al. (2015) suggested that collision initiated at ca. 610-590 Ma in the central part of the Ribeira belt, consistent with the metamorphic ages (630-600 Ma) recorded in the paleoproterozoic metamorphic basement of the Embu terrane (Trouw et al., 2013; Meira et al., 2015); Costa et al., 2017). The younger event is considered by Meira et al. (2015) to be followed by a syn-collisional granulite facies period, with partial melting of the lower crust continuing until ca. 600-550 Ma, and post-orogenic magmatism occurring at ca. 520–480 Ma.

Similarly, the syn-kinematic metamorphism, which is considered coeval with deformation, partial melting and tonalitic/granodioritic magmatism, has been dated at ~580 Ma in the Araçuaí and ~590 Ma in the Ribeira belt (Petitgirard et al., 2009; Machado et al., 1996) respectively. Both regions show very slow cooling rates, which have been estimated to ~3 °C/Ma for the Araçuaí belt (Petitgirard et al., 2009) and ~1 °C/Ma in the Ribeira belt (Bento dos Santos et al., 2015).

Machado et al. (1996) conclude that a significant portion of the northern Ribeira belt attained peak-metamorphic conditions at 590-565 Ma. Younger ages of 519–513 Ma of post-tectonic plutons and the late metamorphic event (M2) are recorded only in the Paraiba do Sul complex that could be due to the influence of the Buzios orogeny (510-470 Ma; Schmitt et al. (2004)).

Thermobarometric estimates for the Ribeira belt suggest temperatures of ~800 °C and pressures of 0.7 GPa (Fig. 2b, d) (Munhá et al., 2005; Bento dos Santos et al., 2010). For the Araçuaí belt, preliminary pressure and temperature evaluation in mylonites from the western mylonitic unit suggest temperatures ranging between 800 and 730 °C, and pressures of ~0.6 GPa (Petitgirard et al., 2009). Similarly, in the eastern Anatectic Unit, temperature estimates using the Titani-Q geothermometer suggest that quartz crystallized at ~800 °C, supporting peak temperature ≥800 °C (Cavalcante et al., 2014). This melt crystallization gives a minimum age of initial partial melting of the core of the Araçuaí belt, and has been dated to 600-572 Ma (Hollanda et al., 2014). Temperatures in excess of 800 °C and pressures around 0.6–0.7 GPa are therefore considered to be representative of the metamorphic peak conditions in both the Ribeira and Araçuaí sections, as shown in Fig. 2.

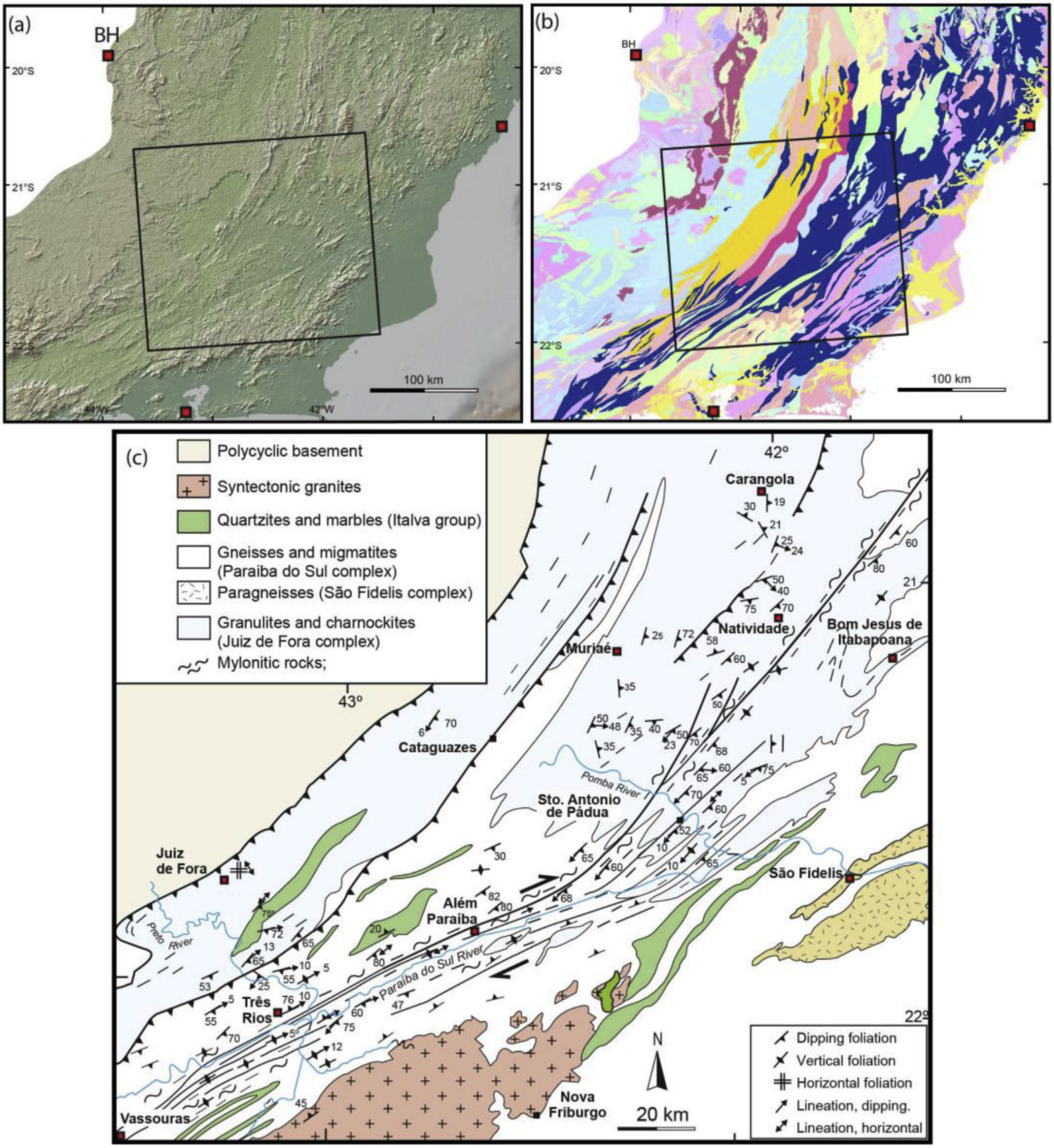


Fig. 8. Junction between the Araçuai and Ribeira orogenic segments: a) Shaded elevation model (made from GeoMapApp) of the transitional zone between Ribeira and Araçuaí belts. B) Lithologic map of the same area, showing the lithologic units of the southern Araçuai belt being thinned into the Ribeira belt as a result of dextral shearing (based on public digital maps from CPRM). c) Structural map of the subarea indicated in (a) and (b), showing the orientation of the dominant orogenic fabric. These three maps show that there is both structural and lithologic continuity.

4. The structural transition between Araçuaí and Ribeira belts

Comparing the structural geology of the Araçuaí and Ribeira belts reveals a gradual transition in tectonic style between these two belts, which is already reflected in the topographic expressions of the two domains (Fig. 8a). The Araçuaí belt shows foreland-directed thrusting with an anatectic core in which the tectonic fabric (especially lineations) displays lateral variations consistent with 3-D flow. In contrast, the central part of the Ribeira belt is characterized by a wide, well-defined NE-SW trending set of shear zones that display a steeply dipping foliation bearing a subhorizontal lineation (Fig. 9 a, b, d). Outside the shear zones, the foliation progressively changes to gently dipping and the lineation to NW-SE. This supports a combination of orogen-parallel strike slip and orogen-normal thrusting kinematics.

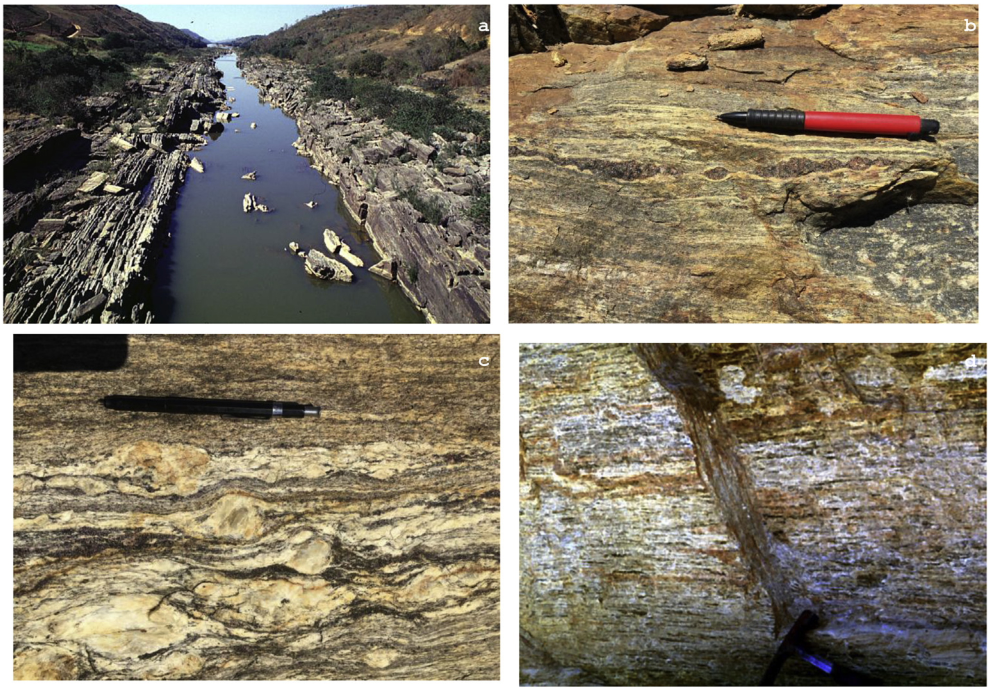


Fig. 9. Representative examples of mylonites from the HT Alem Paraiba dextral shear zone: a) outcrop within the Além Paraíba shear zone (Rio de Janeiro state). B) Porphyroclasts of garnets stretched in strongly deformed in high temperature paragneisses. c) Close-up of a sigma porphyroclast in the mylonitic rocks (dextral sense of shear). d) Subhorizontal stretching lineation marked by biotite, quartz and orthopyroxene on a subvertical foliation plane in the Além Paraíba trascurrent shear zone.

Toward the southern termination of the São Francisco craton the structural pattern changes progressively. The trend of the orogenic fabric is curved from North-South to NE-SW, and the lithologic units, as mapped in the Araçuaí belt, generally become narrower southward, and display a very clear development of parallel bands that reflect the progressive dominance of transcurrent shear strains approaching of the Ribeira belt (Fig. 8b).

Narrow belt-parallel ductile strike-slip shear zones progressively widen and merge southward, forming several NE-SW trending HT mylonite zones, the main one being the Alem Paraiba dextral shear zone (Figs. 2b and 9 a, b, c) in the central portion of the Rio de Janeiro state, which is ~15 km thick and is considered to represent a lithospheric-scale strike slip zone (Vauchez et al., 1994; Heintz et al., 2003; Assumpção et al., 2006).

A progressive change from one system to the other was substantiated through mapping of magnetic foliations and lineations using

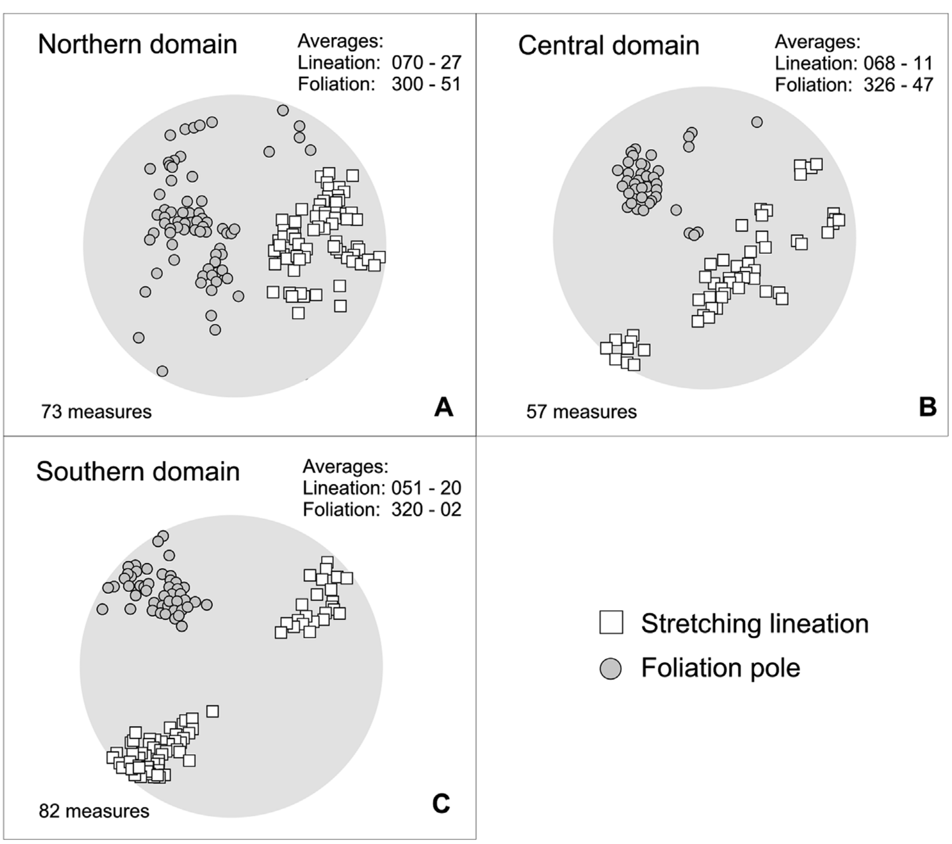


Fig. 10. Spherical projections of the magnetic foliations and lineations from the three different structural patterns showing gradual transition in the fabric orientations from Araçuaí belt (A) to Ribeira belt (C) through the transition zone (B). Plots are lower hemisphere, equal area projection. Modified from Egydio-Silva et al. (2005).

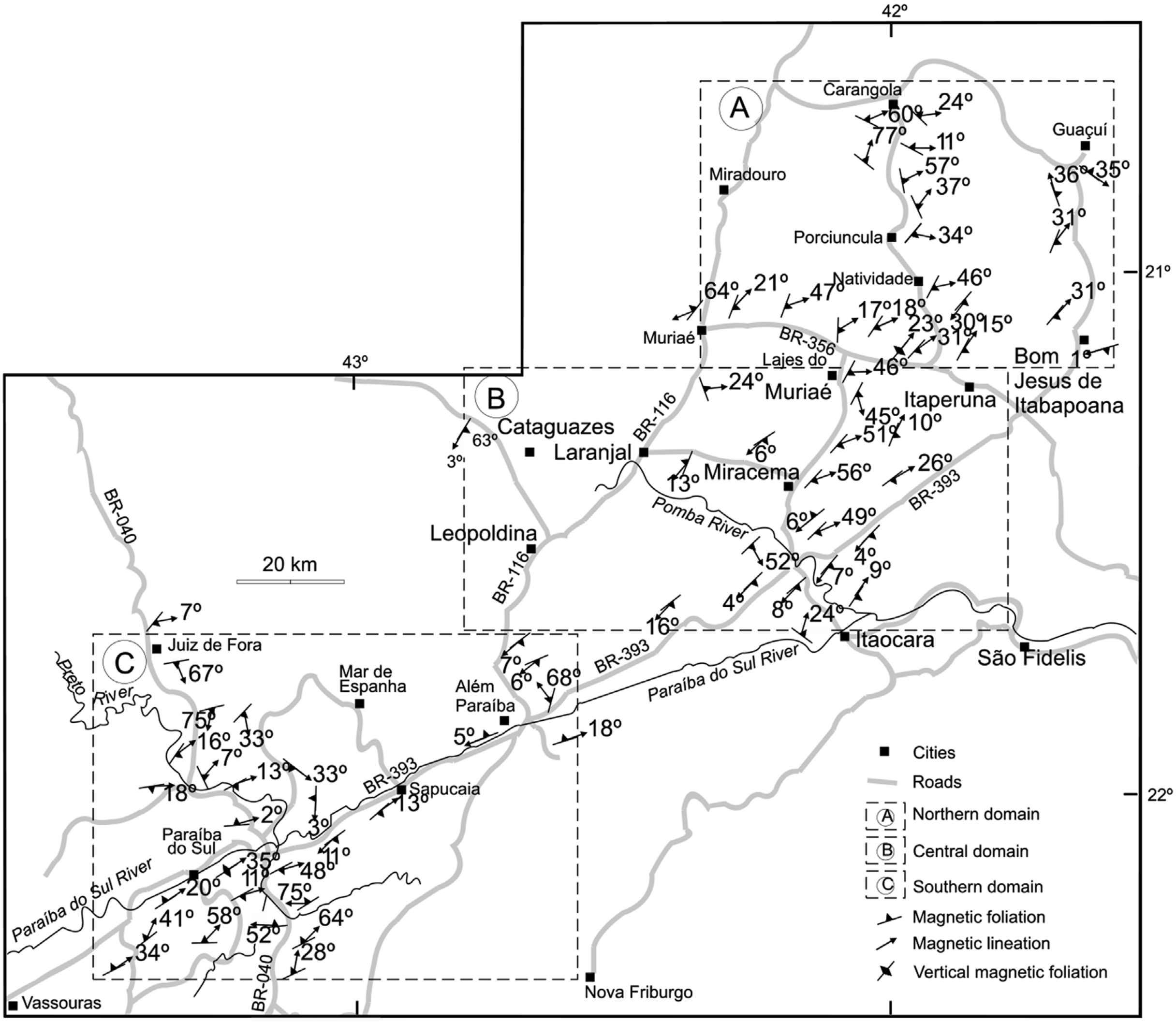


Fig. 11. Map showing variations in the magnetic lineation and foliation from a transcurrent-dominated southern domain to a contraction-dominated northern domain. Modified from Egydio-Silva et al. (2005).

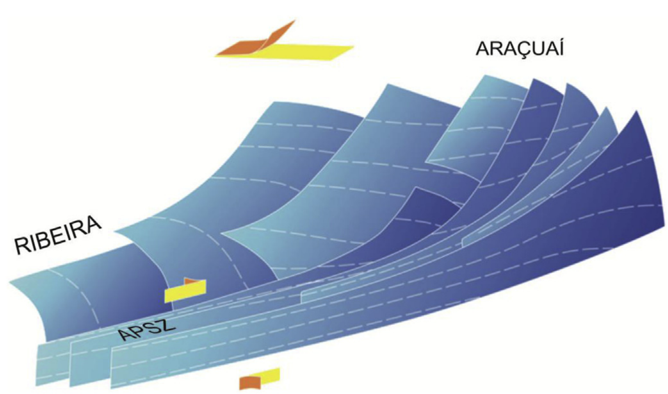


Fig. 12. Schematic illustration of how the structural style and kinematics vary along the transition between Ribeira (southern) and Araçuaí (northern) domains and the Alem Paraiba shear zone (APSZ). Surfaces represent the foliation and dashed white lines represent the lineation as defined by AMS data and field observations. Modified from Egydio-Silva et al. (2005).

the Anisotropy of Magnetic Susceptibility technique in three different domains, where a transition in deformation regime occurs from sector A to C, inside the Ribeira and Araçuaí belts (Figs. 10 and 11). Magnetic fabrics, compared with field measurements, have shown to be a good proxy of tectonic fabrics. The continuity of the structures and a progressive rotation of the structural trend suggest that there is structural continuity between the two belts.

Structural measurements at the transition between the contraction-dominated Araçuaí domain and the transpressional Ribeira domain provide new insights into how the transition between these two deformation regimes was accommodated in a broad transpressional zone where strike-slip and thrusting under HT conditions coexist at various scales (Figs. 11 and 12).

Numerical modeling of the deformation of a lithospheric plate containing a stiff block undergoing E-W shortening suggests that the modification of the structural trend and deformation regime between the Ribeira and Araçuaí belts may be due to the termination of the São Francisco craton (Vauchez et al., 1994). In these models, approaching the termination of the craton southward, the structural trend rotates progressively from north-south to northeast-southwest and correspondingly, the kinematics change from a dominant east-west shortening accompanied by significant crustal thickening to dextral shearing along the northeast-southwest trend associated with a limited thickening that decreases southwestward along the shear zone (Fig. 13).

Vauchez et al. (1994) concluded that during a continental collision, the rheological contrast between a stiff craton and weaker surrounding

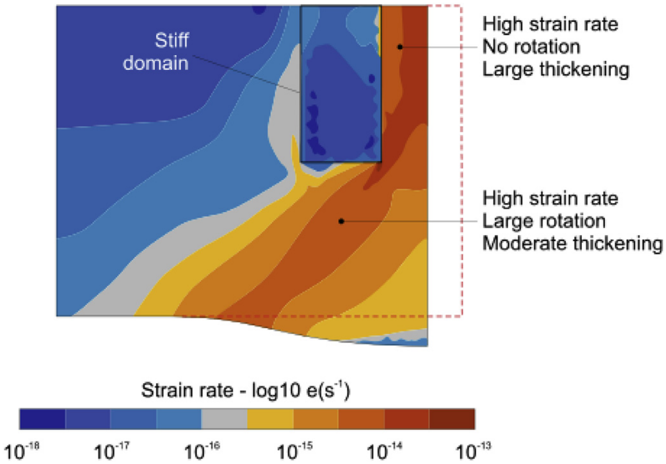


Fig. 13. Numerical model simulating the deformation of a lithospheric plate involving a cratonic domain. Isovalues (logarithmic scale) of the strain rate in the horizontal plane. East of the stiff block the modeled lithosphere underwent high strain, large thickening and mostly coaxial deformation (no rotation component). South of the termination of the cratonic domain, high strain deformation is localized in an oblique, narrower domain in which non-coaxial deformation (dextral shearing) and moderate thickening predominate. Modified from Vauchez et al. (1994).

terranes can control the amount of strain and related displacement field over a large continental area.

A similar structural pattern can be observed in the Canadian shield (Hoffman, 1987; Tommasi and Vauchez, 2015), where the collision between the Churchill province and Slave craton (2.0–1.8Ga) resulted in the development of the Queen Maud/Thelon belt characterized by a dominantly contractional regime, and the Great Slave Lake transcurrent shear zone at the southern termination of the Slave craton (Fig. 14a). In South Australia, the tectonic fabric of the Adelaide belt, formed during the Delamerian orogeny (514-490 Ma), also displays a marked curvature likely due to the southern termination of a corner of the Gawler craton (Marshak and Flöttmann, 1996). The Ribeira-Araçuaí belt and the Canadian and Australian orogenic systems display strikingly similar strain pattern related to the termination of a cratonic domain, as supported by numerical modeling (Vauchez et al., 1994).

Heintz et al. (2003) and Assumpção et al. (2006) have characterized the upper mantle seismic anisotropy in southeast and central Brazil using measurements of core-refracted shear wave splitting (mainly SKS phases). Although the fast polarization direction in western Brazil tends to be close to the current absolute plate motion, larger delay-time, rotation of the polarization direction over short distances (< 50 km) outside the transcurrent corridor, and correlation with geologic structures are observed in the southern Brasilia belt and in the Ribeira belt SE and S of the São Francisco craton (Fig. 14b). In the central Ribeira belt the fast split shear-wave polarization direction is sub-parallel to the NE-SW structural trend. Northward, it becomes oblique as the structural grain turns N-S. In addition, contrasts in polarization of the fast S-wave occurring at a scale shorter than the Fresnel zone of S-waves at the base of a normal lithosphere, supports a lithospheric source of the anisotropy in the Ribeira belt (Heintz et al., 2003; Assumpção et al., 2006).

Wu et al. (2002) used magnetoteluric and seismic anisotropy surveys to probe the anisotropy beneath the Great Slave Lake shear zone and determined a subparallelism of the fast S-wave polarization, the fast conductivity directions and the fabric of the shear zone. Tommasi and Vauchez (2015) emphasize that thermal heterogeneities in the lithospheric mantle frequently explain the large-scale strain pattern in continental plates that underwent multiple collision events. They further highlight that stress concentration at the tips of large-scale stiff heterogeneities within continental plates during convergent tectonics may result in the development of transpressional shear zones of the kinds seen in the Ribeira belt and in the Great Slave shear zone.

5. Discussion and conclusion

We have reviewed the structural situation at the transition between the Araçuaí and Ribeira belts, and shown that the two belts, despite

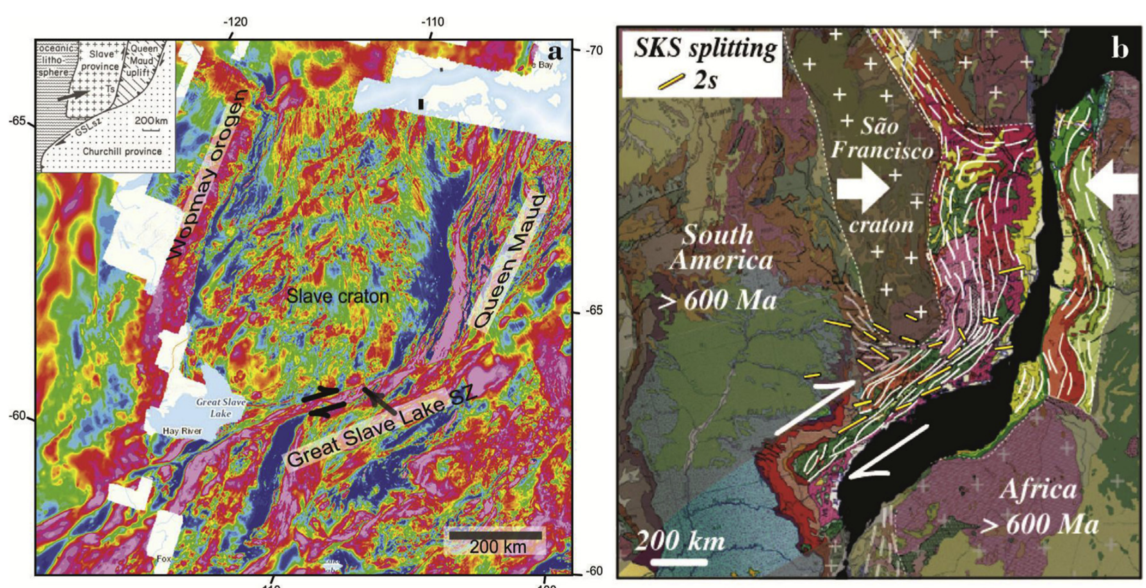


Fig. 14. Transpressional shear zones developed at the termination of a cratonic domain: a) First vertical derivative of the magnetic field of the Slave Craton, Great Slave Lake shear zone and surrounding geodynamic domains in the Canadian shield. 200 m grid. Geological Survey of Canada. The Great Slave Lake Shear Zone system formed at the tip of the Slave craton that represents the rigid element. Insert is the tectonic model from Hoffman (Hoffman, 1987). B) The Ribeira belt, with the rigid São Francisco craton. In both cases the shape or termination of the craton imposed changes in kinematics and tectonic style. SKS splitting data in the Ribeira belt, indicated by yellow bars showing polarization of the fast S-wave (thick bars represent more reliable data in b) support lithosphere mantle flow reflects shear belt-parallel mantle anisotropy. SKS data from Heintz et al. (2003), Assumpção et al. (2006), Assumpção et al. (2011). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

their differences in tectonic fabric and strain regime formed concomitantly during the Neoproterozoic amalgamation of West Gondwana due to the convergence of the São Francisco and Congo cratons.

The structural geological map of the transition zone is mainly based on the Anisotropy of Magnetic Susceptibility data (Figs. 10 and 11) and field observations (Fig. 8c) and both suggest that the lineation and foliation progressively rotate from a NE-SW vertical foliation and horizontal lineation in the southern domain, to a N-S trending foliation with a down dip lineation in the northern domain. Structural observations in the southernmost Araçuaí belt (e.g., Cunningham et al., 1998) clearly show that the transpressional regime, dominant in the Ribeira belt, still contributes significantly to the bulk strain regime in all curved domain of the belt. This spatial change in fabric orientation is likely associated with the termination of a stiff lithospheric block, the São Francisco craton. This stiff domain represents a first-order heterogeneity that is responsible for the localization of strain to a belt along the edge of the craton (Vauchez et al., 1994).

Besides the structural continuity between Ribeira and Araçuaí belts, geochronologic data (Noce et al., 2000; Petitgirard et al., 2009; Bento dos Santos et al., 2010, 2015; Mondou et al., 2012; Hollanda et al., 2014) also sustain the contemporaneity of the Pan-African events in both orogens, and existing data support that the main orogenic activity (deformation, metamorphism and magmatism) occurred between 600 and 570 Ma in the both the Ribeira and Araçuaí orogens (Fig. 2). In addition, theses two orogenic segments show a similar thermal evolution characterized by an abnormally high orogenic geotherm that triggered melting in the middle crust and prolonged high-temperature conditions (cooling rate of $< 5\,^{\circ}$C/My) typical of “hot orogens” (Bascou et al., 2002; Munhá et al., 2005; Petitgirard et al., 2009; Bento dos Santos et al., 2010; Cavalcante et al., 2014; Bento dos Santos et al., 2015). Furthermore, the peak metamorphic pressures for the internal parts of the belts are also similar, and generally around 0.6–0.7 GPa.

A transition from a contractional to a transpressional or transcurrent deformation regime at the tip of the cratonic São Francisco block has been substantiated and this validate the numerical models by Vauchez et al. (1994). A similar regional deformation pattern is also observed in the Canadian Slave Province and its Paleoproterozoic convergence with the Archean. This orogenic evolution resulted in the development of the Great Slave Lake transcurrent shear zone and of the Queen Maud/Thelon orogenic belt (Hoffman, 1987) with a structural pattern very similar to that of the Ribeira-Araçuaí orogenic system.

Numerical modeling supports that such a transition is mechanically realistic when stiff heterogeneities are present in the lithosphere. The pioneer work of Vilotte et al. (1984) developed from the example of the Althyn Tagh Fault zone nucleated at the boundary of the Tarim cratonic domain in the Himalaya, showed that during continental collision, stiff heterogeneities in a “normal” lithosphere may generate changes in orogenic trend and deformation regime. This concept was then used to model the formation of the Ribeira-Araçuaí orogenic system (SE Brazil) and the continental scale shear-zones system of the Borborema Province in NE Brazil (Vauchez et al., 1994; Tommasi et al., 1995).

Altogether, the data and models presented above support that the Araçuaí and Ribeira belts should be considered as two segments of the same orogenic belt and that the difference between them is mostly about kinematics and resulting tectonic style. We show that the transition between them is gradual; hence there is no definable that boundary between the Araçuaí and Ribeira orogenic segments along the parallel 21°, as previously suggested. The Ribeira-Araçuaí orogenic system should be regarded as the result of the deformation of a heterogeneous continental lithosphere during the convergence of proto-continents that built West Gondwana.

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