

# Toward an integrated model of geological evolution for NE Brazil–NW Africa: The Borborema Province and its connections to the Trans-Saharan (Benino-Nigerian and Tuareg shields) and Central African orogens

Fabrício de Andrade Caxito<sup>1\*</sup> , Lauro César Montefalco de Lira Santos<sup>2</sup> , Carlos Eduardo Ganade<sup>3</sup> , Abderrahmane Bendaoud<sup>4</sup> , El-Hocine Fettous<sup>4</sup> , Merlain Houketchang Bouyou<sup>5</sup> 

## Abstract

Both the Borborema Province of NE Brazil and the geological provinces of NW Africa (the Trans-Saharan Orogen consisted of the Tuareg and Benino-Nigerian shields and the Central African Orogen of Cameroon, Chad, and Central African Republic) are complex geological regions with superposition of distinct deformational, metamorphic and magmatic events and final structural configuration during the Brasiliano/Pan-African Orogeny (ca. 625–510 Ma). These provinces represent the site of major mountain building processes in the Ediacaran/Cambrian transition that culminated in the amalgamation of West Gondwana after the collision of the West African–São Luís, São Francisco–Congo, and Saharan paleocontinents. In the last years, discovery and characterization of key tectonic units such as ophiolites, eclogites, HP/UHP rocks, and both oceanic and continental magmatic arcs are helping to clarify these processes and propose tectonic models for the geological evolution of NE Brazil–NW Africa. Connections of the marginal belts that frame these provinces, bordering the eastern margin of the West African–São Luís Craton (Médio Coreáú–Dahomeyides–Gourma–West Tuareg Shield) and the northern margin of the São Francisco–Congo Craton (Rio Preto–Riacho do Pontal–Sergipano–Yaoundé–Central African) are progressively better constrained, while correlations within the interior, highly reworked and sectioned portions of both the Borborema Province, the Benino–Nigerian Shield, the Central and East Tuareg Shield, Western Cameroon, and Adamawa–Yadé domains are more complicated and demand further investigation. Some of the questions of prime importance in this context are the continuation or not of the 1000–920 Ma Cariris Velhos Belt of NE Brazil into NW Africa, and if the basement-dominated North Borborema/Benino-Nigerian (NOBO-BENI) and Alto Pajeú–Alto Moxotó–Rio Capibaribe–Pernambuco–Alagoas/Adamawa–Yadé (APAMCAPAY) domains could represent major decretionized blocks (such as LATEA in the Central Tuareg Shield), perhaps developed due to hyperextension and detachment of a Greater São Francisco–Congo paleocontinent northern margin. In this case, the Goiás–Pharusian and Transnordestino–Central African oceanic realms along with restricted internal oceans such as the hypothetical Piancó–Alto Brígida/Western Cameroon (PAB-WECA) Seaway probably separated these ancient paleocontinental blocks during the Neoproterozoic. The development of subduction zones and the docking of Neoproterozoic juvenile terranes welded the hyperextended Archean/Paleoproterozoic lithospheric fragments together and they became squeezed and reworked in between the major cratonic landmasses during the Brasiliano/Pan-African Orogeny. The quest for the sites of ancient oceans and continents that once composed NE Brazil and NW Africa goes on and tentative scenarios will surely benefit from novel geological, isotopic, and geochronological data put forward in the near future.

**KEYWORDS:** Borborema Province; West Gondwana; Neoproterozoic; Transaharan; Brasiliano/Pan-African.

## INTRODUCTION

The Borborema Province (Ebert 1970, Almeida *et al.* 1981) in northeastern Brazil (Figs. 1, 2 and 3) is a region of great

structural complexity, with superposition of distinct deformational, metamorphic, and magmatic events and final structural configuration in the collisional and post-collisional (transcurrent) stages of the Brasiliano/Pan-African Orogeny (ca. 625–510 Ma). Currently, there are various proposed models for the geological evolution of this area. A first group of hypothesis suggests the development of plate tectonic processes during the Neoproterozoic, either involving: progressive accretion of exotic terranes (*e.g.*, Santos 1996, Santos *et al.* 2000, Brito Neves *et al.* 2000, Santos L.C.M.L. *et al.* 2017b, 2018); complete Wilson cycles involving crustal rifting, opening and closing of oceans, installation of subduction zones and continental collision (*e.g.*, Oliveira *et al.* 2010, Caxito *et al.* 2014b, 2014d, 2016, Basto *et al.* 2019); or a combination of complete tectonic cycles at the province's borders and reworking of pre-Neoproterozoic crust in an intracontinental setting at its core (Ganade de Araújo *et al.* 2014c). A second hypothesis is that the province involves the reworking of a single continental

<sup>1</sup>Centro de Pesquisas Manoel Teixeira da Costa, Universidade Federal de Minas Gerais – Belo Horizonte (MG), Brazil. E-mail: caxito@ufmg.br

<sup>2</sup>Universidade Federal de Pernambuco – Recife (PE), Brazil. E-mail: lauromontefalco@gmail.com

<sup>3</sup>Geological Survey of Brazil – Rio de Janeiro (RJ), Brazil. E-mail: caegeo@gmail.com

<sup>4</sup>Laboratoire de Géodynamique, Géologie de l'Ingénieur et Planétologie, Université des Sciences et de la Technologie Houari Boumediene – Algiers, Algeria. E-mails: abendaoud@gmail.com, hfettous@gmail.com

<sup>5</sup>Centre for Geological and Mining Research – Garoua, Cameroon. E-mail: mbouyou2001@yahoo.fr

\*Corresponding author.



block, which remained relatively stable from approximately 2.0 Ga (part of the Atlantica supercontinent of Rogers 1996) and was then affected by the installation and further inversion of mainly intracontinental basins (and local basins with restricted development to a proto-oceanic state; Neves 2003, 2018; Neves *et al.* 2006, 2009) throughout the remainder of the Proterozoic. In this last scenario, the metamorphism, deformation, and magmatism associated with the Brasiliano Orogeny in this region would have been essentially caused by intracontinental processes, although locally, subduction and common plate convergence processes are not completely ruled out (Neves 2018).

Correlations between the Borborema Province and provinces in NW Africa equally affected by the Brasiliano/Pan African Orogeny have long been proposed (*e.g.*, Hurley *et al.* 1967, Caby 1989, Castaing *et al.* 1994, Toteu *et al.* 2001, Brito Neves *et al.* 2002, Oliveira *et al.* 2006, Arthaud *et al.* 2008, Dada 2008, Santos *et al.* 2008b, Van Schmus *et al.* 2008, Kalsbeek *et al.* 2013, Ganade de Araújo *et al.* 2016). The NW Africa provinces (Figs. 1, 2, 4 and 5) comprise the Benino-Nigerian Shield, the Tuareg Shield of Algeria, Niger and Mali, the Dahomeyides-Gourma Orogen of Togo, Benin and Mali (the former composing the Trans-Saharan Orogen) and the Oubanguides Orogen of Cameroon and Chad continuing into the Central African Fold Belt in the Central African Republic (CAR). For simplification, the Oubanguides-Central African orogenic system will herein be called Central African Orogen. Along with the Borborema Province, these major orogenic areas represent the site of agglutination of the West African-São Luís, São Francisco-Congo and Saharan paleocontinents (Figs. 1 and 2).

In this contribution, a brief summary of the state-of-the-art of geological knowledge of the Borborema Province will be presented and compared to its counterparts in NW Africa. This contribution is not intended to be fully comprehensive; for a complete discussion of stratigraphic, deformational, magmatic, and metamorphic aspects of each domain, the reader is referred to the cited works. Here, the focus will be mainly on tectonic units, their possible geodynamic meaning and context, and their correlations with similar units in NW Africa. As the focus of the paper is mainly the Borborema Province, the geology of this region will be described in greater detail; then, a brief description of the Trans-Saharan and Central African areas will be presented; and finally, a domain-by-domain tentative comparison with a unified evolutionary model proposal.

## GEOLOGICAL FRAMEWORK

### NE Brazil: Borborema Province

There are various subdivision proposals for the Borborema Province, most involving the individualization of different tectono-stratigraphic domains separated by regional, hundreds-of-km-long shear zones (Almeida *et al.* 1976, Brito Neves 1983, Santos and Brito Neves 1984, Jardim de Sá *et al.* 1992, Santos *et al.* 2000, Brito Neves *et al.* 2000). Santos (1996) used the concept of terrane accretion (Coney *et al.* 1980) to interpret each of these domains as accreted exotic blocks and proposed that the Borborema Province was built in the Neoproterozoic by agglutination of allochthonous lithospheric fragments during the Cariris Velhos (~ 1000–920 Ma) and Brasiliano (~ 625–510 Ma) orogenies. Recently, both field and geophysical data

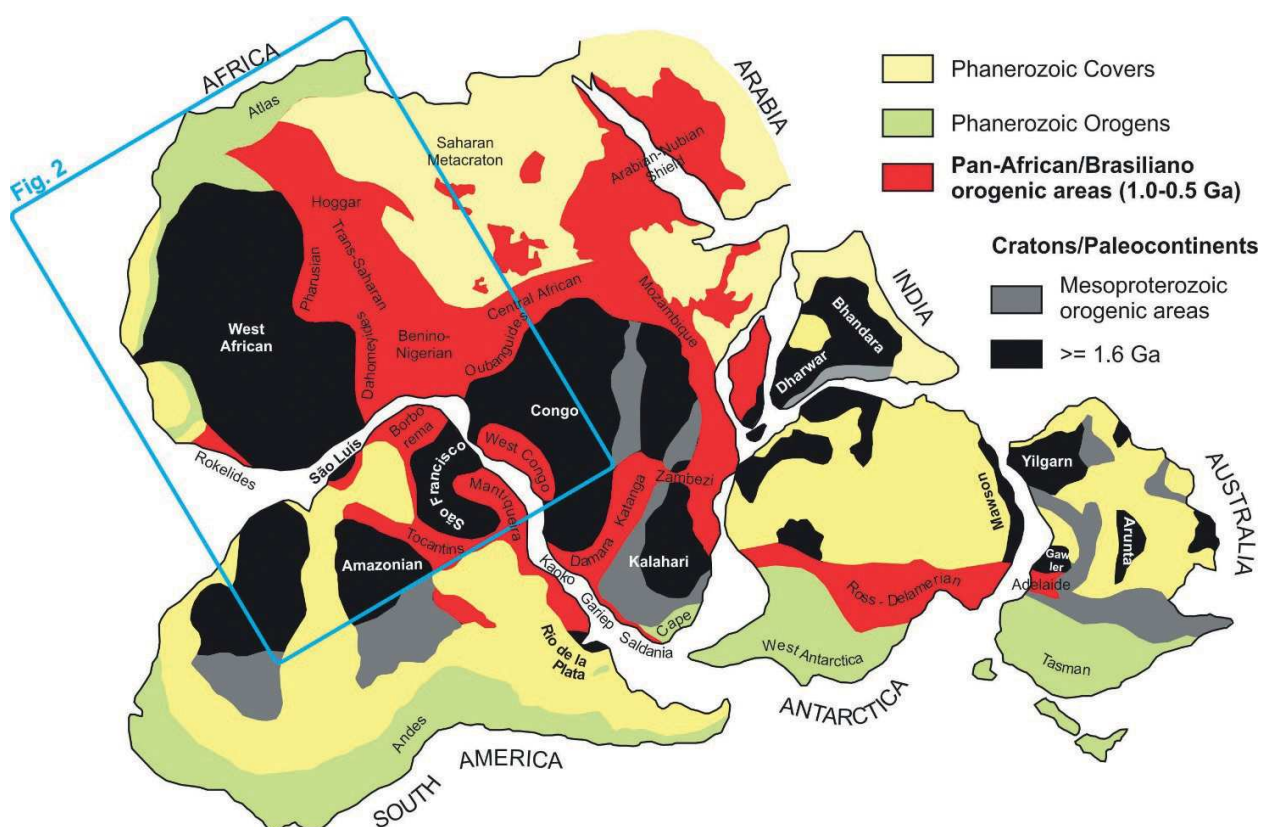


Figure 1. NE Brazil–NW Africa in the context of West Gondwana.

suggest that at least part (if not most) of the regional shear zones are late-stage structures that crosscut through similar crustal domains, i.e., they do not always separate domains of distinct geological or geophysical features (e.g., Neves and Mariano 1999, Caxito *et al.* 2016, Oliveira and Medeiros 2018), but constitute late-stage structures that crosscut the entire Brasiliano/

Pan-African orogenic edifice. Thus, although surely some of the regional shear zones were nucleated and developed at least in part in the ancient sites of plate interaction (e.g., Padilha *et al.* 2014, Oliveira and Medeiros 2018) they cannot always be directly interpreted as suture zones between blocks of distinct nature and composition.

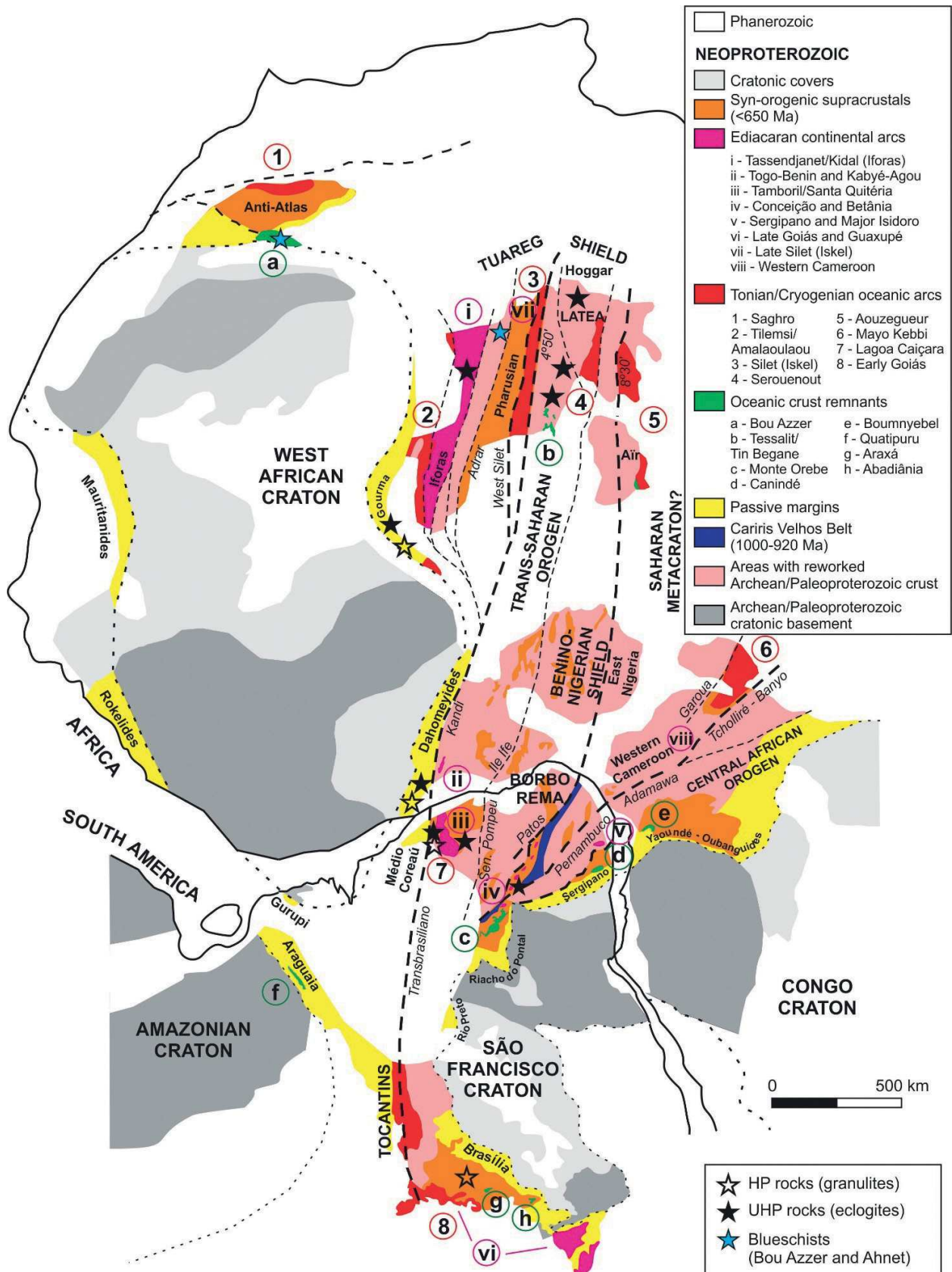
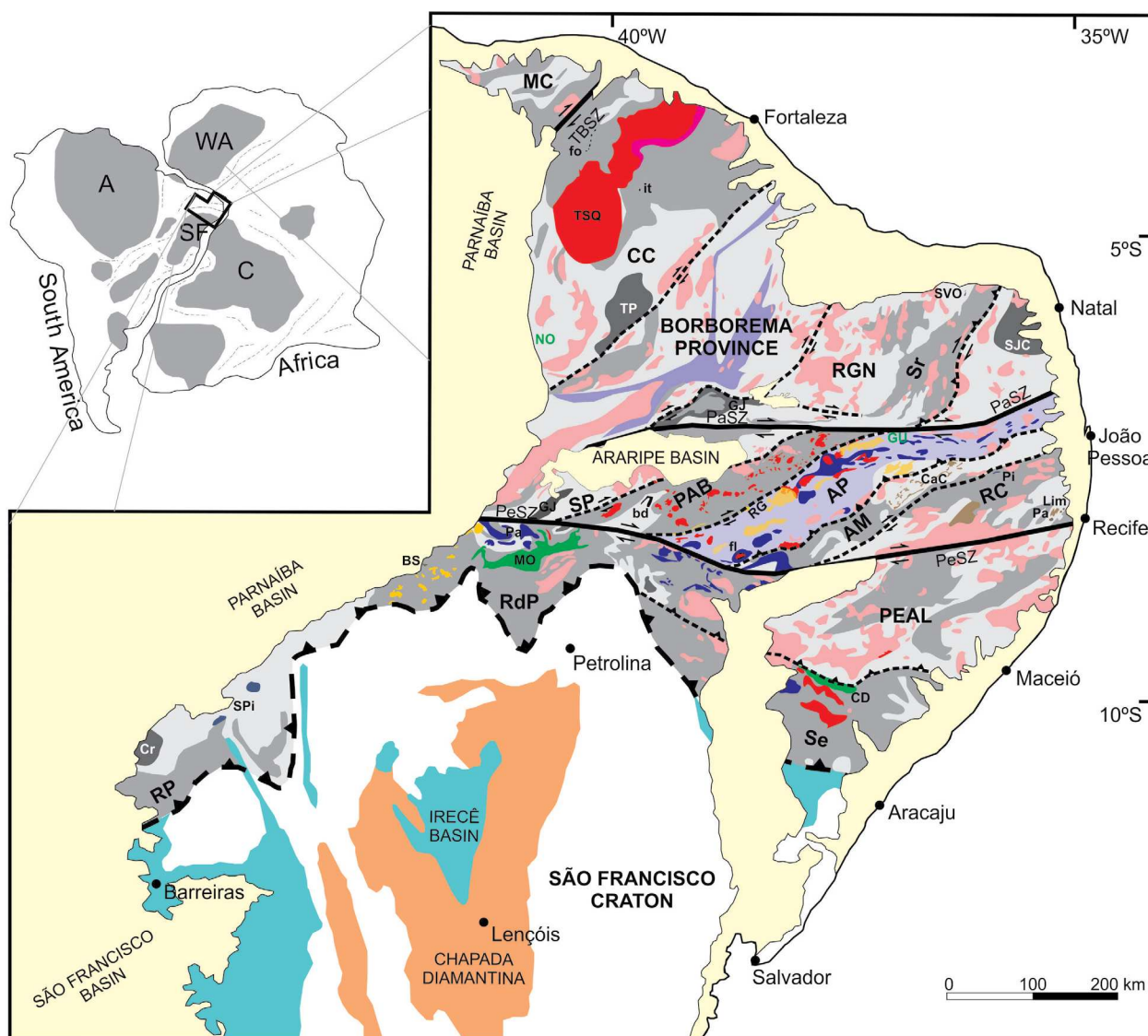


Figure 2. Simplified geological features of NE Brazil and NW Africa.



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|--|---|
| Phanerozoic covers   | Cariris Velhos orthogneisses (1000-920 Ma)  |
| Late- to post-collisional high-K granitoids and syenites (syenitoid line - Stage III-V) - 590-530 Ma   | Cariris Velhos supracrustals (1000-920 Ma)  |
| Eclogite relicts (630-610 Ma)<br>fo - Forquilha<br>bd - Bodocó (?) it - Itataia<br>fl - Floresta (Serrote das Pedras Pretas)   | Paleo/Mesoproterozoic rift-related plutons (ca. 1.7-1.5 Ga)<br>CaC - Carnoió - Coloete Pa - Passira   |
| Undifferentiated Brasiliano granitoids (both syn-collisional and syn-transcurrent - Stage II/IV) - 620-550 Ma  | Orós-Jaguaribeano Belt (ca. 1.8-1.7 Ga)   |
| Calc-alkaline, continental arc (?) granitoids (Stage I) - 640-620 Ma<br>TSQ - Tamboril-Santa Quitéria Complex<br>Lagoa Caiçara Unit - juvenile granodioritic to tonalitic metatexites (870-800 Ma) | Borborema Province basement ( $\geq 2.0$ Ga)  |
| Metavolcanosedimentary belts (mostly < 650 Ma)   | Main Archean inliers<br>TP - Tróia-Pedra Branca - 2.7-2.5 Ga<br>Cr - Cristalândia do Piauí - 3.2-2.5 Ga<br>GJ - Granjeiro - 3.5-2.5 Ga<br>SJC - São José do Campestre - 3.5-2.7 Ga<br>SVO - Serra Verde/Oiticica - 3.75-3.53 Ga |
| Ophiolite complexes (820-650 Ma)<br>MO - Monte Orebe NO - Novo Oriente (?)<br>CD - Canindé GU - Gurjão (?)   | Neoproterozoic cratonic covers  |
| Tonian rift-related rocks (900-860 Ma)<br>A-type granites<br>Pi - Pinhões<br>SPi - Serra da Pintada  | Mesoproterozoic cratonic covers   |
| Mafic-ultramafic complexes<br>BS - Brejo Seco; Pa - Paulistana<br>Lim - Limoeiro (?)   | São Francisco Craton / Borborema Province boundary thrust   |
|  | Main strike-slip shear zones  |
|  | Domain boundaries   |
|  | Main thrusts  |

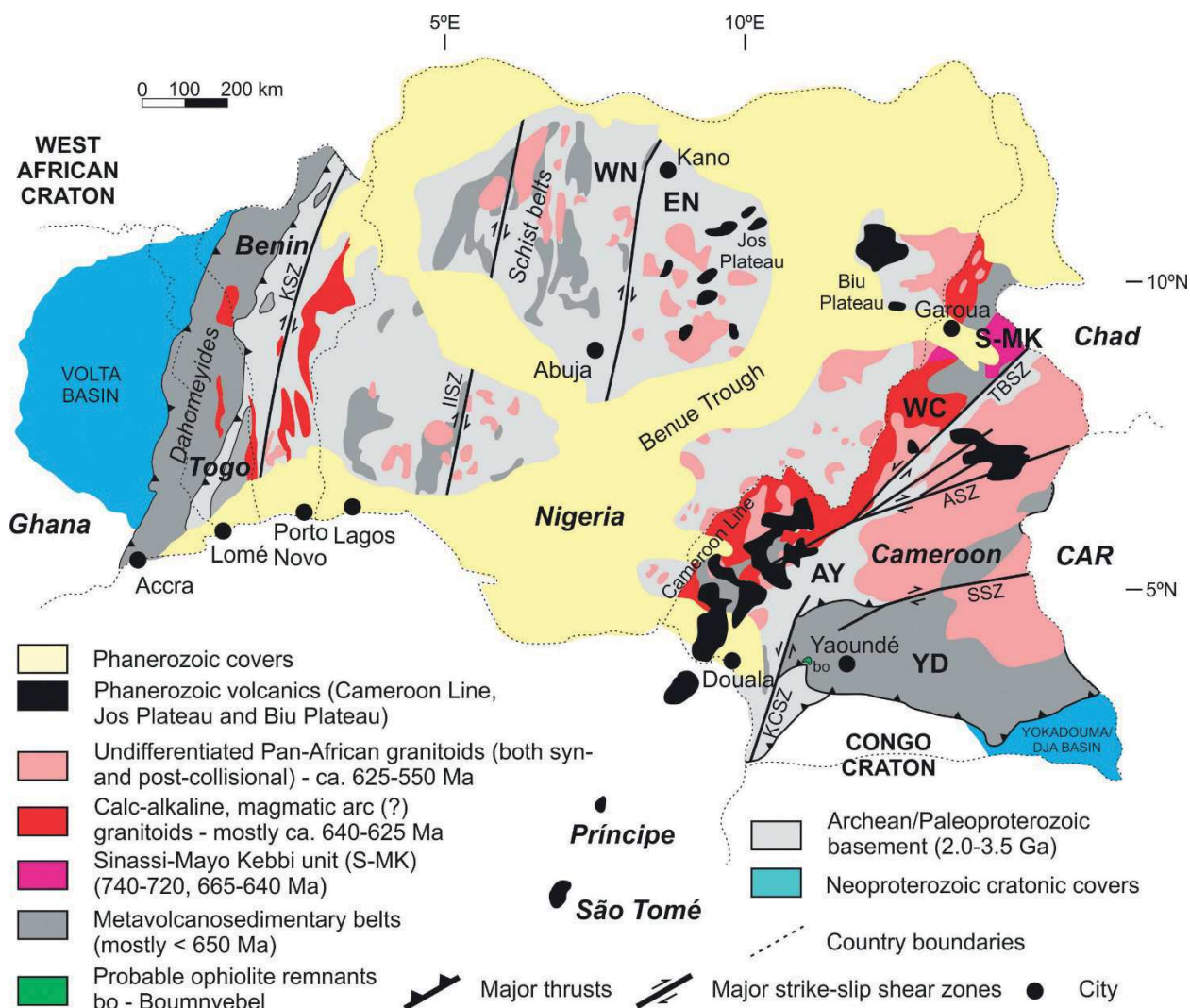
**Figure 3.** Simplified geological features of the Borborema Province. Domains and subdomains: RP - Rio Preto, RdP - Riacho do Pontal, Se - Sergipano, PEAL - Pernambuco-Alagoas, RC - Rio Capibaribe, AM - Alto Moxotó, AP - Alto Pajeú, RG - Riacho Gravatá, PAB - Piancó-Alto Brígida, SP - São Pedro, MC - Medio Coreaú, CC - Ceará Central, RGN - Rio Grande do Norte, Sr - Seridó. PeSZ - Pernambuco Shear Zone; PaSZ - Patos Shear Zone; TBSZ - Transbrasiliano Shear Zone.

The main shear zones can be used to subdivide the Borborema Province into three major tectonic zones or sub-provinces (similar to the proposition of Van Schmus *et al.* 2011): the northern, transversal, and southern zones, further subdivided into internal domains (Almeida *et al.* 1976, Brito Neves 1983, Santos and Brito Neves 1984, Jardim de Sá *et al.* 1992, Santos *et al.* 2000, Brito Neves *et al.* 2000). The term “domains” will be used here for purely descriptive purposes, instead of the term “terrane”, that could lead to the genetic/geodynamic implication that all of the distinct geological domains represent exotic, allochthonous terranes (*sensu* Coney *et al.* 1980). The main structures that divide these domains are the NE-trending Transbrasiliano (locally called Sobral-Pedro II) Shear Zone at the NW corner of the province and the major E-W trending Patos and Pernambuco shear zones that separate the transversal zone from the other domains to the north and south (Figs. 2 and 3). Subsidiary NE-SW shear zones splay from the main EW shear zones, further subdividing the northern and transversal zones into domains (Ebert 1964, Almeida *et al.* 1976, Brito Neves 1983, Santos and Brito Neves 1984, Vauchez *et al.* 1995). The northern Borborema zone is subdivided into the Médio Coreaú (MC), Ceará Central (CC), Orós-Jaguaribeano, Seridó, and Rio Grande do Norte (RGN)

domains; the transversal zone is subdivided into several sigmoidal domains named, from west to east: São Pedro (SP) or São José do Caiano, Piancó–Alto Brígida (PAB) or Salgueiro–Cachoeirinha, Alto Pajeú (AP), which includes the Riacho Gravatá subdomain, Alto Moxotó (AM), and Rio Capibaribe (RC); and the southern zone is divided into the Pernambuco-Alagoas (PEAL) Domain, and the Rio Preto (RP), Riacho do Pontal (RdP) and Sergipano (Se) belts. The Transbrasiliano Shear Zone that separates the Médio Coreaú domain from the Ceará Central domain at the NW corner of the province is, in fact, part of a major transcontinental structure that continues both SW to central Brazil (Brasília Belt of the Tocantins Province) and into NW Africa in a pre-Atlantic fit, composing the ca. 6000 km-long Transbrasiliano–Kandi–4°50’ shear system, sometimes interpreted as marking the vicinities of one of the main collisional suture zones of West Gondwana (Caby 1989, Arthaud *et al.* 2008, Cordani *et al.* 2013b, Ganade de Araújo *et al.* 2014b, Santos *et al.* 2015).

The geological framework of the Borborema Province is composed of:

- Paleoproterozoic basement units (mainly 2.2–2.0 Ga, but with restricted occurrences as old as 2.3–2.4 Ga), with important local Archaean nuclei, such as the Granjeiro



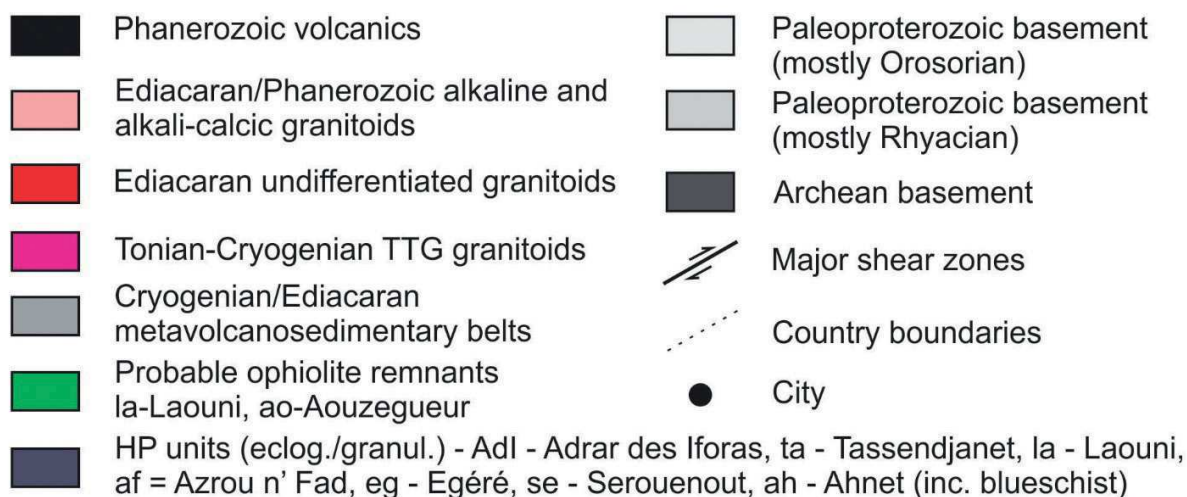
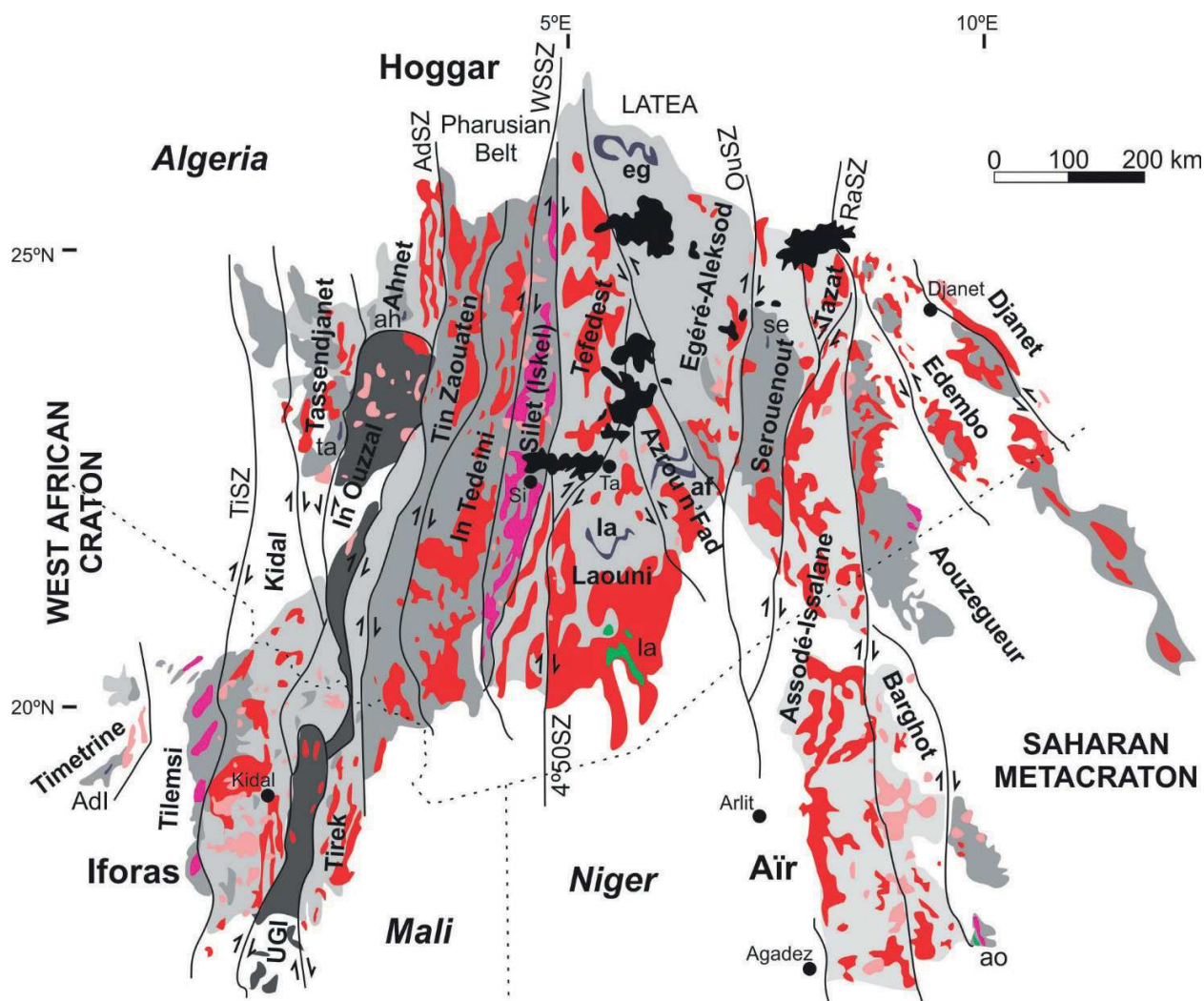
WN: West Nigeria; EN: East Nigeria; WC: West Cameroon; S-MK: Sinassi-Mayo Kebbi; AY: Adamawa-Yadé; YD: Yaoundé; KSZ: Kandi Shear Zone; IISZ: Ile-Ife Shear Zone; TBSZ: Tcholliré-Banyo Shear Zone; ASZ: Adamawa Shear Zone; SSZ: Sanaga Shear Zone; KCSZ: Kribi-Campo Shear Zone; CAR: Central African Republic.

**Figure 4.** Schematic geological features of the Benino-Nigerian Shield and Cameroon. See text for data sources.

Complex (3.5–2.5 Ga; Ancelmi 2016; Pitarello *et al.* 2019), the São José do Campestre Massif (3.45–3.2 Ga, with 2.7 Ga alkaline intrusions; Dantas *et al.* 2004, 2013) and mafic-ultramafic rocks dated ca. 3.7–3.5 Ga in the RGN domain (Santos *et al.* 2020); the Tróia-Pedra Branca Massif in the CC domain (ca. 2.8–2.7 Ga, Fetter *et al.* 2000; Ganade de Araújo *et al.* 2017); and part of the Cristalândia do Piauí block in the RP belt basement (ca. 3.2 Ga with 2.7–2.5 Ga

alkaline intrusions; Barros 2019). These basement units are composed mainly of TTG-type orthogneisses and metasedimentary rocks such as paragneisses and schists;

- Paleo–Mesoproterozoic metavolcanosedimentary units, developed in extensional (continental rift) settings, mainly in the Orós-Jaguaribeano (1.8 Ga) belt (Sá *et al.* 1995) and in the transversal zone, where Paleo- and Mesoproterozoic anorogenic magmatism (ca. 1.7–1.5 Ga) is locally important



Ta: Tamanrasset; Si: Silet; TiSZ: Tilemsi Shear Zone; AdSZ: Adrar Shear Zone; WSSZ: West Silet Shear Zone; OuSZ: Ounane Shear Zone; RaSZ: Raghane Shear Zone; UGI: Iforas Granulite Unit.

**Figure 5.** Schematic geological features of the Tuareg Shield. See text for data sources.

in the RC, AM, and AP domains (Accioly 2001, Sá *et al.* 2002, Lages *et al.* 2019);

- Early Tonian magmatism and sedimentation (1000–920 Ma) comprising the Cariris Velhos belt in the AP domain (and adjacent Riacho Gravata subdomain) of the transversal zone, a hallmark feature of the Borborema Province, with sparse occurrences also in the southern zone (Brito Neves *et al.* 1995, Van Schmus *et al.* 1995, Kozuch 2003, Carvalho 2005, Santos *et al.* 2010, Oliveira *et al.* 2010, Caxito *et al.* 2014b, 2020);
- components of complete plate tectonics cycles during the Neoproterozoic (ca. 900–540 Ma), as described below.

Recent discoveries of ophiolitic rocks (Caxito *et al.* 2014d, Lages *et al.* 2017) and eclogites/HP-UHP rocks (Beurlen *et al.* 1992, Castro 2004, Santos *et al.* 2009, 2015, Amaral *et al.* 2011, 2012, 2015, Ganade de Araújo *et al.* 2014b, Lages and Dantas 2016) within the metavolcanosedimentary belts of the Borborema Province, along with detailed geophysical data that suggest the amalgamation of lithospheric blocks of distinct composition, underlying structure and age (Padilha *et al.* 2014, 2016, Santos *et al.* 2014, Lima *et al.* 2015, Oliveira and Medeiros 2018) reinforce the interpretation of Phanerozoic-style plate tectonics during the Neoproterozoic (Caxito *et al.* 2014d, 2016, Ganade de Araújo *et al.* 2014b, Lages and Dantas 2016, Padilha *et al.* 2016). In order to understand the geological evolution of the Borborema Province during the Neoproterozoic (post-Cariris Velhos), it is worth differentiating the events occurring in:

- its western margin, which faced a large, Pacific-type ocean (the Goiás-Pharusian ocean);
- its southern margin, separating the Borborema lithospheric blocks from the São Francisco-Congo paleocontinent to the south;
- the interior of the province. The available data suggest a chronology of events as follows:

i) Ca. 900–800 Ma:

At the southern margin, the crustal extension is marked by mafic-ultramafic intrusions (Brejo Seco, ca. 900 Ma; Salgado *et al.* 2016), continental rift-like basic volcanics (Paulistana, 882 Ma; Caxito *et al.* 2016) and A-type orthogneisses (Pinhões, ca. 869 Ma; Neves *et al.* 2015). The grouping of rock units of similar tectonic setting in this age range suggests that continental rifting processes separated the lithospheric blocks composing the transversal and southern zones of the Borborema Province from the São Francisco–Congo paleocontinent to the south in the early Tonian. A different scenario occurs on the western margin, with the development of the Lagoa Caiçara arc complex, marked by juvenile or transitional subduction-related magmatism (Ganade de Araújo *et al.* 2014a). Within the interior of the province, events in this age range are not well defined. The Brejo Seco intrusion might represent the central portion of a triple junction with the development of a rift system, which would involve the Serra dos Olhos D'água Formation conglomerate of the PAB and the Equador Formation of the Seridó Belt (Caxito *et al.*

2016). However, these connections need to be further investigated.

ii) Ca. 820–650 Ma:

At the southern margin, continental drift followed the Tonian rifting and culminated with oceanic crust development in the 820–650 Ma age range (Caxito *et al.* 2014d). Broad passive margins were developed separating the Borborema lithospheric blocks from the São Francisco-Congo paleocontinent to the south. At the western margin, there is no direct evidence of arc magmatism in this age range, but indirect evidence is found as detrital zircon populations in the metavolcanosedimentary belts of the CC Domain (Ganade de Araújo *et al.* 2014a). Within the interior of the province, further development of rift/passive margin units that crosscut the province ensued.

iii) 650–620 Ma:

From this moment on, the chronology of events is similar for all of the Borborema Province, with a widespread onset of subduction and continental arc development. The ophiolite-bearing passive margin sequences of the southern zone were scrapped off and obducted while covered by widespread syn-orogenic, greywacke-rich units with intermediate to felsic volcanic and volcanoclastic intercalations (Caxito *et al.* 2016), marking an important shift of sedimentary provenance with the development of flysch-like basins that characterize all of the supracrustal fold belts throughout the province (Fig. 3). All of these belts present very similar detrital zircon contents with younger U-Pb ages at about 650 Ma (Van Schmus *et al.* 2003, Kozuch 2003, Medeiros 2004, Neves *et al.* 2006, Oliveira *et al.* 2010, Ganade de Araújo *et al.* 2012a, 2016, Arthaud *et al.* 2015, Hollanda *et al.* 2015, Oliveira *et al.* 2015a, Brito Neves *et al.* 2015, Caxito *et al.* 2016, Brito Neves and Campos Neto 2016, Lima *et al.* 2018, Basto *et al.* 2019), suggesting a genetic link with Ediacaran pre-collisional calc-alkaline plutons (Conceição or Stage I, Tamboril-Santa Quitéria, Major Isidoro, Betânia, and similar plutons in the Sergipano Belt), dated at 650–630 Ma (Fetter *et al.* 2003, Santos *et al.* 2008a, Van Schmus *et al.* 2011, Ganade de Araújo *et al.* 2012b, 2014a, Oliveira *et al.* 2015a, Silva *et al.* 2015, Brito Neves *et al.* 2016, Sial and Ferreira 2016, Perpétuo 2017, Santos *et al.* 2019).

iv) 620–590 Ma:

Main collisional stage of the Brasiliano Orogeny. The metavolcanosedimentary basins were inverted, deformed and metamorphosed. Crustal anatexis generated syn-collisional plutons (Stage II) throughout the province (Fetter *et al.* 2003, Bueno *et al.* 2009, Van Schmus *et al.* 2011, Oliveira *et al.* 2015a, Caxito *et al.* 2016, Sial and Ferreira 2016). Within the Sergipano Belt, this stage might have lasted up to ca. 575 Ma (Bueno *et al.* 2009, Oliveira *et al.* 2010), although recently, Lisboa *et al.* (2019) interpreted the Glória Norte shoshonitic stock emplaced at ca. 588 Ma as post-collisional in the area. Eclogitic metamorphism at the NW Borborema Province and at the transversal zone is also dated in this age range, indicating continental collision at ca. 625–615 Ma (Ganade de Araújo *et al.* 2014b, Santos *et al.* 2015, Lages and Dantas 2016).

## v) 590–510 Ma:

At the final stages of the Brasiliano Orogeny, an extensive network of shear zones that crosscut the Borborema Province and characterizes the structural framework of NE Brazil was developed (Ebert 1964, Brito Neves 1975, Almeida *et al.* 1981, Santos and Brito Neves 1984, Vauchez *et al.* 1995, Brito Neves *et al.* 2000). These shear zones are spatially and temporally linked to several post-collisional granite plutons (Stages III-V) throughout the province (Corsini *et al.* 1991, Vauchez and Egydio-da-Silva 1992, Vauchez *et al.* 1995, Neves *et al.* 1996, Neves and Mariano 1999, Archanjo *et al.* 1999, 2008, Weinberg *et al.* 2004, Hollanda *et al.* 2010, Viegas *et al.* 2014). Ar-Ar plateau cooling ages show that extension associated to dextral shearing in the younger shear zones might have extended up to ca. 510 Ma (Hollanda *et al.* 2010). Ordovician and younger reactivation of the main lineaments is shown by ca. 460 Ma felsic dykes crosscut by faults parallel to the main trend of the Transbrasiliano shear zone (Amaral *et al.* 2017).

The chronology of the events presented above is a rough approximation: certainly, subduction, collisional and post-collisional processes were diachronous throughout the Borborema Province, taking place at different times in different portions of the province. Diachronism of events could have been caused by various processes and features, such as:

- rotational interaction between the involved blocks in a zipper-like model, generating continental collision in a given part of the Borborema Province while other parts (such as the apparently younger Sergipano belt, with syn-collisional granitoids and deformation at ca. 590–570 Ma; Oliveira *et al.* 2010) were still in the subduction-accretion phase (and other areas might be going through strike-slip or extensional processes);
- paleogeography of the margins involved in continental collision. For example, the RdP belt external nappes were thrust upon a northwards-pointing (present-day position) promontory of the São Francisco paleocontinent (Caxito *et al.* 2016) while the Sergipano belt corresponds to a reentrant or embayment of the northeastern paleocontinent margin. That might explain why collisional processes seem to have happened before at the RdP belt (ca. 610 Ma), as the cratonic northward-pointing promontory would interact earlier with the upper plate blocks to the north, while the Sergipano belt, carved in a cratonic reentrant, would still be going through the accretionary phase and would only reach the collisional phase later on, at ca. 590–570 Ma (Bueno *et al.* 2009, Oliveira *et al.* 2010);
- models of multiple collisions, such as the model presented by Ganade de Araújo *et al.* (2014a) suggesting a two-stage evolution with collision I at 620–610 Ma along the west side of the province, followed by collision II at 590–580 Ma at the southern side, causing northward extrusion of the Borborema Province.

Refined geochronological data are still surely needed to fully understand the timing and extent of these processes in

each part of the Borborema Province, and to confirm or reject contentious points of the current models.

The diachronous transition of collisional tectonics at ca. 620–575 Ma to strike-slip deformation at 590–530 Ma is reflected in the structural evolution of the fold belts and surrounding areas in the Borborema Province, commonly characterized by two groups of structures. The first group comprises early-stage tangential deformation with development of low-angle pervasive deformational foliation and/or nappe structures interpreted as related to plate convergence tectonics (*e.g.*, Caby and Arthaud 1986, Jardim de Sá *et al.* 1992, Medeiros 2004, Santos *et al.* 2008a, Caxito *et al.* 2016). Complex deformation patterns including frontal, oblique, and lateral mylonite ramps, sheath folds, isoclinal and recumbent nappe folds are not uncommon, normally showing cratonward vergence, *i.e.*, mass transport to the south toward the São Francisco craton in the case of the fold belts of the southern zone (Jardim de Sá *et al.* 1992, Oliveira *et al.* 2010, Uhlein *et al.* 2011, Caxito *et al.* 2016); and to the northwest toward the West African-São Luís craton in the MC domain (Santos *et al.* 2008b). Regional metamorphism reached the upper amphibolite facies and anatectic conditions in the orogenic cores, as well as local granulitic and eclogitic conditions. Generally, the external nappes show Hymalaian-type reverse metamorphism, with higher-grade allochthonous thrust upon lower grade sheets (Caby and Arthaud 1986, Caxito *et al.* 2016). The tangential structures are superposed by the second group of structures, comprising vertical or steeply-dipping shear zones that characterize the late-stage strike-slip deformation throughout the province. These structures are sometimes interpreted as related to a lateral escape phase of the continental blocks involved in the collision, when tangential tectonics was no longer able to accommodate the whole of crustal deformation due to squeezing of the blocks that compose the Borborema Province between the major São Francisco-Congo and West African-São Luís cratons and other smaller cratonic pieces such as the concealed Parnaíba block that behaved as rigid continental blocks during the Brasiliano Orogeny (Ganade de Araújo *et al.* 2014c, Caxito *et al.* 2016).

In the interior of the province, the late-stage strike-slip and transpressional deformation is so pervasive that it rotates and partially to completely obliterates the former compressional structures, especially at the expressive sub-vertical mylonitization fronts of the major shear zones. The internal domains, away from the edge of these shear zones, might also have undergone stresses related to this large strike-slip system causing internal deformation and reactivation of previous flat-lying foliation and, in some places, nucleation of newborn thrust systems (Ganade de Araújo *et al.* 2014c). The northern Borborema and especially the transversal zone are characterized by S-shaped or almond-shape domains sectioned by the major E-W trending shear zones and by the NE-SW trending subsidiary shear zones (*e.g.*, Vauchez *et al.* 1995). Dextral ductile kinematics predominate in both the Pernambuco and Patos shear zones, while some of the NE-SW trending zones might show associated sinistral movement. Available geothermobarometric data suggest HT-LP development of the shear zones, with peak conditions at 600–700°C and 6 kbar for the Pernambuco

shear zone (Vauchez and Egydio-da-Silva 1992), where horizontal to slightly oblique syn-kinematic prismatic sillimanite marks a stretching lineation in Al-rich metasedimentary rocks. Syn-kinematic melting and pluton intrusion are common and widespread both in the Pernambuco and Patos and in the subsidiary shear zones (Vauchez and Egydio-da-Silva 1992, Hollanda *et al.* 2010, Viegas *et al.* 2014).

## Late Neoproterozoic and Cambrian magmatism

The Brasiliano magmatism of the Borborema Province can be subdivided into five general stages, based on petro-structural, lithochemical, geochronological, and isotopic data and in cross-cutting relations to the main Brasiliano deformation phases (Almeida 1967, Sial 1986, Ferreira *et al.* 1998, 2004, Santos and Medeiros 1999, Brito Neves *et al.* 2003, Van Schmus *et al.* 2011, Sial and Ferreira 2016, Brito Neves *et al.* 2016, Granade de Araujo *et al.* 2014a, Caxito *et al.* 2016). Following the nomenclature of Van Schmus *et al.* (2011) but with slightly modified age ranges due to the incorporation of novel geochronological data, these are defined as:

- Stage I (640–620 Ma): Pre-collisional plutons that pre-date the development of the main thrust foliation in the supracrustal belts. This corresponds to the main age range of pre-collisional magmatism in the large Tamboril/Santa Quitéria batholithic complex, in the NW of the province (Fetter *et al.* 2003, Santos *et al.* 2008a, 2008b, Ganade de Araújo *et al.* 2012b, 2014a) and to a plethora of smaller magmatic epidote-bearing calc-alkaline I-type plutons (Conceição-type) found throughout the PAB and AP domains of the transversal zone and interpreted as probably related to a continental magmatic arc (Sial and Ferreira 2016, Brito Neves *et al.* 2016, Santos *et al.* 2019). The Betânia granites of the internal RdP belt (Perpétuo 2017), and pre-collisional tonalites, granites, monzodiorites, and granodiorites of the Sergipano belt (Bueno *et al.* 2009, Oliveira *et al.* 2015a) and of the PEAL domain (Silva *et al.* 2015) are all dated at the same age range and also interpreted as emplaced in continental arc settings. Volcanic and volcanoclastic rocks of rhyolitic to dacitic composition interleaved within the syn-orogenic sedimentary belts of both the northern, transversal, and southern zones, as well as hypabyssal intrusions, are also dated in this same age range (Kozuch 2003, Medeiros 2004, Caxito *et al.* 2019). Their lithochemical and isotopic signatures support a genetic link with the granitic intrusions (Caxito *et al.* 2019);
- Stage II (625–590 Ma): Leucogranites and foliated two-mica granites, whose emplacement coincides with the peak of Brasiliano metamorphism and deformation (Ganade de Araújo *et al.* 2014b, Caxito *et al.* 2016); in the Sergipano belt, these can span ages as young as ca. 570 Ma (Bueno *et al.* 2009). There seems to be a slight diachronism between the NW Borborema Province, where syn-collisional magmatism has been proposed since ca. 615 Ma (*e.g.*, Ganade de Araújo *et al.* 2014b), and the transversal zone, where pre-collisional, magmatic arc plutonic and volcanic activity,

seems to extend to ca. 620 Ma (*e.g.*, Kozuch 2003, Medeiros 2004, Brito Neves *et al.* 2016, Caxito *et al.* 2019). Caxito *et al.* (2019) proposed a model to conciliate this diachronism, where continental collision in the NW Borborema Province pushed the northern Borborema blocks toward the central-southern Borborema blocks in a clockwise fashion, forcing or speeding subduction in the PAB belt of the transversal zone in the ca. 625–610 Ma interval;

- Stage III (590–575 Ma): generally corresponds to granitic to syenitic and locally shoshonitic plutons, intruded in the transition between the collisional and the late-stage strike-slip deformations that crosscuts the province. Diachronism is also observed here, as syn-collisional granites were emplaced in the Sergipano belt with ages as young as ca. 570 Ma (Bueno *et al.* 2009), while clearly post-collisional syenites of the Serra da Aldeia Suite were emplaced in the RdP belt with ages as old as ca. 586–576 Ma (Caxito *et al.* 2016, Perpétuo 2017). This diachronism of syn- and post-collisional magmatic activity, even in adjacent domains such as the RdP and Se belts, probably reflects the effects of zipper-like rotational closure of the intervening oceanic domains and/or syntaxis-antitaxis effects on mountain building related to the paleogeography of the continental margins, interacting with one another at different times;
- Stage IV (575–550 Ma): late- and post-collisional plutons coeval to regional strike-slip deformation (*e.g.*, Hollanda *et al.* 2010). Dextral HT-LP transpression of the Seridó belt is constrained to ca. 575 Ma through U-Pb dating of the coeval Acari granite and Santa Luzia migmatite; mylonitization in the Patos shear zone is constrained to ca. 566 Ma through U-Pb dating of a leucogranite with transitional contacts with host diatexites (Viegas *et al.* 2014);
- Stage V (550–530 Ma): generally non-deformed plutons, except along younger shear zones. Hollanda *et al.* (2010) demonstrated that Cambrian plutonic rocks of the transversal zone were emplaced in a regional strain field combining extension and ductile dextral shearing, developing low- to medium-grade vertical mylonite belts with syn-kinematic intrusion of mafic stocks, mafic to felsic dykes and granite batholiths with U-Pb zircon ages between 548 and 533 Ma. Syn-kinematic micas from the associated mylonites yielded Ar-Ar plateau cooling ages between ca. 550 and 510 Ma (Hollanda *et al.* 2010).

## Tectonic context of the Borborema Province

In the context of the amalgamation of the Gondwana paleocontinent, the Borborema Province represents the orogenic region between the São Francisco–Congo and West African–São Luís cratons (Figs. 1 and 2), structured by the collisional interaction between these two major lithospheric fragments and other possible smaller intervening fragments during the Proterozoic, such as, for example, the Parnaíba block, concealed below the Phanerozoic sedimentary rocks of the Parnaíba Basin (Trompette 1994, Brito Neves *et al.* 2002, Cordani *et al.* 2003). The region comprised between these two cratonic landmasses also involves part of the geological domains of NW Africa, which are bound to the east by the

Saharan metacraton. Correlations between these two major areas will be discussed further on.

As previously explained, one of the theories for the geodynamic evolution of the Borborema Province is that this region would be part of a large lithospheric block stabilized at about 2.0 Ga (Neves 2003, Neves *et al.* 2006), comprising the Amazonian, São Francisco–Congo, and West African–São Luís paleocontinents, as part of the hypothetical Atlantica supercontinent (Rogers 1996). In the cited works, this view is supported, in part, by an interpretation based on the detrital zircon U–Pb ages record, which is similar for several Neoproterozoic metavolcanosedimentary units throughout the province and involves primary age sources which are not yet recognized in the Borborema Province, but are common, for example, in the Amazonian Craton, mainly in the late Paleoproterozoic and Mesoproterozoic. If this hypothesis is correct, all these units would have been deposited upon a fairly continuous basement, which underwent an almost exclusively intracontinental stretching shortly before the Brasiliano deformation, metamorphism and plutonism that would, in this view, have been developed mainly in an intracontinental orogenic setting.

On the other hand, paleomagnetic data (Trindade *et al.* 2003, 2006, Tohver *et al.* 2006) suggest that between 1080 and 525 Ma ago, the São Francisco–Congo paleocontinent and the Rodinia supercontinent (including the future Amazonian and West African–São Luís cratons) were separated by a large ocean (the Goiás–Pharusian or Brasilides ocean). The Amazonian and West African–São Luís paleocontinents might also have been separated from each other by the Clymene ocean or seaway during the Neoproterozoic (*e.g.*, Trindade *et al.* 2006, Tohver *et al.* 2010). Thus, approximation and accretion of these continental blocks and, subsequently, the construction of the Borborema Province would have occurred with the progressive convergence between distinct paleoplates during the Neoproterozoic, most likely through plate tectonic processes similar to those found in Phanerozoic orogens. This hypothesis is supported by geological evidence, such as the occurrence of rock suites that fingerprint Neoproterozoic suture zones such as ophiolites, eclogites, and magmatic arc rocks (Fetter *et al.* 2003, Santos *et al.* 2009, 2015, Caxito *et al.* 2014d, Ganade de Araújo *et al.* 2014a, 2014b, Brito Neves *et al.* 2016, Lages *et al.* 2016, Pitombeira *et al.* 2017). Geophysical (aeromagnetic, gravimetric, electromagnetic, and magnetotelluric) data also support the hypothesis of lithospheric structures related to major continental collision both in NW Africa (*e.g.*, Trompette 1994) and in NE Brazil (Padilha *et al.* 2014, 2016, Santos *et al.* 2014, Lima *et al.* 2015, Oliveira and Medeiros 2018). In this context, the suture zones between different lithospheric blocks are marked by paired linear gravimetric anomalies (positive-negative in the upper and lower block or plate, respectively), especially in the Trans-Saharan Orogen, with possible continuity in the Sobral-Pedro II (Transbrasiliano) shear zone (Fetter *et al.* 2003), suggesting subduction of the West African–São Luís plate under the hypothetical Northeast

Brazil–Central West African plate (Trompette 1994), which underwent reworking during the Brasiliano orogeny.

According to Oliveira and Medeiros (2018), the most important geophysical anomalies of the Borborema Province, which could represent suture zones between ancient continental blocks, are:

- the boundary between the southern zone and the São Francisco craton, represented by a strong dipole gravimetric anomaly whose axis crosses the inner portion of the Riacho do Pontal and the Sergipano belts and follows the approximate contour of the northern cratonic margin, truncating the Paleoproterozoic N–S trending gravimetric lineaments within the craton;
- the Transbrasiliano shear zone, marked by the positive axis of a dipole anomaly (the negative axis coincides with the Tamboril/Santa Quitéria Complex).

Other important internal limits, which represent geophysical discontinuities of lithospheric expression, are:

- the western branch of the Pernambuco shear zone and its continuation in the NE–SW trending Congo shear zone separating the AM and RC domains of the transversal zone (the eastern branch of the Pernambuco shear zone represents a shallow and discontinuous structure, with less expressive lateral displacement; Neves and Mariano 1999);
- the Patos shear zone;
- the NE–SW trending Jaguaribe shear zone and its continuation in the Tatajuba shear zone in the north.

## NW AFRICA

### The Trans-Saharan Orogen: Benino-Nigerian and Tuareg shields

The Trans-Saharan Orogen of NW Africa (Figs. 1 and 2) lies between the West African craton to the west and the enigmatic Saharan Metacraton (Abdelsalam *et al.* 2002) to the east, representing the site of ancient orogenic activity related to the Pan-African Orogeny due to collision and amalgamation of the two major ancient landmasses (Caby 1987). “Metacraton” is a concept proposed and developed by Abdelsalam *et al.* (2002) and Liégeois *et al.* (2003, 2013) for vast tracts of Precambrian lithosphere in the Saharan region, which would represent partially remobilized, deformed, and metamorphosed Archean/Paleoproterozoic fragments, intruded by plutons during the Pan-African Orogeny, either as a passive margin or in the context of intra-continental deformation.

The Trans-Saharan Orogen is composed of the Benino-Nigerian Shield, including the basement-dominated domains of West and East Nigeria and the Dahomeyides and Gourma belts of Togo, Benin, and Mali (Fig. 4), and of the Tuareg Shield, comprising the Hoggar region in Algeria, the Iforas region in Mali, and the Air region in Niger (Fig. 5).

The Benino-Nigerian Shield is commonly divided into two main domains in Nigeria, West Nigeria and East Nigeria (Ferré *et al.* 1996), separated by a ca. 500 km-long N–S structural lineament (Fig. 4). The West Nigeria Domain is characterized

by Archean basement with sparse metavolcanosedimentary belts, while the East Nigeria domain is characterized by ca. 2.1 Ga rocks of Eburnean affinity crosscut by Neoproterozoic granite suites emplaced at 605–580 Ma with associated high-grade Neoproterozoic migmatitic rocks (Dickin *et al.* 1991, Ferré *et al.* 1996, 1998, 2002). The West Nigeria domain bears remnants of some of the oldest rocks in Africa, with gneisses as old as  $3571 \pm 3$  Ma (Kröner *et al.* 2001), an age range also found in zircon cores from ca. 3.0 Ga gneisses (Bruguier *et al.* 1994), and numerous Nd  $T_{DM}$  model ages between 2.7 and 3.5 Ga (Dada 1998). The Nigerian schist belts, composed of greenschist and amphibolite facies metavolcanosedimentary rocks of probable Proterozoic age, also occur in this domain, and voluminous granitic plutons with widespread migmatization at ca. 620–580 Ma attests to substantial reworking during the Pan-African Orogeny (Dada 1998).

The Tuareg Shield outcrops in the Hoggar region in southern Algeria, in the Iforas region in northeastern Mali, and in the Air region in northern Niger (Fig. 5). The Tuareg Shield is classically interpreted as the result of a collage of ca. 25 terranes (Black *et al.* 1994, Liégeois 2019), which were welded together and dislocated along vertical shear zones due to squeezing between the West African craton to the east and the Saharan metacraton to the west during the Pan-African Orogeny (Caby 2003, Liégeois 2019, and references therein).

Some of the terranes of the Tuareg Shield represent Archean and Paleoproterozoic basement, which were variably reworked (*i.e.*, deformed, metamorphosed and intruded by plutons) during the Pan-African Orogeny, such as the Laouni/Azrou-n-Fad/Tefedest/Egéré-Aleksod/Aouilène assembly of terranes in Central Hoggar, which was interpreted by Liégeois *et al.* (2003) as representing a metacratonic unit dubbed LATEA, and the In Ouzzal/Iforas granulite units (IOGU/IGU) and surrounding Tirek, Kidal, Tassendjanet and Ahnet terranes, which could probably represent another archean-paleoproterozoic microcontinent in the West Tuareg Shield. To the east, the Assodé-Issalane and Tazat terranes are composed of Paleoproterozoic basement and were interpreted by Liégeois (2019) as forming an “Orosirian Stripe” which could also represent a metacratonic unit in the East Tuareg Shield. The easternmost domains of Eastern Hoggar and Air comprise the Aouzegueur, Edembo, Djanet and Barghot terrains, also considered to be at least in part Paleoproterozoic and constitute the westernmost part of the Saharan paleocontinent.

Other terrains probably represent Neoproterozoic juvenile and/or transitional rocks docked or thrust upon the basement-dominated blocks, and the contacts between these mark the sites of ancient suture zones. These are represented by the Tilemsi island arc (ca. 730–650 Ma) separating the West Tuareg basement-dominated terrains from the Gourma HP-UHP nappes thrust upon the West African craton margin to the west, the Pharusian terrains and the Silet (former Iskel) magmatic arc separating the West Tuareg terrains from LATEA, and the Serouenout terrane separating LATEA from the “Orosirian Stripe” to the east. The Raghane shear zone

marks the eastern boundary of the Orosirian Stripe and is interpreted by Liégeois (2019) as the western boundary of the East Saharan paleocontinent.

The Dahomey belt of Ghana, Togo, and Benin (Fig. 4) and its continuation, the Gourma Belt in Mali, are recognized as resulting from the collision of the eastern margin of the West African craton with the Transaharan province to the east (Caby 1987, Affaton *et al.* 1991, Castaing *et al.* 1994). An orogenic architecture with passive-margin related rocks to the west bordering the West African craton and active-margin related rocks to the east in the internal portion of the belt is recognized for the Dahomey belt (Affaton *et al.* 1991, Agbossoumondé *et al.* 2004, Attoh and Nude 2008) and supported by U-Pb and Lu-Hf detrital zircon data (Ganade de Araújo *et al.* 2016). Important eclogite-facies metamorphism at ca. 620–610 Ma is recorded in both belts (Caby 1994, Ganade de Araújo *et al.* 2014b), and Neoproterozoic arc terrains are represented, from north to south, by the Amalaoulaou, Iforas, and Kabyé-Agou complexes (Ganade de Araújo *et al.* 2016, Guillot *et al.* 2019).

Bordering the northeastern margin of the West African craton, the Anti-Atlas Belt of Morocco (Fig. 2) probably represents a continuation of the Trans-Saharan Orogen, with important Neoproterozoic ophiolitic remnants (Bou Azzer, Tasriwine; Saquaque *et al.* 1989, Samson *et al.* 2004, Bousquet *et al.* 2008), arc complexes (Saghro, Walsh *et al.* 2012) and relics of subduction-related rocks metamorphosed in blueschist-facies (Hefferan *et al.* 2002).

## The Central African Orogen (Cameroon, Chad, and Central African Republic)

The areas affected by the Pan-African Orogeny in Cameroon (Fig. 4) are divided, from north to south, into the main structural units of the Western Cameroon, the Adamawa-Yadé and the Yaoundé domains (Toteu *et al.* 2004). Sometimes these are grouped as the Oubanguides Orogen or as part of the Central African fold belt. Here, we prefer the term Central African Orogen to encompass all of the orogenic systems, and avoid confusion with the external fold-thrust belts (*e.g.*, the Yaoundé domain and the Central African fold belt of CAR), that are actually only a part of this system, which also encompasses the internal domains of Adamawa-Yadé and Western Cameroon. Penaye *et al.* (2006) also recognized the Mayo Kebbi domain of SW Chad, a very important unit made up of calc-alkaline suites emplaced during magmatic pulses at 737–723 and 665–640 Ma, intruded by porphyritic granodiorite and monzodiorite dated at ca. 570 Ma. The Cameroon counterpart is known as the Sinassi Batholith (Bouyo Houketchang *et al.* 2016). The Mayo Kebbi area is interpreted as part of an arc complex marking the tectonic collage of the Adamawa-Yadé and Western Cameroon domains (Penaye *et al.* 2006). Adjacent to the Mayo Kebbi-Sinassi plutons and separated from the Adamawa-Yadé domain by the Tcholliré-Banyo shear zone, the Rey Bouba belt is interpreted as representing continental arc-related metavolcanosedimentary deposits developed between 670 and 630 Ma and metamorphosed at ca. 600 Ma (Bouyo Houketchang *et al.* 2015).

The Western Cameroon domain, located west of the Tcholliré-Banyo shear zone, extends along the western border of Cameroon and consists of Neoproterozoic metavolcanosedimentary rocks of the arc-related Poli Group, formed between 830 and 665 Ma (Toteu *et al.* 2006, Ngako *et al.* 2008, Bouyo Houketchang *et al.*, 2009, 2013) intruded by pre-, syn- and late-tectonic Pan-African granitoids of mainly calc-alkaline composition of 660 to 580 Ma and post-tectonic alkaline granitoids. These are superposed by molassic basins of the Mangbaï-type (Béa 1990, Montes-Lauar *et al.* 1997). Rb-Sr and Sm-Nd isotope data suggest that most of the rocks in this domain are either juvenile Neoproterozoic rocks or contaminated by ca. 2.1 Ga crust (Toteu *et al.* 2001). This domain is sometimes considered as a continuation of the East Nigeria domain, including schists and gneisses (Ferré *et al.* 1996, 2002).

The Adamawa-Yadé domain is located east of the Tcholliré-Banyo shear zone. It includes vast remnants of Paleoproterozoic crust, mainly highly sheared metasedimentary belts and orthogneisses, which have undergone at 2.1 Ga Eburnean granulitic metamorphism and with significant Archean contributions revealed by inherited zircon and Nd isotope data (Toteu *et al.* 2001, Ganwa *et al.* 2016, Tchakounté *et al.* 2017). The Neoproterozoic Pan-African amphibolite-facies Lom metavolcanosedimentary belt and widespread syn- to late-tectonic crustal-derived granitoids also occur (Soba *et al.* 1991, Toteu *et al.* 2001, 2006, Tchameni *et al.* 2006). This domain is interpreted as a Paleoproterozoic basement tract that was dismembered and reworked during the Pan-African Orogeny (Toteu *et al.* 2004).

Finally, the Yaoundé domain is interpreted as an allochthonous nappe terrane thrust southwards onto the Congo craton margin, composed of low- to high-grade Neoproterozoic schists with youngest detrital zircon grains at ca. 625 Ma (Toteu *et al.* 2006), paragneisses and orthogneisses, reaching granulite facies metamorphism during the Pan-African Orogeny (Nzenti *et al.* 1988, Penaye *et al.* 1993, Toteu *et al.* 1994, 2004, 2006, Owona *et al.* 2011, Kalsbeek *et al.* 2013). Pre- to syn-tectonic plutonic rocks are preponderant, with mafic to intermediate rocks and serpentinized Cr- and Ni-rich ultramafic rocks associated with gabbros, diorites, and mafic dykes. The Yaoundé metasedimentary rocks are interpreted as Neoproterozoic passive to active margin deposits, with U-Pb and Nd isotope data indicating mixtures of Neoproterozoic juvenile and Paleoproterozoic sources, with strong contributions from the Congo craton (Penaye *et al.* 1993, Toteu *et al.* 1994, 2001, Kalsbeek *et al.* 2013). The Yaoundé domain extends eastward to the Central African Republic as the Bolé metasedimentary rocks and the Gbaya high-grade gneisses (Pin and Poidevin 1987, Poidevin 1991), forming the Central African fold belt thrust upon the northern Congo craton margin (*e.g.*, Shellnutt *et al.* 2017).

### Domain-by-domain description and possible correlations between NE Brazil and NW Africa

Below a simplified domain-by-domain description of geologic units within the Borborema Province and probable

correlations with NW Africa is presented (see the graphic chart for the chronology of tectonic events in each domain in Fig. 6).

The regional shear zones that crosscut both NE Brazil and NW Africa are important keys to understanding the connections between these two major areas; various correlative schemes have been proposed. A continuation of the Transbrasiliano (Sobral/Pedro II) shear zone into the Kandi–4°50' shear zone seems well established (Caby 1989, Arthaud *et al.* 2008, Cordani *et al.* 2013b), as well as between the Senador Pompeu and Ile Ife shear zones. However, at the level of the Tuareg Shield, Brahim *et al.* (2018) and Liégeois (2019) suggest that, in fact, the extension of the Transbrasiliano–Kidal area is located west of the Silet terrane and not at the 4°50' lineament. In fact, these two shear zones (4°50' and the West Silet accident), as shown by magnetic data, converge both north and south of the Hoggar.

For the other shear zones, correlations are more contentious. Some authors suggest continuation of the Patos Shear Zone into the Garoua Shear Zone of NW Cameroon (*e.g.*, Brito Neves *et al.* 2002), while others suggest that the region between the Patos and Pernambuco shear zones opens in a wedge-like geometry toward NW Africa, and thus the Patos Shear Zone would continue through the limit between the East and West Nigeria provinces (Ferré *et al.* 1996) to the 8°30' Shear Zone separating East from Central Tuareg Shield (*e.g.*, Dada 2008, Van Schmus *et al.* 2008). According to the tectonic models for Cameroon (*e.g.*, Toteu *et al.* 2004, 2006), the Garoua Shear Zone does not seem to represent a major lithospheric structure. Thus, in Figure 2, a connection of the Patos–8°30' shear zones through the limit between West and East Nigeria is proposed. Continuation of the Pernambuco Shear Zone into the Adamawa Shear Zone, and splaying to the Tcholliré-Banyo Shear Zone marking the southern limit of the Mayo Kebbi Terrane, an exotic block accreted to the northern Adamawa-Yadé Domain (Penaye *et al.* 2006), is preferred here.

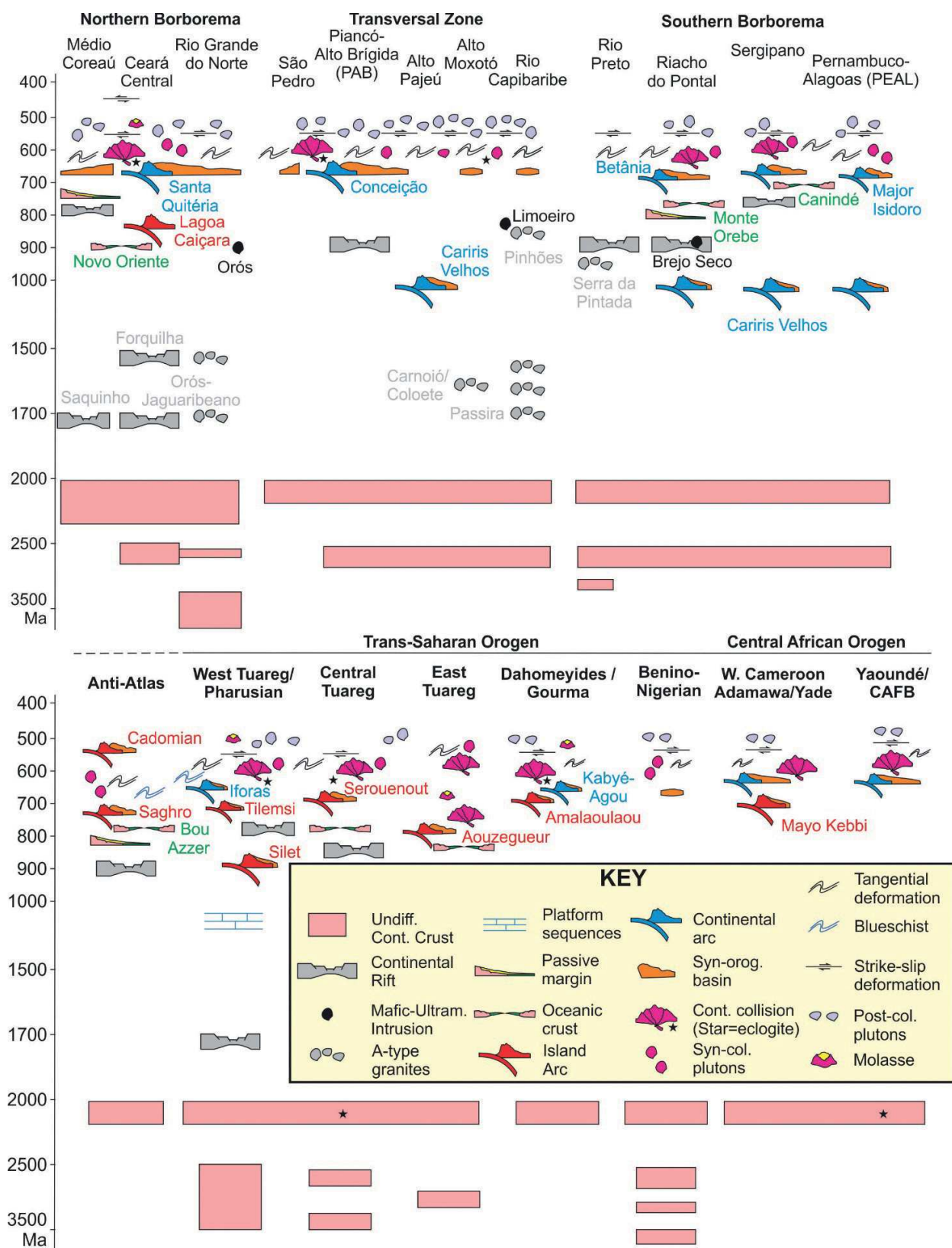
### The West Gondwana Orogen

The denomination “West Gondwana Orogen” (Ganade de Araújo *et al.* 2014b) is used for the region involved in the closure of the major Goiás–Pharusian (or Brasilides) ocean that encompasses part of the Northern Borborema Province (Médio Coreau, Ceará Central and possibly part of the Rio Grande do Norte domains) in NE Brazil; the Trans-Saharan Orogen composed of the Benino-Nigerian and Tuareg shields in NW Africa; and the Tocantins Province bordering the western margin of the São Francisco craton in central Brazil (Fig. 2). This whole area was strongly deformed, metamorphosed, and injected by numerous plutons during the Late Neoproterozoic to Cambrian, characterizing typical accretionary and collisional processes during the Pan-African/Brasiliano Orogeny. The main suture zone of this orogen is probably located in the vicinities of the Transbrasiliano–Kandi–4°50'/West Silet shear zone (Cordani *et al.* 2013b). For the remainder of the Borborema Province and NW Africa to be amalgamated, other oceanic tracts had to be consumed, such as the longitudinal Transnordestino-Central African ocean connecting the trans-versal Goiás–Pharusian and East African oceans (see next

sections), and smaller hypothetical oceans such as the Piancó-Alto Brígida/Western Cameroon (PAB-WECA) seaway (see discussion in the next sections and models in Figs. 7 to 11).

The connections between the lithostructural units that make up the domains involved in the West Gondwana Orogen are being progressively tightened up, with recent contributions on isotopic and geochronological data which allow

provenance patterns and tectonic meaning of lithostructural units to be further determined (Arthaud *et al.* 2008, 2015, Santos *et al.* 2008b, Kalsbeek *et al.* 2012, Ganade de Araújo *et al.* 2016, Guillot *et al.* 2019). Passive margin sedimentary units bordering the West African craton are superseded by active margin basins related to Neoproterozoic arc domains throughout the Médio Coreau–Dahomeyides–Pharusian belts.

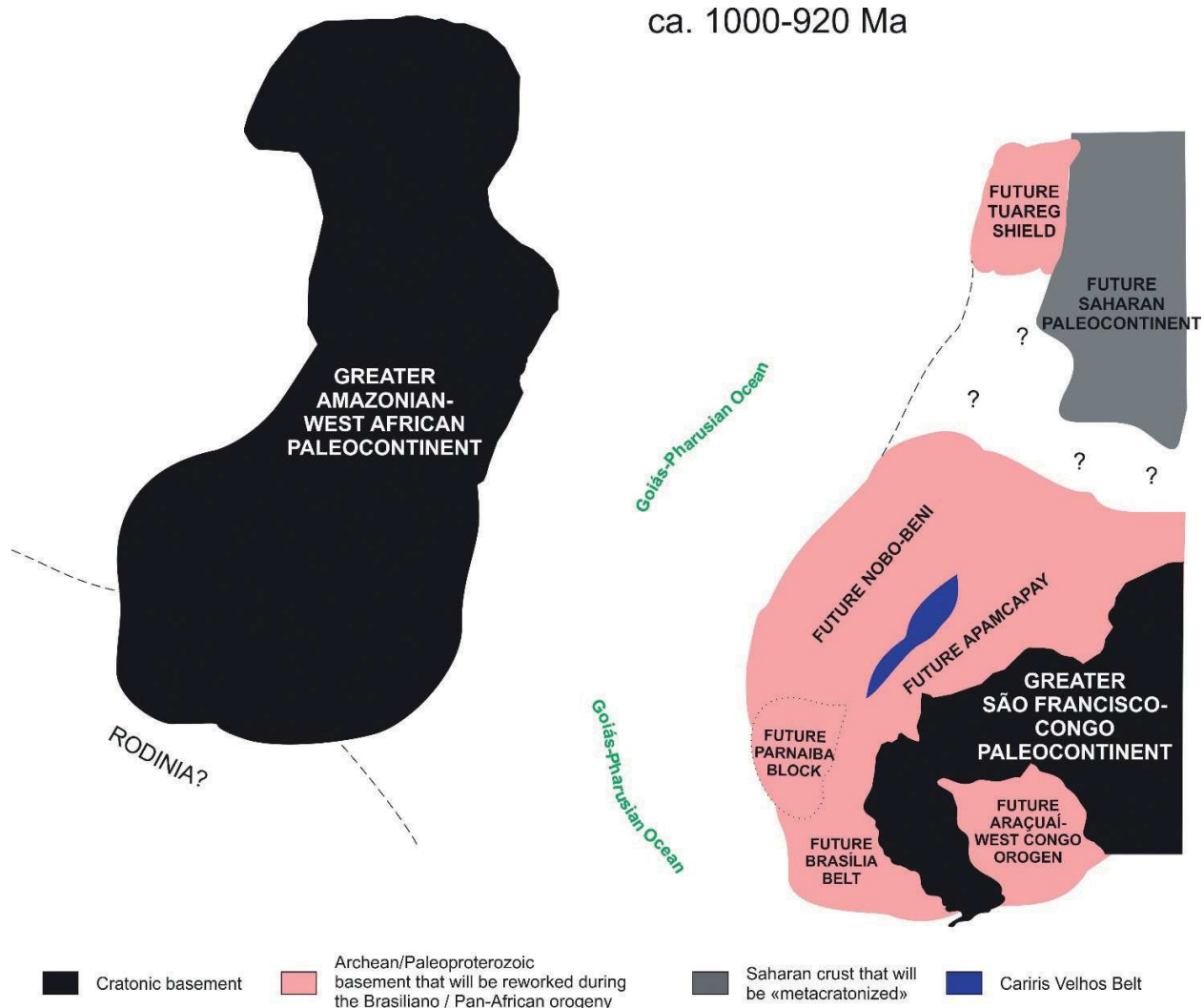


**Figure 6.** Simplified chart of the chronology of the main geodynamic events in each of the geological domains of NE Brazil and NW Africa. See text for data sources.

These are separated from the Northern Borborema/Benino-Nigerian (NOBO-BENI; see discussion in the next sections) and LATEA reworked basement areas by the transcontinental-scale Transbrasiliano–Kandi–4°50′/West Silet shear zone. HP and UHP rocks such as coesite-bearing eclogites are found in the vicinities of this major structure both in NE Brazil and NW Africa (Caby 1994, Jahn *et al.* 2001, Santos *et al.* 2015) and are dated at ca. 608–620 Ma in both Mali, Togo, and Brazil, suggesting deep continental subduction such as in a typical Himalayan collision in an at least 2,500 km-long trending zone during the Ediacaran (Ganade de Araújo *et al.* 2014b). Eclogites of the Tassendjanet–Tidérijjaouine terrane in the West Tuareg Shield, dated at ca. 623 Ma (Berger *et al.* 2014) are also possible correlatives. The Ceará Central domain in NE Brazil is characterized by the extensive Tamboril/Santa Quitéria magmatic complex, interpreted as encompassing both active margin arc magmatism and syn-collisional plutonic phases developed at 650–610 Ma (Fetter *et al.* 2003, Ganade de Araújo *et al.* 2014a); this is roughly coeval with similar aged magmatic arc-related plutonic rocks in Benin, in Togo, and in the western Tuareg Shield (Caby 2003, Ganade de Araújo

*et al.* 2016), besides corresponding to the main phase of continental arc magmatism further south in the Brasília belt (Laux *et al.* 2005, Fuck *et al.* 2017).

Neoproterozoic closure of the Goiás–Pharusian ocean occurred through crustal accretion processes, including the docking of various intraoceanic or transitional magmatic arcs, beginning as early as ca. 900–800 Ma (from south to north: the early intraoceanic phase of the Goiás Magmatic Arc in the Brasília Belt; Pimentel and Fuck 1992, Laux *et al.* 2005, Fuck *et al.* 2017; the early stages of the Tamboril/Santa Quitéria Arc or Lagoa Caiçara Arc in NW Borborema; Ganade de Araújo *et al.* 2014a; the early stages of the Silet (former Iskel) Arc in Hoggar; Caby *et al.* 1982, Caby 2003), but with possible younger accretion events such as, from south to north, in the Amalaoulaou Arc of Mali (onset at ca. 790 Ma; Berger *et al.* 2011), the Tilemsi Arc (ca. 730 Ma) of western Hoggar (Caby *et al.* 1989), and the Saghro Arc of Morocco (onset at ca. 760 Ma; Saquaque 1992, Walsh *et al.* 2012). Whenever available, Nd isotope data for these massifs suggest the involvement of large volumes of juvenile mantle material (*e.g.*, Pimentel and Fuck 1992, Berger *et al.* 2011, Ganade de Araújo *et al.* 2014a)



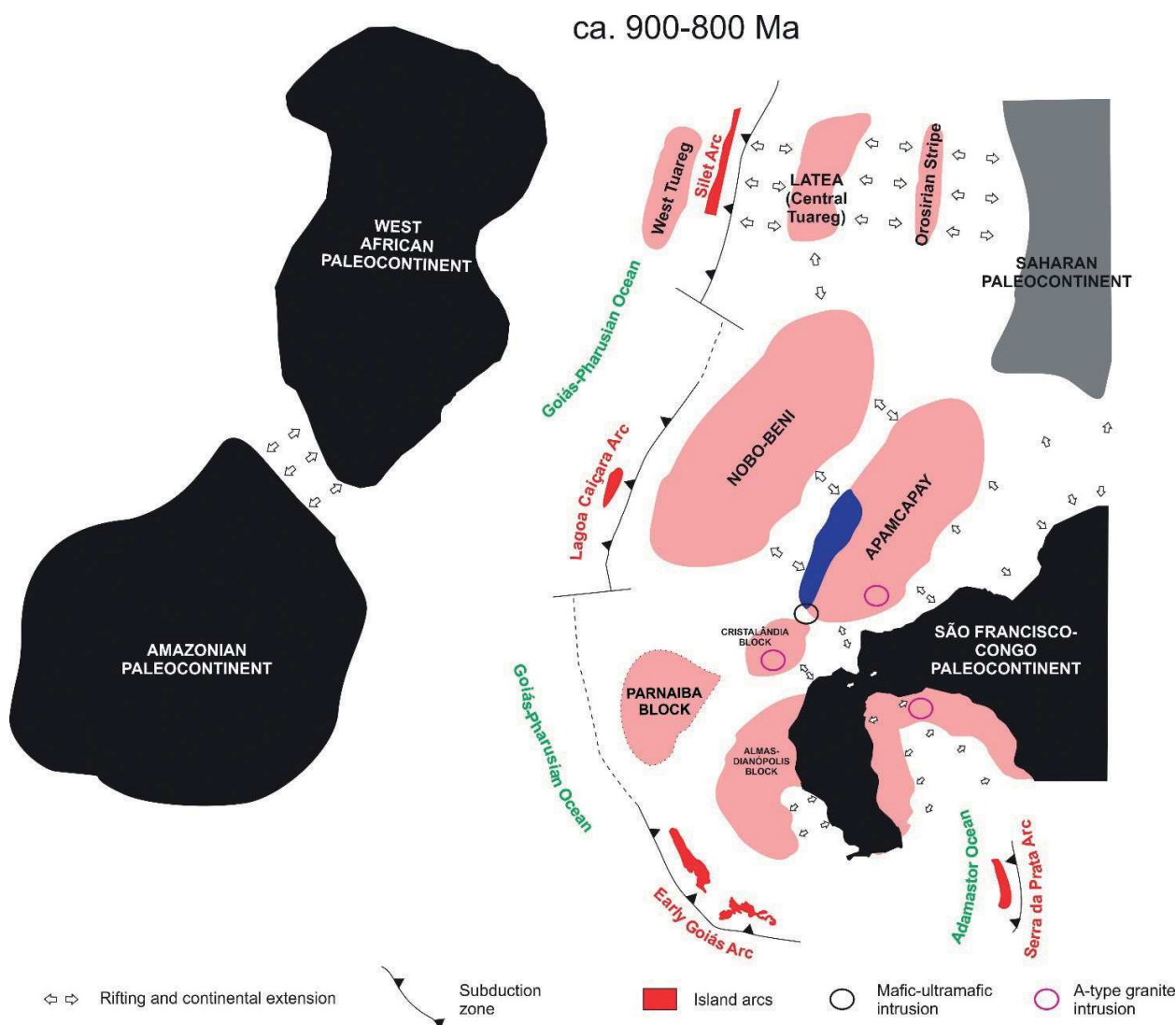
**Figure 7.** Schematic model for NE Brazil–NW Africa evolution at 1000–900 Ma. The enigmatic Carris Velhos belt might represent (i) a complete Wilson Cycle, with rifting of the northern Borborema block from the Greater São Francisco–Congo–Saharan paleocontinent followed by development of a continental arc system and continental collision; (ii) a peripheral continental arc system not linked to a complete Wilson Cycle; or (iii) a continental rift system.

with  $T_{DM}$  model ages close to the U-Pb zircon crystallization ages and positive  $\epsilon Nd(t)$ ,  $\epsilon Hf(t)$  and mantle-like O isotopic signatures, attesting to the intra-oceanic or transitional (*i.e.*, developed over thinned or newly formed continental crust) nature of most of these units.

After successive accretionary processes and collisions during the Neoproterozoic, this ocean was closed giving rise to the West Gondwana Orogen that sutured the West African-São Luís and São Francisco-Congo cratons and the Saharan metacraton in NW Africa, NE and central Brazil. Thrusting of passive margin sequences, including possible ophiolitic remnants and HP and UHP rocks described in the western and central Tuareg Shield (Sautter 1986, Caby 2003, Liégeois *et al.* 2003, Berger *et al.* 2014, Doukkari *et al.* 2014, 2019, Adjerid *et al.* 2015, Arab *et al.* 2019), further north in the Neoproterozoic Bou Azzer ophiolitic mélange of the Anti-Atlas in Morocco, which also includes blueschist assemblages (Saquaque *et al.* 1989, Hefferan *et al.* 2002, Bousquet *et al.* 2008), and of syn-orogenic volcanosedimentary sequences onto the cratonic borders, injection of multiple phases of

syn-, late-, and post-orogenic plutons, regional greenschist- to amphibolite- facies metamorphism and local HP and UHP metamorphism related to continental subduction occurred throughout the orogenic zone.

It is important to notice that some authors suggest that the closure of the Goiás-Pharusian ocean at ca. 616–608 Ma was not the terminal event responsible for the amalgamation of West Gondwana. The closure of the Clymene ocean (Trindade *et al.* 2006, Tohver *et al.* 2010, 2012) separating the West African-São Luís and Amazonian cratons to the west, testified by Neoproterozoic ophiolites and/or exhumed mantle in a hyperextended continental margin in the Araguaia belt region (Paixão *et al.* 2008, Hodel *et al.* 2019) seems to have occurred much later, at ca. 530–520 Ma, in the early Cambrian (*e.g.*, McGee *et al.* 2012). Early Cambrian collisional events are also noticed elsewhere in West Gondwana (*e.g.*, Schmitt *et al.* 2004) and represent the last mountain building expressions of the Brasiliano Orogeny. The collision of the large Amazonian paleocontinent with the amalgamated West African-São Luís/Borborema/São Francisco-Congo paleocontinent



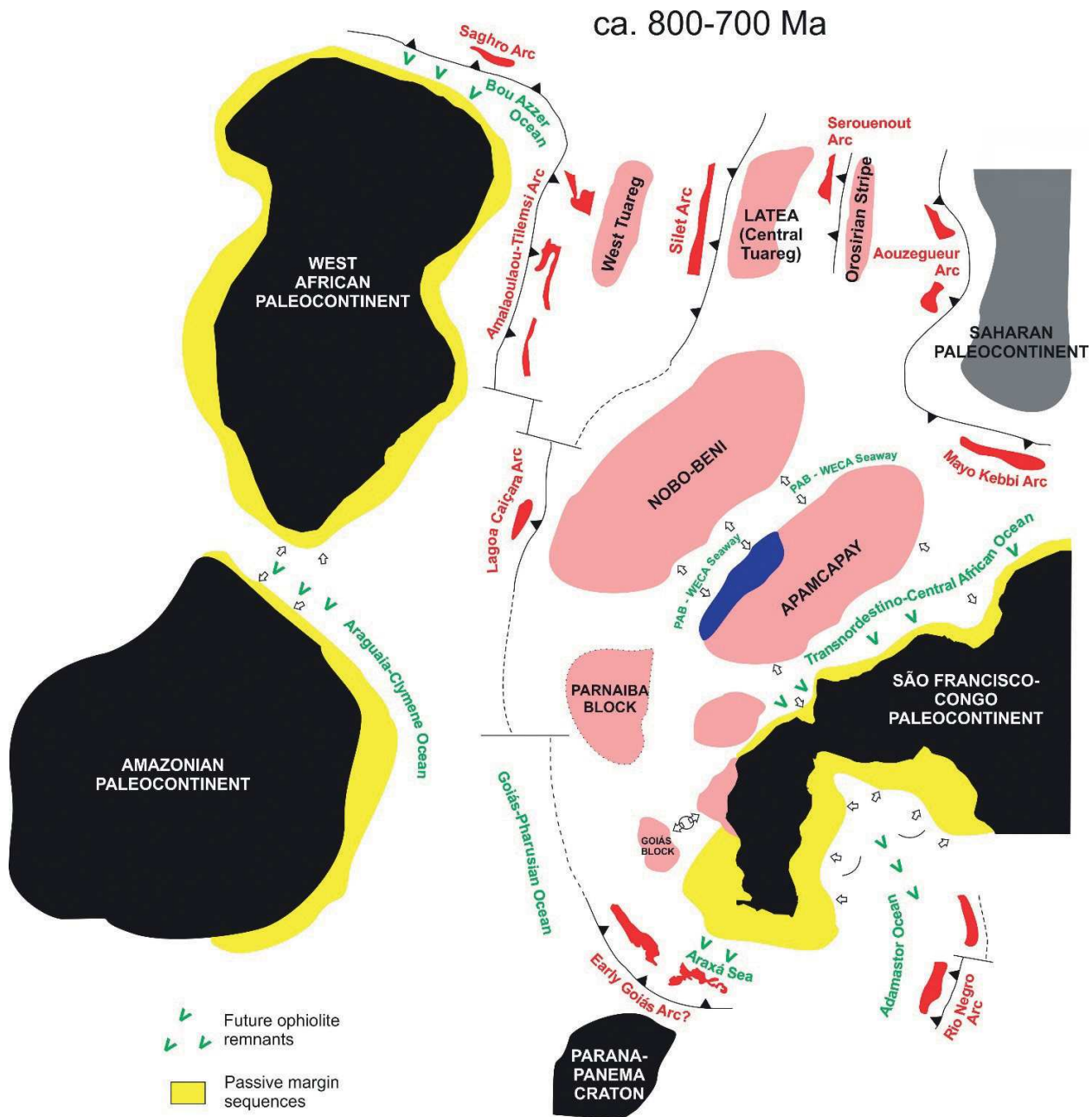
**Figure 8.** Schematic model for NE Brazil–NW Africa evolution at 900–800 Ma. See text for discussions. In pink, the Archean-Paleoproterozoic basement-dominated blocks of West Tuareg (IOGU/IGU and surrounding Tirek, Kidal, Tassendjanet and Ahnet terranes), Central Tuareg (LATEA) and East Tuareg or “Orosirian Strip” (Assodé-Issalane and Tazat), NOBO-BENI (Northern Borborema/Benino-Nigeria) and APAMCAPAY (Alto Pajeú-Alto Moxotó-Rio Capibaribe-Pernambuco-Alagoas/Adamawa-Yade) are shown.

might have influenced the final structuring of the Borborema Province, perhaps triggering the extensive development of late-stage strike-slip shear zones that characterize this region, as its hot, reworked lithosphere behaved as a less competent block in respect to the rigid lithosphere of the surrounding West African–São Luís and São Francisco–Congo cratons. On the other hand, Cordani *et al.* (2013a) dispute the existence of an Ediacaran ocean separating the Amazonian and West African–São Luís cratons, suggesting instead that the Araguaia and Paraguay belts bordering the Amazonian craton represent mainly epicontinental seaways.

**Médio Coreaú–Dahomeyides–Gourma–West Tuareg Shield (Pharusian)**

The Médio Coreaú domain lies to the NW of the Transbrasiliano shear zone in Ceará, Brazil, and is composed of four main lithotectonic units:

- Paleoproterozoic (2.35–2.1 Ga) TTG orthogneisses and high-grade rocks of the Granja Complex;
- the Late Paleoproterozoic Saquinho metavolcanosedimentary unit;
- the Neoproterozoic Martinópolis and Ubajara metasedimentary groups;

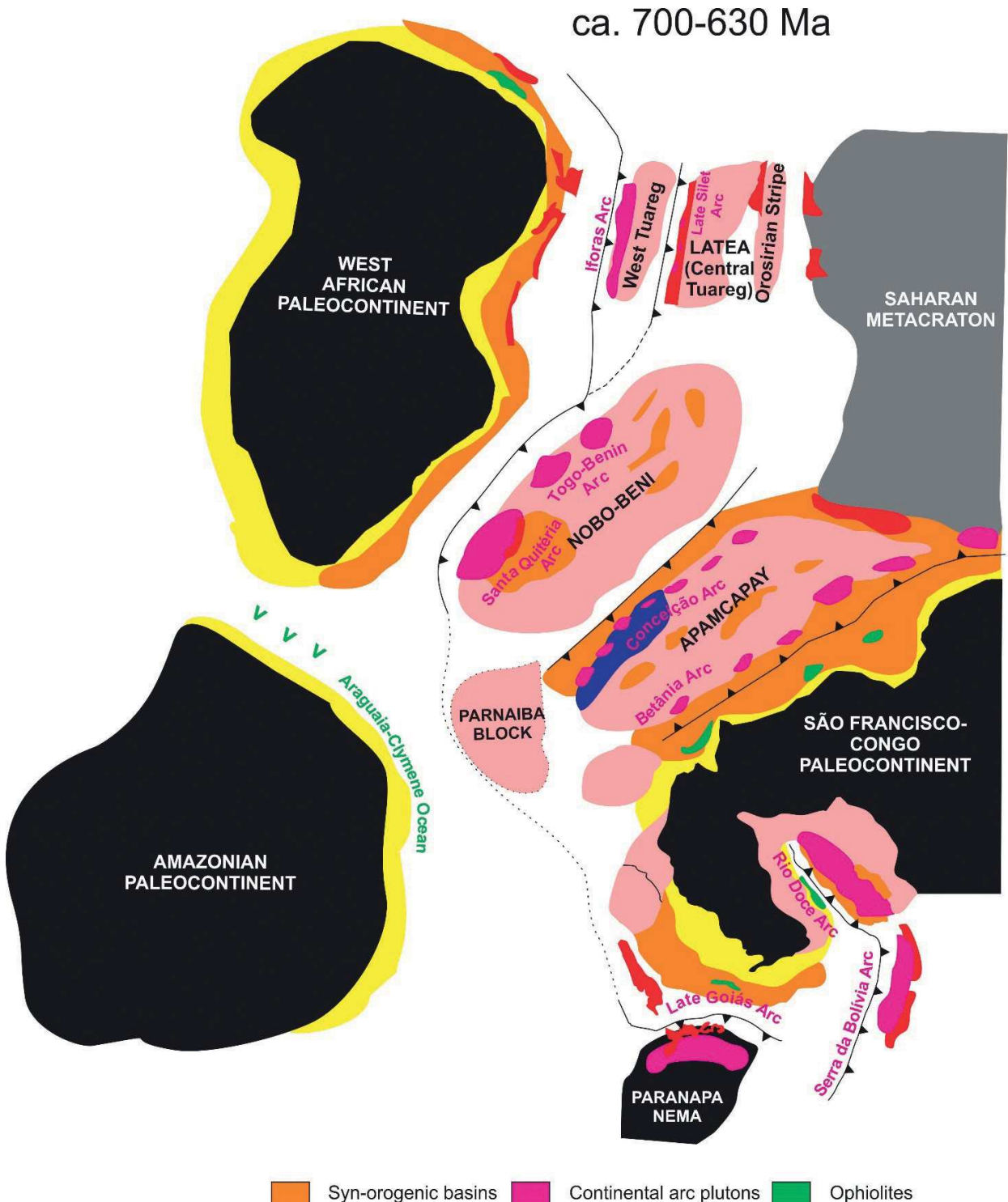


**Figure 9.** Schematic model for NE Brazil–NW Africa evolution at 800–700 Ma. See text for discussions. Notice the beginning of development of early island arcs with juvenile (intra-oceanic) signatures in both the Goiás-Pharusian and Adamastor oceans, and the development of new oceanic domains such as the Transnordestino-Central African ocean.

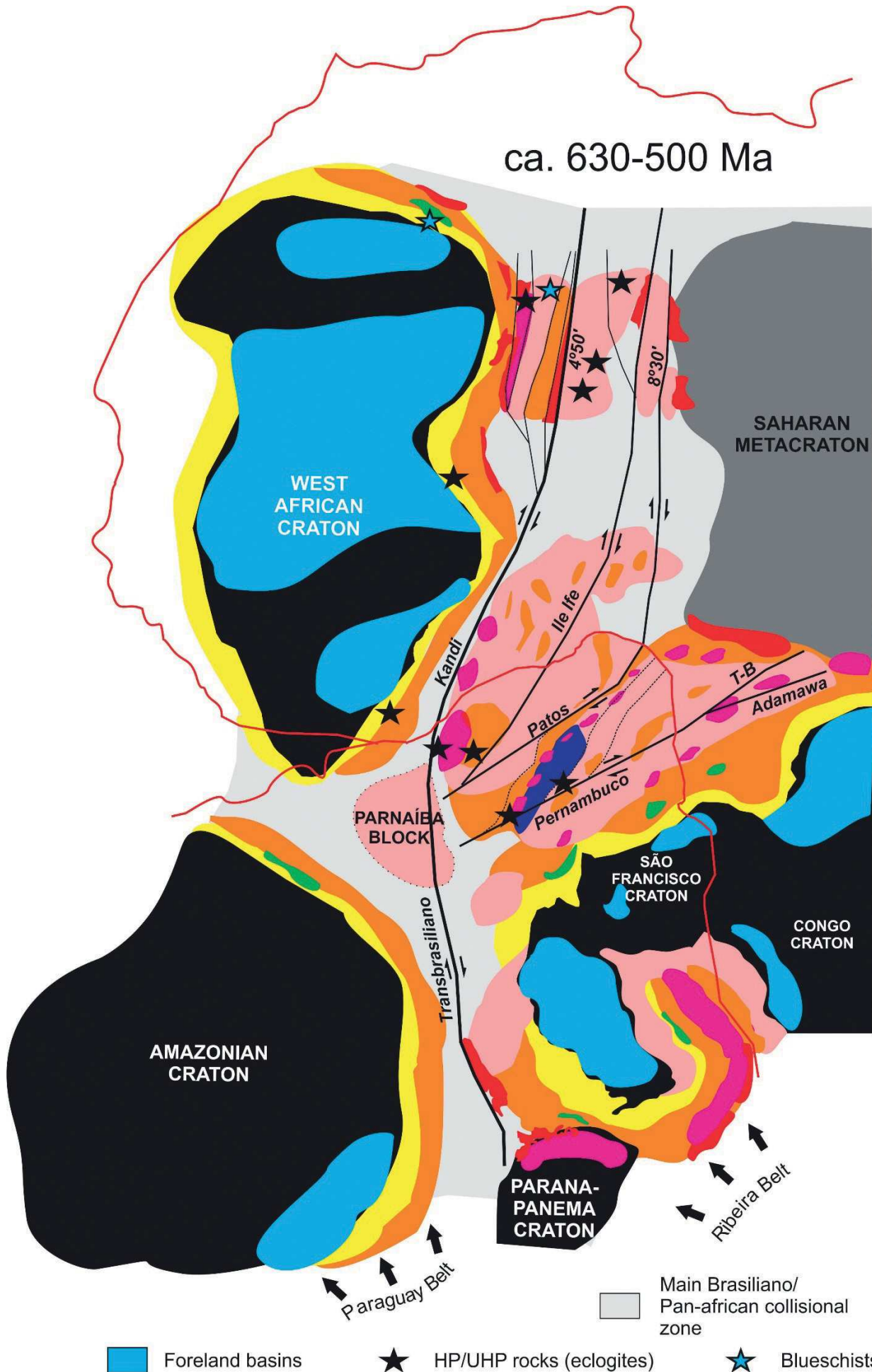
- post-collisional granites emplaced at 590–530 Ma (Santos *et al.* 2008b and references therein; Ganade de Araújo *et al.* 2016).

Santos *et al.* (2008a) described polycyclic deformation of this domain, with a Paleoproterozoic orogeny (2.2–2.0 Ga) that affected the basement rocks and three further phases developed during the Brasiliano Orogeny (ca. 620–557 Ma).

The Martinópolis Group is divided, from bottom to top, into four formations: Goiabeira (metapelite, schist, paragneiss), São Joaquim (quartzite), Covão and Santa Terezinha (metagreywacke, schist, metavolcanics, conglomerate) formations (Santos *et al.* 2008a). Ganade de Araújo *et al.* (2012a) demonstrated that the São Joaquim Formation presents very different provenance patterns in contrast with the upper units, showing mainly Paleoproterozoic detrital zircon grains with main peaks at ca. 2.1 Ga, and thus interpreted this unit as deposited on a



**Figure 10.** Schematic model for NE Brazil–NW Africa evolution at 700–630 Ma. See text for discussions. With docking of the early stage island arcs in the paleocontinental margins, reversal of subduction polarity occurs with remelting of the accreted island arc + continental margins and development of extensive Ediacaran continental magmatic arc systems.



**Figure 11.** Schematic model for NE Brazil–NW Africa evolution at 630–500 Ma. See text for discussions. The Goiás-Pharusian ocean closed at ca. 620 Ma, but final configuration of West Gondwana might have been achieved after closure of the Clymene ocean to the west and development of the extensive strike-slip system of NE Brazil and NW Africa due to a lateral escape phase.

passive margin bordering the West African craton during the Proterozoic. A metavolcanic rock interleaved within the São Joaquim quartzites yielded a U-Pb age of  $777 \pm 11$  Ma (Fetter *et al.* 2003). The upper units of the Martinópolis Group display important ca. 700–660 Ma detrital zircon grains and were thus interpreted as derived from an active margin developed during eastward subduction of oceanic crust attached to the West African craton under the Borborema Province basement crust during the Neoproterozoic.

As noted by Santos *et al.* (2008b), the Granja Complex represents a singular crustal block with a time frame of magmatism that is unknown in the adjacent Ceará Central domain or in adjacent areas of the São Luís–West Africa craton and could have constituted a crustal block with no affinity to neither of the former. A possible correlation with the Accra Plains migmatite of the Dahomey belt is proposed, but further geochronological work is needed in order to clarify this issue.

A correlation of the Neoproterozoic metasedimentary units of the MC domain, especially the Martinópolis Group, with those of the western external zone of the Dahomeyides belt in Togo and Benin (*e.g.*, the Atacora Structural Units) is proposed based on the similar detrital zircon age spectra of both units by Ganade de Araújo *et al.* (2016), thus suggesting a similar provenance shift from passive margin deposits flanking the West African craton to active margin basins related to Brasileiro/Pan-African magmatism.

Correlations with the West Tuareg Shield are more complicated, as this region clearly records a more complex history of oceanic closure (Caby 2003, Liégeois 2019). Accretion of exotic terranes such as the Neoproterozoic Tilemsi magmatic arc between the West African paleocontinent and the Archean–Paleoproterozoic granulitic terranes of West Hoggar (IOGU-OGU and the Tirek, Kidal, Tassendjanet and Ahnet terranes reworked during the Neoproterozoic; Ouzegane *et al.* 2003, Caby 2003, Bosch *et al.* 2016, Fezaa *et al.* 2019) and the Silet (former Iskel; Béchiri-Benmerzoug *et al.* 2017) magmatic arc between the latter and LATEA (Liégeois *et al.* 2003) suggest a more complex scenario, with intervening exotic blocks between the main plates involved in continental collision.

Neoproterozoic deformation in the MC domain is marked by an early phase of tangential deformation, marked by a medium- to low-angle SE-dipping foliation and a NE- or SE-oriented stretching lineation of sillimanite, kyanite, staurolite, and muscovite developed under amphibolite facies in the Martinópolis Group and greenschist facies in the Ubajara Group. The tangential compression was superseded by strike-slip deformation, characterized by strongly sub-vertical NE-striking foliation defining large dextral-sense shear zones. Available U-Pb zircon and monazite ages from variably deformed igneous rocks indicate that the tangential collision happened around 620 Ma, and the transition to strike-slip tectonics took place between 614 and 591 Ma (Santos *et al.* 2008b). Mineral cooling dates suggest that transcurrent tectonics was active until at least ca. 540 Ma in the NW Borborema Province (Monié *et al.* 1997). Undeformed post-tectonic extensional granitoids were emplaced adjacent to the Transbrasiliiano shear zone around

532 Ma, and cooling of the deeply buried parts of the orogen continued to about 552 Ma (Monié *et al.* 1997). Thus, a time frame for collisional tectonics at ca. 620 Ma, transition to strike-slip tectonics at 614–591 Ma, a predominant strike-slip regime from 591 to 540 Ma, and post-tectonic granite emplacement and regional cooling of the orogen at 540–532 Ma is defined for this part of the Borborema Province.

### *The Transbrasiliiano–Kandi–4°50′/West Silet shear zone*

the Transbrasiliiano lineament (Schobbenhaus 1975) is a major vertical NE-SW trending structure that crosscuts the entire Brazilian territory from the state of Ceará in NE Brazil (where it is locally called Sobral–Pedro II shear zone) through central Brazil (partly covered by the Phanerozoic sedimentary rocks in the Parnaíba Basin) down southwest until it is covered once again by Phanerozoic sedimentary rocks of the Paraná Basin. Various workers suggested that the Transbrasiliiano lineament continues in Africa as the Kandi–4°50′ shear system (Caby 1989, Trompette 1994, Fairhead and Maus 2003, Santos *et al.* 2008b, Cordani *et al.* 2013b). However, different connections have been proposed, such as a connection of the Transbrasiliiano–Kandi to the Adrar fault separating the Pharusian belt from the remainder of the Tuareg Shield (Santos *et al.* 2008b) or to the West Silet shear zone (Liégeois 2019, Brahimi *et al.* 2018).

Various lines of evidence suggest that the main suture zones related to closure of the Goiás–Pharusian ocean are located within or in the vicinities of the Transbrasiliiano–Kandi–4°50′/West Silet shear system (Cordani *et al.* 2013b):

- the presence of HP and UHP rocks, many of them registering peak metamorphic conditions at around 620–610 Ma or slightly older, in the geologic domains closeby (Sautter 1986, Liégeois *et al.* 2003, Santos *et al.* 2009, 2015, Ganade de Araújo *et al.* 2014b, Berger *et al.* 2014, Doukkari *et al.* 2014, 2019, Adjerid *et al.* 2015, Amaral *et al.* 2012, 2015, Arab *et al.* 2019);
- the occurrence of Neoproterozoic arc-related batholithic complexes in the vicinities of the shear zone, both early intra-oceanic or transitional (early Goiás, Lagoa Caiçara, Amalaoulaou, Silet, Tilemsi arcs) and late continental arcs (late Goiás, Santa Quitéria, Togo–Benin, Iforas arcs);
- the juxtaposition of geological domains of distinct age and constitution along the tectonic corridor;
- high-density gravity anomalies beneath the Parnaíba Basin, interpreted as buried mafic and ultramafic rocks along the strike of the lineament (Lesquer *et al.* 1984).

The ductile fabric kinematic indicators suggest mainly dextral movement during the Neoproterozoic in the Transbrasiliiano shear zone at NW Borborema. Recently, evidence for brittle sinistral reactivation from the Ordovician onwards was presented and discussed by Amaral *et al.* (2017). These authors dated felsic dykes dislocated by faults parallel to the Transbrasiliiano trend within the deformation corridor at the region of Cariré, Ceará, with younger concordant U-Pb ages at ca. 460 Ma. Very similar brittle reactivations of the 4°50′ and other main shear

zones of the Tuareg Shield during the Ordovician are discussed by Guiraud *et al.* (2005).

### HP and UHP Rocks of the West Gondwana Orogen

Several occurrences of Neoproterozoic HP and UHP rocks (eclogites, retro-eclogites, and granulites) are recorded along the vicinities of the Transbrasiliano–Kandi–4°50′/West Silet shear system and surrounding domains on both sides of this major tectonic boundary throughout the West Gondwana Orogen. Ganade de Araújo *et al.* (2014b) studied eclogite occurrences in Mali, Togo and NE Brazil, and concluded that they represent relicts of an orogenic zone marked by deep continental subduction in the West Gondwana Orogen. U-Pb SHRIMP dating of zircon from the three occurrences studied by Ganade de Araújo *et al.* (2014b) indicate that UHP metamorphism occurred virtually synchronously over this wide geographical area at ca. 608–616 Ma. Santos *et al.* (2015) presented a similar age of 615 Ma for a coesite-bearing retro-eclogite of NE Brazil. Igneous zircon cores indicate protolith ages of > 1.0 Ga for the Mali eclogites and ca. 700 Ma for the Togo ones; older ages of ca. 1.57 Ga have been presented for the protoliths of the Forquilha eclogites (Ceará, Brazil), interpreted by Amaral *et al.* (2015) as mafic dykes emplaced in an extensional setting. The same is the case for the Telouine eclogites (Tassendjanet, western Hoggar), whose geochemistry shows that they correspond to continental basalts and that their Nd model ages are between 700 and 800 Ma (Berger *et al.* 2014).

Retro-eclogites are found in NE Brazil as boudins interleaved within partially melted HT metasedimentary sequences, in the Forquilha Zone of Ceará, adjacent to the Transbrasiliano shear zone, to the west of the Tamboril/Santa Quitéria Complex. The eclogite lenses are intensely retrogressed and are composed of garnet, Ca-rich pyroxene, hornblende, and Na-augite/plagioclase symplectite (Santos *et al.* 2009, Ganade de Araújo *et al.* 2014b). Recently, Santos *et al.* (2015) described coesite associated with atoll garnets in retro-eclogite samples of this area. Minimum P-T conditions for the decompression stage are established from the study of relict phases at 1.7 GPa and 770°C (Santos *et al.* 2009). Ti-in-zircon thermometry indicates temperatures around 700°C for zircon formation (Ganade de Araújo *et al.* 2014b). Detrital zircon analysis of the metasedimentary rocks associated with the retro-eclogites (Ancelmi *et al.* 2015) shows a simple pattern with Paleoproterozoic zircon grains (1800–2480 Ma), reinforcing the suggestion that the Forquilha retro-eclogites represent Mesoproterozoic basaltic rocks related to a continental rift involved in the Late Neoproterozoic subduction/collision and then tectonically juxtaposed to an active margin sequence, whose sedimentation is derived from erosion of the Santa Quitéria Magmatic Arc (the Ceará Group, which contains ca. 650 Ma detrital zircon grains; Ganade de Araújo *et al.* 2012b, Garcia *et al.* 2014).

Retro-eclogites are also found in the Itaitia region of the CC domain bordering the eastern side of the Tamboril/Santa Quitéria Complex, interleaved within the aluminous migmatitic paragneisses of the Independência unit. These indicate minimum conditions of 1.4–1.7 GPa and 700–800°C, with monazite U-Pb ages of ca. 630 Ma (Castro 2004). The presence

of retro-eclogites bordering both sides of the Tamboril/Santa Quitéria Complex, as well as electromagnetic evidence for convergent subduction zones below the NW Borborema lithosphere, led Padilha *et al.* (2014) to propose a model involving a subduction polarity reversal, described in the next section.

In the Tuareg Shield, various HP metamorphic units could be related to continental subduction, and thus, considered as probable correspondents of the above discussed HP/UHP occurrences, such as the ca. 620 Ma HP metamorphic units (550–650°C, 1.4–2.2 GPa) of Tideridjaouime-Tileouine-Tassendjanet exposed along the edge of the IOGU terrane or microcontinent (Caby 2003, Berger *et al.* 2014), the Tin Begane eclogites of southern LATEA (790°C, 1.5 GPa; Boughrara 1999), the Azroun N’Fad eclogite, with a decompression path from 1.5 to 1.1 GPa between 800 and 700°C (Zetoutou *et al.* 2004) and the Egeré-Aleksod terrane, where outcrops the deepest units within the LATEA metacraton, and where a complete P-T path is recognized in preserved eclogites. The starting conditions correspond to 1.3–1.4 GPa and 580°C, followed by an increase up to 1.9 GPa and 650–700°C at fluid-saturated conditions, followed by a retrogression involving near-isothermal decompression to 0.8–0.9 GPa and 700–750°C at fluid-undersaturated conditions (Doukkari *et al.* 2014, 2015, 2019, Arab *et al.* 2019).

High-pressure metamorphic conditions over juvenile oceanic rocks have also been recognized in central Hoggar, in eclogitic talc-schists from the Serouenout terrane (Adjrid *et al.* 2015); and in western Hoggar, at the Ahnet terrane, where a root of a Neoproterozoic island arc which underwent blueschist facies metamorphism outcrops (Caby 2003).

### Magmatic arc rocks of the West Gondwana Orogen

The Santa Quitéria (or Tamboril/Santa Quitéria) Complex is a NE-SW trending complex of Brasiliano granitoid plutons and migmatites covering ca. 40,000 km<sup>2</sup> of the Ceará State in NW Brazil, and is located ca. 200 km to the SE of the high-density gravity anomalies that represent the continuation of the Transbrasiliano shear zone under the Phanerozoic Parnaíba Basin sedimentary rocks (Fetter *et al.* 2003). This complex involves a large variety of dioritic to granitic bodies and is flanked by metavolcanosedimentary units interpreted by Fetter *et al.* (2003) as the infilling of classic fore- and back-arc basins.

Fetter *et al.* (2003) interpreted the extensive plutonic rocks of the Santa Quitéria Complex dated at ca. 665–591 Ma as representing a large continental arc batholith. Dating of metavolcanic rocks within the metasedimentary sequences indicates arc activity as early as 777 Ma. Nd T<sub>DM</sub> model ages of 1.6–0.8 Ga and associated εNd<sub>(600 Ma)</sub> between -10 and +3 are consistent with variable mixtures of juvenile Neoproterozoic magmas (such as those generated in a mantle wedge above a subduction zone) and the surrounding Paleoproterozoic gneisses of the Ceará Central domain basement (Fetter *et al.* 2003). Ganade de Araújo *et al.* (2012b) presented a distinct interpretation based on geochemistry analysis of the plutonic rocks and the fact that the Santa Quitéria Complex U-Pb zircon ages are closely related in time with those of the ca. 620 Ma Forquilha eclogites and HT metamorphic rocks in the CC domain, thus pointing

out to a syn-orogenic setting, arguably developed during the collisional stage. According to these authors, the crustal-derived magmatism would be the product of continental thickening resulting from the collision of the West African–São Luís craton and the Paleoproterozoic–Archean basement of the CC domain along the Transbrasiliano shear zone. Ganade de Araújo *et al.* (2014a) presented a more complete scenario for the evolution of the Tamboril-Santa Quitéria Complex based on U-Pb and Nd-Sr-O-Hf isotopes, suggesting:

- an early period comprising juvenile arc magmatism at ca. 880–800 Ma (the Lagoa Caiçara arc), which might have continued to ca. 650 Ma, as indirectly evidenced by detrital zircon grains from associated syn-orogenic deposits;
- a mature arc period at ca. 660–630 Ma, characterized by hybrid mantle–crust magmatic rocks;
- crustal anatexis at 625–618 to ca. 600 Ma.

Recently, Ganade de Araújo *et al.* (2016) interpreted a variety of granitoids in Togo and Benin aged between 670 and 610 Ma as arc-related plutons resulting from the east-dipping subduction of the Goiás–Pharusian oceanic lithosphere beneath the Benino-Nigerian Shield lithosphere, mainly sourced from crustal reservoirs with subordinate juvenile input. These could be chrono-correlated to the Santa Quitéria continental arc in NE Brazil. Detrital zircon U-Pb analysis of adjacent syn-orogenic deposits in the Benino-Nigerian Shield suggest that continental arc development could have started as early as ca. 780 Ma (Ganade de Araújo *et al.* 2016), thus suggesting temporal evolution of this probable arc system in the same time frame as that proposed by Fetter *et al.* (2003) and Ganade de Araújo *et al.* (2014a) for the Brazilian counterpart. The Tassendjanet and Kidal terranes (Iforas Arc) in the western portion of the Tuareg Shield (Caby 2003, Bosch *et al.* 2016) and the Kabyé massif of the Dahomeyides could be possible correlatives (Guillot *et al.* 2019). The late stages of the Silet arc dated at ca. 650–638 Ma (Béchiri-Benmerzoug *et al.* 2011) are other possible correlatives in the Tuareg Shield.

Although most authors interpret a SE-dipping subduction zone with consumption of the Goiás-Pharusian oceanic lithosphere beneath the northern Borborema (CC) lithosphere as responsible for magmatism of the accretionary phase of the Santa Quitéria Complex, the presence of relicts of eclogitic facies metamorphism on both sides of the complex has led to alternative interpretations suggesting a westward polarity of the subduction zone (Castro 2004). Padilha *et al.* (2014) detected opposed resistive slabs converging at mantle depths beneath the NW Borborema Province through electromagnetic studies, interpreting this feature as caused by a subduction polarity reversal. In the model presented by these authors, this would have occurred after the docking of oceanic arc rocks (the Lagoa Caiçara Arc) with the NW Borborema block due to westward subduction, followed by the closing of the oceanic domain between the West African–São Luís paleocontinent and partial melting of the accreted Lagoa Caiçara-NW Borborema lithosphere by new eastward-dipping subduction at ca. 650–610 Ma. This led to the formation of the mature continental arc phase of the Santa Quitéria Arc and ultimately

to closure of the Goiás–Pharusian ocean and collision of the two main lithospheric blocks, squeezing the Lagoa Caiçara unit between them, development of syn-collisional anatexis and continental subduction-related eclogitic metamorphism (Ganade de Araújo *et al.* 2014b). An alternative model without subduction polarity reversal is presented by Ganade de Araújo *et al.* (2014a), who interpret the Lagoa Caiçara Complex as representing a transitional arc developed upon thinned continental crust, with the NW-dipping resistive slab of Padilha *et al.* (2014) interpreted as the scar of a back-arc closure and subduction during the continental collision at ca. 615–620 Ma.

Most of the rock suites interpreted as developed in magmatic arc settings in the vicinities of the Transbrasiliano–Kandi–4°50′/West Silet shear system seems to follow a similar island arc-continental collision model, suggesting the evolution of the Goiás–Pharusian realm as a typical “Pacific-type” ocean. Island arc formation started as early as ca. 900 Ma and as late as ca. 730 Ma (early Goiás in the Brasília belt; Lagoa Caiçara in NW Borborema; Amalaoulaou in Mali; Tilemsi in the west Tuareg Shield; Saghro in Morocco) and is characterized by juvenile magmatism with a strong mantle input probably formed in oceanic-oceanic subduction settings. These island arcs were then accreted to the continental margins as allochthonous terranes and the accreted margins were further remelted during oceanic-continental subduction, forming the late-stage continental arcs at ca. 650–610 Ma. This was immediately followed by continental collision at ca. 615–605 Ma, causing crustal anatexis and remelting of the whole crustal pile, including the associated pre-collisional basins (Pimentel and Fuck 1992, Saquaque 1992, Laux *et al.* 2005, Ganade de Araújo *et al.* 2014a, Caby *et al.* 1982, 1989, Caby 2003, Berger *et al.* 2011, Walsh *et al.* 2012).

#### *Northern Borborema/Benino–Nigerian Shield (NOBO-BENI) and possible connections to the Tuareg Shield*

The remainder of the northern Borborema Province, north of the Patos shear zone, is mainly composed of Archean and Paleoproterozoic basement rocks of the CC and RGN domains with interleaved Paleo–Mesoproterozoic (Orós–Jaguaribeano) and Neoproterozoic (Ceará, Seridó, and Lavras da Mangabeira) metavolcanosedimentary belts. Most of the basement rocks are Rhyacian; in fact, the fundamental crustal framework of the northern Borborema (and of all of the Borborema Province) was assembled during this very important Paleoproterozoic orogenic event. The Paleoproterozoic gneisses surround three major Archean nuclei located at the CC (Troia-Pedra Branca) and RGN (Granjeiro and São José do Campestre) domains. Alternatively, based on geophysical constraints and on the distinct geological units, Arthaud *et al.* (2008) proposed the Orós–Jaguaribe domain separating the RGN domain and the remainder of the CC domain and limited by the Portalegre shear zone to the east and the Senador Pompeu shear zone to the west. For the sake of simplification, this will be here treated as part of the Ceará Central domain, crosscut by a distinct Paleo–Mesoproterozoic metavolcanosedimentary belt (the Orós–Jaguaribeano belt).

Basement of the Ceará Central domain is constituted of the Troia–Pedra Branca massif, a gneissic Archean complex with crystallization ages around 2.86–2.68 Ga (Fetter *et al.* 2000, Ganade de Araújo *et al.* 2017). This complex is surrounded by Paleoproterozoic orthogneiss and migmatites. U–Pb zircon geochronology and Sm–Nd whole-rock studies allow to recognize two major pulses of Paleoproterozoic crustal growth, the first at ca. 2.35–2.30, characterized exclusively by juvenile growth and accretion, and the second at ca. 2.19–2.05 Ga, involving the incorporation of reworked or enriched crust and Archean crustal fragments (Fetter *et al.* 2000, Martins *et al.* 2009, Costa *et al.* 2015). Also comprising the Paleoproterozoic basement, amphibolites, granulites, and paragneisses occur, sometimes grouped as Canindé Complex (Ancelmi 2016). The Granjeiro Complex (mostly 2.7–2.5 Ga; Silva *et al.* 1997, Ancelmi 2016) configures an Archean succession at the southern RGN domain, truncated by the Patos shear zone to the south, and is composed of orthogneisses and a metavolcanosedimentary sequence composed of metamafic-ultramafic rocks, metachert, banded iron formations, marbles and other metasedimentary rocks. Recently, Pitarello *et al.* (2019) reported U–Pb ages for the Granjeiro Complex from  $3535 \pm 14$  to  $2384 \pm 35$  Ma, suggesting that some of the oldest rocks in South America might be present in this area.

Eastward in the São José do Campestre massif of the Rio Grande do Norte domain, Dantas *et al.* (2004, 2013) characterized another of the oldest fragments of continental crust in South America, occurring as an isolated enclave of migmatitic gneisses comprising an area of ca. 6,000 km<sup>2</sup> around the city of Natal. The oldest isotopic ages in this crustal block were obtained from the Bom Jesus tonalitic migmatitic gneiss, with crystallization of the igneous protoliths at ca. 3.45 Ga, as indicated by the TIMS and SHRIMP U–Pb zircon analyses (Dantas *et al.* 2004), and  $T_{DM}$  model ages of > 3.7 Ga. This older core is flanked by both reworked and juvenile 3.25–3.18 Ga rocks intruded by 3.0 and 2.69 Ga plutonic bodies. This protracted evolution is interpreted by Dantas *et al.* (2004) as a characteristic of detached pieces of an evolved craton or larger crustal mass that became entrained within other crustal blocks during the Paleoproterozoic (2.2–2.0 Ga) orogenic event, which characterizes the surrounding larger tracts of gneissic rocks of the RGN domain around the São José do Campestre massif.

Recently, older Paleo to Eoarchean mafic-ultramafic rocks were characterized in the RGN domain by Santos *et al.* (2020). The authors obtained U–Pb (SHRIMP) ages of  $3526 \pm 5$  Ma (MSWD = 0.0084) for the serpentinites of the Serra Verde mine and  $3,747 \pm 12$  Ma (MSWD = 9.8) for serpentinites from the Oiticica mine, interpreted as fragments of Archean greenstone belts. These represent the oldest crustal fragments yet described in the whole South American platform, and further studies will surely be necessary in order to better constrain their significance and implications for Archean geodynamics.

These recent findings also suggest that other Paleo and Eoarchean crustal fragments might be present in the Borborema Province. Barros (2019), for example, recovered Archean zircon crystals from the Cristalândia do Piauí block, in the Rio Preto belt, with evolved  $\epsilon Hf$  and  $T_{DMHF}$  model ages of

3.6–4.3 Ga, which might suggest the presence of cryptic (reworked) Eoarchean or even Hadean crust in the basement of the Borborema Province. Thus, the “race” is open for the finding of still older crustal fragments, which will certainly provide crucial clues for the understating of the early stages of Earth’s history.

The remainder of the RGN domain basement is composed of Paleoproterozoic gneisses and migmatites, with crystallization ages mainly in the 2.25–2.01 Ga range (Van Schmus *et al.* 1995, Silva *et al.* 1997, Fetter *et al.* 2000, Souza *et al.* 2007, 2016, Hollanda *et al.* 2011, Medeiros *et al.* 2012, Sá *et al.* 2014). Locally, however, the presence of rocks as old as ca. 2.4 Ga has been described (Hollanda *et al.* 2011). Unlike the MC and CC basements, these rocks show evidence of incorporation of large amounts of crustal material during magma genesis.

The Orós–Jaguaribeano metavolcanosedimentary belt crosscuts the Ceará State in a bifurcated sigmoidal shape. It consists of a metasedimentary sequence (mainly quartzites with subordinate carbonatic rocks) with interleaved bimodal volcanism with a predominance of felsic volcanics interpreted as deposited in a rift-related setting at ca. 1.8–1.75 Ga (Sá *et al.* 1995), coeval to similar rift sequences of the São Francisco craton and Brasília belt such as the Espinhaço, Chapada Diamantina, and Araí basins (Fig. 3; Guadagnin and Chemale Jr. 2015 and references therein). This probably represents a first attempt to break the hypothetical paleocontinent formed during the 2.2–2.0 Ga orogenic phase. Felsic plutonics with geochemical signatures and ages similar to the rhyolites occur and are crosscut by alkaline anorogenic intrusives at 1.7 Ga, all successions being crosscut by a ca. 0.9 Ga mafic-ultramafic sill (Sá *et al.* 1995). The succession was later deformed and metamorphosed during the Brasiliano Orogeny, accompanied by the intrusion of syn-orogenic granites.

The Ceará Group comprises most of the metasedimentary cover exposed within the CC domain. This unit is composed of metagreywacke, metapelites, quartzites, marbles, and calc-silicate rocks associated with amphibolites, with some local felsic metavolcanics. A westward to southwestward verging low-angle foliation formed during nappe stacking is the most prominent deformational feature of the unit (Caby and Arthaud 1986), associated with regional amphibolite-facies metamorphism. U–Pb dating of garnet amphibolites interpreted as basic volcanic rocks indicates rifting of the Archean–Paleoproterozoic basement and commencement of deposition of the Ceará Group at ca.  $749 \pm 5$  Ma (Arthaud *et al.* 2015). Detrital zircon data show three main age groups, in Paleoproterozoic (ca. 2.2–2.0 Ga), in early Neoproterozoic (ca. 1,000–850 Ma), and at ca. 660 Ma. The latter is close to the peak of pre-collisional magmatic activity of the Santa Quitéria Arc, and thus most of the Ceará Group is interpreted as deposited in a syn-orogenic basin with detritus deriving mainly from the Brasiliano mountain chain to the NW (Ganade de Araújo *et al.* 2012b, Garcia *et al.* 2014, Arthaud *et al.* 2015). Also comprising the supra-crustal rocks of the CC Domain, the Novo Oriente Group is a low-grade metavolcanosedimentary unit thrust over the southern portion of the Tamboril/Santa Quitéria Complex with a loosely constrained maximum depositional age based on

detrital zircon U-Pb analysis at ca. 2.0 Ga and  $T_{DM}$  model ages at ca. 1.4–1.7 Ga for associated metabasic rocks (Ganade de Araújo *et al.* 2010). The intercalations of mafic and ultramafic rocks of uncertain age were interpreted as probable remnants of a continental margin-type ophiolite (Pitombeira *et al.* 2017).

The Seridó belt crosscuts the RGN domain in a sigmoidal shape, and is composed of metasedimentary rocks of the Equador (quartzites), Jucurutu (paragneisses, marbles, and banded iron formations) and Seridó (greywacke schists) formations. The Equador Formation is characterized by exclusively Archean–Paleoproterozoic detrital zircon U-Pb age populations, while the Seridó and Jucurutu formations are characterized by distinct major late Neoproterozoic detrital zircon age peaks (Van Schmus *et al.* 2003, Hollanda *et al.* 2015), with younger grains at ca. 630 Ma. Metasedimentary rocks of the Lavras da Mangabeira region, bordering the northern margin of the Patos shear zone, yield similar provenance patterns and were interpreted by Hollanda *et al.* (2015) as correlatives to the Seridó units. A major provenance shift between the lower Equador quartzites and the upper Seridó Formation metagraywackes is proposed for the sedimentary record of the Seridó Belt. Syn-orogenic granites associated with HT–LP transpression of the belt are dated at ca. 595–575 Ma (Archanjo *et al.* 2008, Hollanda *et al.* 2010). These data provide a lower limit for deposition of the Seridó Formation, which must have been deposited between 630 and 595 Ma.

The Jucurutu marbles sit atop Banded Iron Formation (BIF) and are locally associated with diamictites of uncertain stratigraphic position. They show negatively fractionated  $\delta^{13}C$  values near the basal contact, mostly around -5‰, superseded upsection by positive values up to +10‰, with  $^{87}Sr/^{86}Sr$  ratios at 0.7074–0.7075. The isotope stratigraphy suggests deposition during the late Cryogenian to early Ediacaran, and correlation of possibly glaciogenic-related diamictites, BIF, and marbles with other worldwide sequences of this age (Nascimento *et al.* 2004, 2007, Sial *et al.* 2015). Chemostratigraphic data, including Cr isotope data, led Sial *et al.* (2015) to interpret the Jucurutu BIF as deposited in a restricted rift basin with anoxic and acidic deep waters under the influence of hydrothermal vents, while the overlying marbles possibly represent post-glacial cap carbonate sequences deposited in anoxic to slightly oxic shallow marine environments.

Striking similarities can be observed between the northern Borborema Province and the Benino–Nigerian Shield of NW Africa (*e.g.*, Brito Neves *et al.* 2002, Ferré *et al.* 2002, Dada 1998, 2008). Paleo- (3.6–3.5 Ga), Meso- (3.2–3.1 Ga), and Neoproterozoic (2.7–2.5 Ga) crust remnants are present in both provinces; including the oldest rocks in West Africa (migmatitic gneiss from Kabala, Kaduna, Nigeria, with zircon dated by U-Pb at  $3571 \pm 3$  Ma; Kröner *et al.* 2001; see also Bruguier *et al.* 1994), as well as the extensive 2.1–2.0 Ga orogenic events. The classical “Schist Belts” of Nigeria (Turner 1983) might correlate either to the Paleo–Mesoproterozoic Orós–Jaguaribeano belt or to the Neoproterozoic Seridó belt, or, more likely, might bear correlatives to both Proterozoic metasedimentary units (Brito Neves *et al.* 2002). Nappe deformation, regional metamorphism up to the granulite facies, and

emplacement of syn-collisional biotite-muscovite granites at ca. 615 Ma followed by strike-slip deformation at ca. 585 Ma (Ferré *et al.* 2002) are approximately coeval with similar events in the northern Borborema Province (*e.g.*, Souza *et al.* 2016).

A very important correlation can be drawn between the Orós–Jaguaribeano belt of Ceará and monocyclic Late Paleoproterozoic metasedimentary rocks identified in the western Tuareg Shield (Caby and Andreopoulos-Renaud 1983, Moussine-Pouchkine *et al.* 1988, Bertrand-Sarfati *et al.* 1987, Caby 2003). Felsic metavolcanic rocks interlayered within a metasedimentary succession composed of aluminous quartzite, pebbly layers, and metapelite were dated (U-Pb in zircon) at 1837 and 1755 Ma in Adrar des Iforas and western Hoggar, respectively (Caby and Andreopoulos-Renaud 1983), providing a direct chronocorrelation with the rift-related sequences of the Orós–Jaguaribeano belt and of the extensive Espinhaço rift system of eastern-central Brazil (Guadagnin and Chemale Jr. 2015, and references therein).

With the continuation of the Transbrasiliano–Kandi shear zone as the 4°50′/West Silet shear zones of the Tuareg Shield, there is a possibility that the LATEA metacraton of the Central Tuareg Shield (Liégeois *et al.* 2003) represents a similar crustal section to the Benino–Nigerian Shield and the northern Borborema Province blocks. These areas would then be bounded by the Patos shear zone in Brazil, which defines the southern border of the northern Borborema Province, by the limit between the West and East Nigeria provinces in Nigeria (Ferré *et al.* 1996) and by the Ounane shear zone which defines the eastern border of the LATEA metacraton (Fig. 2). In effect, the basement of the LATEA metacraton is composed of granulite facies rocks metamorphosed between 2.07 and 1.9 Ga (Bertrand *et al.* 1986, Bendaoud *et al.* 2008, Peucat *et al.* 2003) whose protoliths are either Paleoproterozoic or Archean (up to 2.7 Ga according to U-Pb zircon ages and showing  $T_{DM}$  Nd model ages of up to 3.3 Ga; Peucat *et al.* 2003). These were strongly deformed, metamorphosed, and injected by granitoid plutons (*e.g.*, Henry *et al.* 2009) during the Pan-African Orogeny, due to the collision between the West African craton to the west and the Saharan metacraton to the east. The main difference in comparison to the Benino–Nigerian Shield and northern Borborema Province is that possibly Neoproterozoic juvenile oceanic units were thrust upon the LATEA metacraton during the Late Neoproterozoic (Laoui thrust sheets), suggesting that the terrains that compose the LATEA metacraton might have been separated from the southern Trans-Saharan (Benino–Nigerian) units by oceanic tracts during the Neoproterozoic. LATEA was also apparently not intruded by subduction-related magmas during this period, functioning as a continental block bounded by passive margins during the Pan-African Orogeny (Liégeois *et al.* 2003).

Finally, the Assodé-Issalane and Tazat terranes of the oriental part of central Hoggar were interpreted by Liégeois (2019) as forming an “Orosirian Stripe”, which could also represent Paleoproterozoic basement similar to what is found southward in the Benino–Nigerian Shield and in the northern Borborema Province. These are bounded to the east by terrains interpreted as belonging to the western Saharan metacraton. Those are

thrust over by metavolcanosedimentary successions bearing probable Neoproterozoic ophiolite remnants emplaced at ca. 730 Ma (such as the Aouzegueur Terrane in Air, Niger; Boullier *et al.* 1991, Liégeois *et al.* 1994). A flat-lying molassic sequence (Proche-Ténééré) bearing rhyolites dated at ca. 660 Ma (Bertrand *et al.* 1978, Caby and Andreopoulos-Renaud 1987) suggests that this crustal block was neocratonized at this time (Caby 2003). Recently, younger deformational and plutonism events at 557–555 Ma were described as a result of intracontinental processes (Murzukian event; Fezaa *et al.* 2010), with no clear links with the other Ediacaran events further west in the central Tuareg Shield.

The similarities between the Archean-Paleoproterozoic basement of northern Borborema, Benino-Nigerian Shield and of the east, central and west Tuareg Shield, specifically the presence of Archean nuclei strongly reworked during the extensive ca. 2.2–2.0 Ga Orogeny, the presence of ca. 1.7–1.5 Ga rift sequences and vestigial Neoproterozoic metavolcanosedimentary belts call for further investigations in order to understand the extent and tectonic significance of the northern Borborema/Benino–Nigerian connection (a fragment of a Paleoproterozoic paleocontinent? — here dubbed NOBO-BENI) and its possible correlation with the terrains composing the Tuareg Shield. Could all of these three domains represent a major Archean–Paleoproterozoic “metacratonic” unit, which underwent crustal rifting and drifting separating the Tuareg Shield basement-dominated terrains from each other and from their southern correlatives during the Neoproterozoic; or could they represent distinct lithospheric fragments that drifted and became amalgamated only during the late Neoproterozoic? Either way, both of these crustal fragments (NOBO-BENI, West, Central and East Tuareg) became squeezed between the West African–São Luís/Saharan/São Francisco–Congo paleocontinents and were reworked during the Late Neoproterozoic to Cambrian, with widespread deformation, metamorphism, and plutonism related to the continental collisions of the Pan-African Orogeny.

#### *Eastern Transversal Zone (Alto Pajeú-Alto Moxotó-Rio Capibaribe)/Pernambuco-Alagoas/Adamawa-Yadé (APAMCAPAY)*

The transversal zone of the Borborema Province is bounded by the E-W trending Patos and Pernambuco dextral-sense shear zones. A series of subsidiary NE-SW trending sigmoidal shear zones branch and connect the two major shear zones, separating the transversal zone in several almond-shaped crustal sections (Fig. 3). Interpretations for the geological evolution of the transversal zone are contentious (Van Schmus *et al.* 2011), from the accretion of exotic terranes bounded by major faults (e.g., Santos *et al.* 2000, Santos L.C.M.L. *et al.* 2017b, 2018) to a major reworking of Archean–Paleoproterozoic crust during the Neoproterozoic in a mostly intracontinental setting (Neves *et al.* 2009).

The easternmost AM and RC domains are mostly composed of Archean (ca. 2.6–2.5 Ga) and Paleoproterozoic (2.2–1.9 Ga; Neves *et al.* 2015, Santos *et al.* 2017b) high-grade rocks (gneisses and migmatites), covered by Proterozoic

metasedimentary successions (the Sertânia and Surubim complexes, with youngest detrital zircon U-Pb ages around 650 Ma; Neves *et al.* 2009) akin to vestigial schist belts, all of them intruded by late Neoproterozoic plutonic rocks. Statherian-Calymmian intrusions occur in the RC (Passira anorthositic complex and related rocks; Accioly 2001, Sá *et al.* 2002), AM, and the southern portion of the AP domains (Coloete and Carnoió alkaline granites and syenites; Lages *et al.* 2019). These are dated in the 1.7–1.5 Ga age range and commonly interpreted as A-type granites related to intraplate extensional events, although Lages *et al.* (2019) presented an alternative view that part of these intrusions might have been related to a crustal accretion event. The Limoeiro mafic-ultramafic complex occurs in the RC domain and hosts important Ni-Cu-PGE deposits (Mota-e-Silva *et al.* 2013). The complex is metamorphosed at ca. 634 Ma but the age of magmatic emplacement and crystallization is poorly constrained to around 800 Ma as the recovered zircon crystals underwent Pb-loss during the metamorphic event (Mota-e-Silva 2014).

The AP domain is unique in the geology of the Borborema Province because it hosts a ca. 700 km long sigmoidal belt of early Tonian metaplutonic, volcanic, and sedimentary rocks, named Cariris Velhos belt (Brito Neves *et al.* 1995, Kozuch 2003, Santos *et al.* 2010). Augen-gneisses are closely associated with pelitic metasedimentary, metavolcanic, and metavolcaniclastic rocks (Santos *et al.* 2010). U-Pb dating of both the gneisses and metavolcanic rocks yielded ages between 1000 and 920 Ma (Brito Neves *et al.* 1995, Van Schmus *et al.* 1995, Kozuch 2003, Medeiros 2004, Santos *et al.* 2019), which according to Santos *et al.* (2010) defines the time span for an orogenic event. Geochemistry of both supracrustal and intrusive rocks is similar to those of mature continental arc rocks, but subordinate intra-plate characteristics are found, especially in the Riacho Gravata subdomain, a contiguous stripe of supracrustal rocks with bimodal volcanics (but mostly felsic) and immature terrigenous metasedimentary rocks at the NW portion of the AP domain that has been interpreted as an adjacent back-arc region (Kozuch 2003, Santos *et al.* 2010) or as the record of the initial breakup of the Borborema Province basement (Guimarães *et al.* 2012).

In the southern zone of the Borborema Province 1000–920 Ma old rocks are also found, at the internal zone of the Riacho do Pontal belt (Caxito *et al.* 2014b, 2016, 2020). There, augen-gneisses of the Afeição Suite, dated at 1000–960 Ma and with identical chemical and isotopic characteristics, are interpreted as a continuation of the Cariris Velhos belt, displaced from their transversal zone counterparts by late Neoproterozoic–Cambrian movement of the Pernambuco shear zone (Caxito *et al.* 2014b). Sparse occurrences in the southern zone have also been reported in the PEAL domain (Silva Filho *et al.* 2002, Cruz *et al.* 2014b) and in the Sergipano belt (Carvalho 2005, Oliveira *et al.* 2010). All of these occurrences show Sm-Nd data with slightly negative to positive  $\epsilon_{\text{Nd}}(t)$  and  $T_{\text{DM}}$  mostly concentrated at 1.2–1.5 Ga, indicating an interaction of the old continental crust with an important input of juvenile mantle melts. This led most authors to interpret the Cariris Velhos belt as the representative of a continental margin magmatic

arc with possible back-arc associations (Medeiros 2004, Santos *et al.* 2010, Caxito *et al.* 2014b, 2020). Alternative interpretations were put forward, making the case that these granites and supracrustals might represent continental rift remnants (Neves 2003, Guimarães *et al.* 2012). Arguably, the lack up to date of sound evidence for a well-defined Cariris Velhos-related metamorphic event hampers the geodynamic interpretation of this belt (see discussion of this and other contentious points in the interpretation of the Cariris Velhos belt in Caxito *et al.* 2020).

Recent studies on the nearby mafic-ultramafic Floresta Complex (also known as Serrote das Pedras Pretas Complex) point to a proto to marginal arc-back-arc basin system evolved between 1025 and 975 Ma, which was metamorphosed into eclogite facies during the Brasiliano Orogeny, as indicated by ca. 625 Ma zircon rim dates from probable retro-eclogites (Lages and Dantas 2016). The nearby Bodocó mafic-ultramafic Complex and related eclogites (Beurlen *et al.* 1992) bear possible correlatives. These are all novel data that need additional refining and detailed studies, but open up various avenues of possible future research directions. For example, the occurrence of back-arc-related rocks with similar age range than the augen-gneisses and metavolcanic rocks might lend additional support for the suggestion of an arc system for the Cariris Velhos belt in the area, and the occurrence of eclogitic metamorphism at 625 Ma might reinforce the interpretation of continental collision of distinct lithospheric blocks during the Brasiliano Orogeny in the transversal zone.

The other domains of the transversal zone are the PAB belt, which will be discussed in the next item, and the westernmost São Pedro or São José do Caiano domain. This domain is the least studied one of the transversal zone. Recently, Basto *et al.* (2019) described the Ipueirinha Group within this domain, forming a sigmoidal belt of metagraywackes and quartzites with intercalations of metaultramafic rocks and metarhyolites, and interpreted as deposited in an arc-related basin during the Ediacaran. Detrital zircon data indicate deposition after ca. 636 Ma, and U-Pb dating of zircon from granite sills and monazite indicate metamorphism and strike-slip deformation at ca. 575 Ma. Here, we interpret the São Pedro or São José do Caiano Domain as part of NOBO-BENI (discussed in the previous item), following Basto *et al.*'s (2019) interpretation that the Ipueirinha Belt represents an arc-related basin associated to the Tamboril-Santa Quitéria Complex. This interpretation is reinforced by recent U-Pb data from Pitarello *et al.* (2019), who interpret part of the basement of the São Pedro domain as pertaining to the Granjeiro Complex (3.5–2.5 Ga), which also comprises the basement to the southernmost RGN domain.

Bounding the curvilinear belts of the transversal zone to the south is the PEAL domain, a complex crustal block composed of a Paleoproterozoic basement with intrusions of ca. 1.0 Ga Cariris Velhos and Late Ediacaran Brasiliano plutonic rocks (Silva Filho *et al.* 2002, 2014, 2016, Cruz *et al.* 2014b, Silva *et al.* 2015), also with local Neoproterozoic metasedimentary belts (youngest detrital zircon grains at ca. 650 Ma; Cruz *et al.* 2014a, Silva Filho *et al.* 2014, Neves *et al.* 2016). The occurrence of ca. 620–610 Ma high-K syn-collisional plutonic rocks related to the Brasiliano Orogeny is also recorded (Silva *et al.*

2015, Silva Filho *et al.* 2016). In plate tectonics models, the PEAL block is commonly interpreted as a microcontinent that acted as an upper plate during northwards subduction of the São Francisco–Congo plate in the early Ediacaran, giving rise to the Riacho do Pontal (Caxito *et al.* 2016) and Sergipano (Oliveira *et al.* 2010) mountain belts after collision with the lower plate (São Francisco–Congo Paleocontinent). This interpretation seems in agreement with recent contributions that interpret arc-related rocks emplaced within the PEAL domain (the Major Isidoro pluton dated at 642 Ma; Silva *et al.* 2015), probably due to northward subduction of the São Francisco paleoplate below the PEAL crust. Caxito *et al.* (2016) suggested that the PEAL domain continues northward to the AP, AM and RC domains of the transversal zone, constituting a microcontinent dubbed “Central-Southern Borborema Block”. This hypothetical microcontinent would probably have continued to the basement-dominated Adamawa-Yadé (AY) domain of Cameroon and is thus here renamed APAMCAPAY.

The APAMCAPAY lithospheric block would have been bounded to the north by the Neoproterozoic PAB belt in Brazil, and by the Neoproterozoic-dominated Western Cameroon and juvenile Mayo Kebbi domains in Cameroon. To the south, it would be bounded by the RP-RdP–Se-Yaoundé-Central African belts. In this model, the eastern portion of the Pernambuco shear zone would not represent a terrane boundary, but a late-stage structure crosscutting rocks of similar age and composition within APAMCAPAY, a proposition also put forward in other works (*e.g.*, Neves and Mariano 1999, Oliveira and Medeiros 2018). The interpretation that the Rio Capibaribe, Alto Moxotó and Alto Pajeú domains were part of the same lithospheric block from 2.0 Ga onward is supported by the occurrence, in all of the three domains, of ca. 1.7–1.5 Ga A-type intrusions related to the intraplate magmatic activity (Accioly 2001, Sá *et al.* 2002, Lages *et al.* 2019), which might represent early unsuccessful attempts of continental breakup of a contiguous continental tract in this area. In effect, the widespread occurrence of similar ca. 2.0–2.2 Ga orogenic rocks and 1.7–1.5 Ga continental rift systems (that failed to evolve to a drift stage) and anorogenic magmatism in the São Francisco Craton (Barbosa and Sabaté 2004, Guadagnin and Chemale Jr. 2015 and references therein) might suggest that APAMCAPAY was once part of a Greater São Francisco–Congo Paleocontinent from ca. 2.0 until the onset of widespread continental rifting at ca. 900 Ma (Salgado *et al.* 2016). This rifting event would finally evolve to a complete drift stage, causing hyperextension of the paleocontinental margins in the early Neoproterozoic (Figs. 8 and 9), leading to detachment and decratonization of Archean-Paleoproterozoic lithospheric stripes such as APAMCAPAY and similar blocks off the paleocontinental margins in the surrounding Tocantins and Mantiqueira provinces (see geological models of Figs. 7 to 11), and the birth of new oceanic realms such as the Transnordestino-Central African ocean (Caxito *et al.* 2014d).

Arguably, the most complicated correlation problem between the transversal zone and the African provinces is the virtual absence of early Tonian rocks that could be related to a similar event as the Cariris Velhos, in NW Africa. The key

for all of these correlations might be hiding in the basement of the Benue Trough (Fig. 4); geophysical information might help to reveal these issues in the near future.

### *Piancó-Alto Brígida/Western Cameroon: a possible PAB-WECA Seaway?*

The PAB belt is composed of a metavolcanosedimentary unit (Cachoeirinha Group; Medeiros and Jardim de Sá 2009) with a lower metaconglomerate unit (Serra dos Olhos D'água Formation) and younger detrital zircon grains at 880 Ma (Marulanda 2013), and an upper metagreywacke succession (Santana dos Garrotes Formation) with younger detrital zircon grains at ca. 650 Ma (Brito Neves and Campos Neto 2016) and felsic metavolcanic intercalations dated by U-Pb on zircon at ca. 630–610 Ma (Kozuch 2003, Medeiros 2004, Brito Neves and Campos Neto 2016, Caxito *et al.* 2019). Ediacaran pre-, syn-, and post-collisional granites are conspicuous and some of the most classic granite suites of the Borborema Province are described in this region (*e.g.*, Guimarães *et al.* 2004, Sial and Ferreira 2016, Brito Neves *et al.* 2016), such as the 650–620 Ma “Conceição-type” magmatic epidote-bearing calc-alkaline granitoids ( $\epsilon\text{Nd}(t) = -1$  to  $-4$ ,  $T_{\text{DM}} < 2.0$  Ga,  $\delta^{18}\text{O}$  (zircon) values from 7.1 to 10‰<sub>VSMOW</sub> interpreted as emplaced in a possible magmatic arc scenario) and the 590–540 Ma “Itaporanga-type” high-K calc-alkaline series ( $\epsilon\text{Nd}(t) = -8$  to  $-20$ ,  $T_{\text{DM}} = 1.5$  to 2.5 Ga;  $\delta^{18}\text{O}$  (zircon) from 6.4 to 7.9‰<sub>VSMOW</sub>; compatible with expressive remelting of continental crust). Evidence for Neoproterozoic subduction (Kozuch 2003, Medeiros 2004, Brito Neves *et al.* 2016, Caxito *et al.* 2019), continental collision in the form of retro-eclogites (Beurlen *et al.* 1992, Lages and Dantas 2016), and probable Neoproterozoic oceanic crust remnants (Lages *et al.* 2017) that support the development of a complete plate tectonics cycle, including the development of oceanic crust, subduction, and continental collision in the PAB area are gathering up, although still elusive (see discussion in Neves 2018).

Correlations of the PAB belt with the Seridó belt further north, displaced by dextral-sense shearing of the Patos shear zone, have been proposed (Brito Neves *et al.* 2000, Caxito *et al.* 2016). However, continental arc-related rocks, ophiolites, and retro-eclogitic remnants are not yet described in the Seridó area, and thus an intracontinental evolution for the Seridó belt as a metavolcanosedimentary belt developed upon the continental crust of NOBO-BENI (akin to the Nigerian Schist Belts) cannot be discarded.

The Western Cameroon domain that occurs NW of the Tcholliré-Banyo shear zone is characterized by Pan-African plutonic rocks, apparently with lesser contributions of Paleoproterozoic basement (Toteu *et al.* 2001, 2004, Van Schmus *et al.* 2008, Bouyo Houketchang *et al.* 2009, 2016). Further NE in the Western Cameroon domain, the Mayo Kebbi terrane of SW Chad seems to represent a juvenile arc accreted at ca. 740 Ma to the remobilized AY Paleoproterozoic microcontinent (Penaye *et al.* 2006) or to the borders of the Saharan metacraton, indicating different evolution in comparison to the AY domain, and the Rey Bouba belt represents a Neoproterozoic arc-related basin between the Mayo Kebbi and AY domains

(Bouyo Houketchang *et al.* 2015). Brasiliano/Pan-African syn-collisional plutonism, deformation, and metamorphism are ubiquitous in both areas, with calc-alkaline arc-related plutons at ca. 640 Ma and continental collision at 640–580 Ma (Ngako *et al.* 2008). U-Pb (TIMS-ID and SIMS) and Sm-Nd dating of metamorphic zircon rims and garnet-whole rock pairs give ages ranging between 594 and 604 Ma, interpreted as the time of HP granulite-facies metamorphism in north-central Cameroon (Bouyo Houketchang *et al.* 2009, 2013).

The Neoproterozoic evolution of the PAB belt and of the Western Cameroon domain contrasts both with the eastern transversal zone domains and with the AY domain to the south, and with the East Nigeria Domain and northern Borborema domains to the north, where Archean and Paleoproterozoic inheritance is more obvious (*e.g.*, Toteu *et al.* 2001, Ferré *et al.* 2002, Van Schmus *et al.* 2011, Souza *et al.* 2016, Ganwa *et al.* 2016, Tchakounté *et al.* 2017). Thus, a connection between the PAB belt and the Western Cameroon domain is proposed here, which would represent an oceanic domain separating the NOBO-BENI and APACAMPAY blocks during the Neoproterozoic. Subduction, accretion, and collision processes probably took place in this domain and caused the collision of NOBO-BENI and APACAMPAY toward the end of the Neoproterozoic.

### *Southern Borborema-Yaoundé-CAR: a Transnordestino–Central African ocean?*

The southern portion of the Borborema Province is composed of a curvilinear E-W trending arrange of fold-thrust belts that thrust the northern São Francisco-Congo craton margin and extends from the RP–RdP–Se belts in Brazil to the Yaoundé–Central African belt in the African side. Recent discoveries of Neoproterozoic oceanic crust rocks (ophiolites) and the characterization of all components necessary for a complete Wilson Cycle (rift-drift-subduction-accretion-collision related rocks) in the RdP (Caxito *et al.* 2014b, 2016) and Se (Oliveira *et al.* 2010) belts suggest the opening and closure of Proterozoic oceans between the Borborema blocks to the north and the São Francisco–Congo craton to the south. In fact, the São Francisco–Congo craton is surrounded by Neoproterozoic oceanic fragments and juvenile terranes and, thus, probably drifted as a separate continent during most of the Neoproterozoic (Caxito *et al.* 2014d). The exception is the RP fold belt, which represents an essentially aulacogenic structure with the infilling of a rift basin during the Neoproterozoic (Caxito *et al.* 2012b, 2014a, 2017) which was later inverted during the Brasiliano Orogeny.

Caxito *et al.* (2016) interpreted the development of a complete Wilson Cycle during the Neoproterozoic in the RdP belt area based on lithostratigraphic, lithochemical, geochronological, and isotopic data. A five-stage model is proposed:

- rift phase, with the development of a triple junction rift system at ca. 900–820 Ma, leading to intense mafic–ultramafic magmatism of the Brejo Seco Ni–Cu–PGE mineralized layered intrusion (ca. 900 Ma; Salgado *et al.* 2016), probably related to a plume head. This was followed by the development of a continental rift system testified by the Paulistana Complex metavolcanosedimentary succession,

- with metagabbros and metabasalts dated at ca. 882 Ma (Caxito *et al.* 2016) and younger detrital zircon grains at ca. 900 Ma (Brito Neves *et al.* 2015, Santos F.H. *et al.* 2017);
- drift phase: evolution of the rift system to a broad passive margin in the northern São Francisco craton edge, represented by the Barra Bonita Formation platformal sediments. This drift phase was caused by continued continental stretching and culminated in the development of new oceanic crust, represented by the Monte Orebe ophiolite around 820 ago (Sm-Nd whole-rock isochron), composed of MORB-like metabasalts with  $\epsilon\text{Nd}(t)$  at ca. +4.5 (Caxito *et al.* 2014b);
  - convergence phase: started at ca. 630–620 Ma, with emplacement of the calc-alkaline Betânia granite, probably related to a continental magmatic arc setting (Perpétuo 2017), culminating in an inversion of the basins, obduction of oceanic crust slices, and sedimentation of the Mandacaru Formation syn-orogenic greywackes, with younger detrital zircon U-Pb populations at ca. 650 Ma (Caxito *et al.* 2016). Part of the Santa Filomena Complex to the north, with similar late Cryogenian detrital zircon grains, might be coeval (Brito Neves *et al.* 2015, Santos F.H. *et al.* 2017);
  - collisional phase: continental collision between the São Francisco craton (lower plate) and the PEAL block (upper plate) around 620–590 Ma, with stacking of the Casa Nova nappes upon the lower plate, crustal thickening, deformation, metamorphism, melt generation, and intrusion of the syn-collisional Rajada Suite two-mica granites (ca. 610 Ma; Brito Neves *et al.* 2015, Caxito *et al.* 2016);
  - lateral escape phase: this stage occurred around 590–530 Ma, generating the western branch of the E-W trending Pernambuco shear zone, which truncates the northern part of the orogen. This phase was accompanied by extensive alkaline magmatism of the Serra da Aldeia Suite, dated at 586–576 Ma (Caxito *et al.* 2016, Perpétuo 2017).

Oliveira *et al.* (2010) present a synthesis of the geologic evolution of the Sergipano belt, and Oliveira *et al.* (2006) present a correlation of the Sergipano and Yaoundé (Oubanguides) belts. According to these authors, the evolution of the Se belt starts with the development of a ca. 980–960 Ma continental arc characterized by tonalitic gneisses of the Poço Redondo domain, developed on the southern margin of the PEAL domain. Lithospheric extension of this block was followed by intrusion of A-type granites and development of the Canindé rift sequence, in turn, followed by passive margin development in both the southern PEAL margin and in the northern São Francisco craton margin. Rifting continued to ca. 640 Ma, with emplacement of a bimodal association with A-type granites dated at ca. 715 Ma and a layered gabbro complex at 700 Ma, magma-mingled gabbro-quartz monzodiorite at 688 Ma and rapakivi granites at 684 and 641 Ma. Also in the Canindé domain, deformed pillow basalts and marble lenses are interpreted by Oliveira *et al.* (2006) as probable oceanic floor relicts. Arc-type granites intruded the Canindé domain at ca. 630 Ma, and convergence of the PEAL block and the São Francisco–Congo craton caused deformation and

metamorphism of passive margin sedimentary successions and syn-collisional granite emplacement in the Macururé, Canindé, and Poço Redondo-Marancó domains between 620 and 570 Ma. Then, exhumation and erosion of the PEAL block along with the Canindé, Poço Redondo-Marancó, and Macururé domains to the north provided debris for infilling of foreland sedimentary basins of the Estância and Vaza Barris domains to the south.

The metasedimentary sequences of the Se belt preserve important remnants of the widespread Neoproterozoic glaciations. Sial *et al.* (2010) describe two distinct cap carbonate successions overlying glaciogenic diamictites, represented by the Jacoca Formation resting on top of the Ribeirópolis Formation (and correlative Acauã Formation sitting on top of the Juetê Formation further west) and the Olhos D'água Formation resting on top of the Palestina Formation diamictites. The  $\delta^{13}\text{C}$  values of these carbonate units are typical of post-glacial cap carbonates, around -5‰ at the base and rising upwards to ca. 10‰ for the Olhos D'água Formation. Strontium isotope ratios within the range of late Neoproterozoic seawater (0.7060–0.7090) provide additional support and, along with detrital zircon age data, suggest that the Jacoca Formation (and correlative Acauã Formation) are probably mid-Cryogenian (Sturtian), while the Palestina and Olhos D'água formations represent the diamictite–cap carbonate pair of the late-Cryogenian (Marinoan) glaciation (Caxito *et al.* 2012a). The Canabrinha Formation diamictites of the Rio Preto belt (Egydio Silva *et al.* 1989) are interpreted as mass-flow deposits associated with a faulted margin of a rift basin (Caxito *et al.* 2012b, 2014a, 2017), but might represent a reworking of glacial debris and thus probably correlate with the Palestina diamictites of the Se belt (Caxito *et al.* 2012a).

As discussed by Oliveira *et al.* (2006), the Yaoundé belt of Cameroon mirrors the lithotectonic distribution of units in the Se belt, comprising schists, quartzites, gneisses, and migmatites thrust upon the São Francisco–Congo craton northernmost margin, with a decrease of metamorphic grade toward the craton. Continental collision in the Yaoundé belt is marked by 620–610 Ma granulite facies metamorphism and deformation (Toteu *et al.* 2004, Li *et al.* 2017). Most of the metasedimentary rocks show the ubiquitous presence of ca. 625 Ma detrital zircon grains, indicating syn-orogenic deposition (Toteu *et al.* 2006), in a similar manner to the Estância and Vaza Barris domains of the Se belt (Oliveira *et al.* 2015b) and to the Mandacaru Formation metagreywackes of the RdP belt (Caxito *et al.* 2016). Increasing evidence also suggests that the infrastructure of both the RP, RdP, Se and Yaoundé belts involve the reworking of various amounts of Paleoproterozoic crust with local Archean inliers, probably representing the reworked northern margin of the São Francisco–Congo craton (Penaye *et al.* 2004, Lerouge *et al.* 2006, Caxito *et al.* 2015, Lima 2018, Loose and Schenk 2018, Bouyo Houketchang *et al.* 2019).

Continuation of the Yaoundé belt through the Central African Fold Belt (CAFB) in the Central African Republic (*e.g.*, Pin and Poidevin 1987) and in south-central Chad (*e.g.*, Shellnutt *et al.* 2017) is confirmed by preliminary U-Pb data that show Ediacaran ages for plutonism and deformation. Thus,

this orogenic belt, as part of the Central African Orogen, probably surrounds the northern São Francisco–Congo craton margin and the southern Sahara metacraton margin, joining the East African Orogen (Stern 1994) on the other side of Africa.

According to the many similarities discussed here, the RP-RdP–Se–Yaoundé–Central African orogenic system seems to represent a complete plate tectonics cycle during the Neoproterozoic, including remnants of oceanic crust that separated the São Francisco–Congo paleocontinent to the south and the APAMCAPAY and Saharan paleocontinents to the north, in all of the portions of the system (Nkoumbou *et al.* 2006, Oliveira *et al.* 2010, Caxito *et al.* 2014d). The RP belt at the western end of this system seems to represent a simple inverted rift basin (aulacogenic structure) that would provide the link between the RdP (Monte Orebe)–Se–Yaoundé–Central African ocean, here called Transnordestino–Central African Ocean, to the east, and the much larger Goiás–Pharusian Ocean to the west, similar to the link between the Mediterranean and Atlantic oceans today. The RP basin would later be inverted in a doubly-vergent fan-like structure during the Brasiliano Orogeny, similar to the structure of the present-day Pyrenees (Caxito *et al.* 2014c).

## DISCUSSION AND CONCLUDING REMARKS: TOWARD AN INTEGRATED MODEL OF GEOLOGICAL EVOLUTION FOR NE BRAZIL–NW AFRICA

Based on the integrated field, petrographic, stratigraphic, petrological, structural, geophysical, geochemical, isotopic, and geochronological wealth of data available in the last decades for the Borborema Province, the Trans-Saharan Orogen (Tuareg and Benino–Nigerian shields), and the Central African Orogen, a few general lines of comparison can be drawn, illustrated in the preliminary models of evolution for NE Brazil–NW Africa during the Neoproterozoic (Figs. 7, 8, 9, 10 and 11). These models should be taken as a background upon which new data will surely be added and used to modify and refine the interpretations and working hypothesis presented here. Also, it should be kept in mind that the diachronism of events will be the rule rather than the exception in such long-ranging, transcontinental correlation schemes, *i.e.*, while convergent events are taking place at certain areas, extensional, transcurrent or collisional events might be taking place in other ones. Even adjacent areas might show some slight diachronism due to the geometry of the interacting paleocontinental borders, with reentrants and promontories causing sintaxial and antitaxial structures during the development of the resulting mountain chains. Finally, most of the times, on a curved surface planet, each of these events might occur in a zipper-like fashion and not as straight thousands-of-km perfectly synchronized fronts.

Correlation of the fold belts that margin the São Luís–West African and the São Francisco–Congo cratons in both the Brazilian and African sides (*i.e.*, the belts that frame the Borborema–NW Africa provinces on its western and southern sides) seems progressively better established (*e.g.*, Brito Neves *et al.* 2002, Oliveira *et al.* 2006, Santos *et al.* 2008b, Ganade de Araújo *et al.* 2016). The MC domain of NE Brazil represents a

continuation of the passive margin to syn-orogenic deposits of the Dahomeyides and Gourma belts that extend from Togo–Benin to the western Tuareg Shield provinces; these deposits extend further south to the Brasília belt of central Brazil. In the same way, the RP-RdP–Se–Yaoundé–Central African belts connection can be established with corresponding passive margin and syn-orogenic deposits on both sides of the Atlantic.

Correlations within the interior of the supracited domains and away from the fold belts flanking the major cratonic landmasses are more complicated, and detailed field, isotopic, geochronological, and petrological data are necessary for further development of the current models. Basement of both the Borborema Province, the Benino–Nigerian Shield, East, Central, and West Tuareg Shield and the Adamawa–Yadé domain of Cameroon yielded similar Archean (3.5–2.7 Ga) and widespread Paleoproterozoic (2.3–1.9 Ga) ages with local rifting and anorogenic magmatism at 1.8–1.7 Ga that is also common in the São Francisco–Congo craton and in the Araçuaí and Brasília belts basement further south. Thus, it is possible that APAMCAPAY, and perhaps NOBO–BENI, were part of a Greater São Francisco–Congo paleocontinent (Fig. 7) from ca. 2.0 Ga until the widespread rifting in the early Neoproterozoic (Fig. 8) created new oceans and separated its constituents in individual blocks (Fig. 9). These individual blocks then drifted apart during the Neoproterozoic until subduction (Fig. 10) and continental collision (Fig. 11) joined them together once again in West Gondwana.

It is unclear whether all or part of the basement-dominated terrains of the Tuareg Shield could have evolved in a similar way, *i.e.*, through hyperextension and detachment of a former major paleocontinental landmass. This hypothesis is illustrated in Figures 7 and 8, but is certainly contentious at this point. If this is correct, then the Greater São Francisco–Congo paleocontinent would actually involve a much larger area, perhaps encompassing both the terrains which would later participate in amalgamation of the Saharan metacraton and those that became detached from the continental margins to develop into the West (IOGU/IGU, Tirek, Kidal, Tassendjanet and Ahnet) and the Central Tuareg (LATEA and Assodé–Issalane/Tazat forming the Orosirian Stripe) microcontinents.

Occurrences of Neoproterozoic ophiolitic thrusts in southern LATEA suggest that, for at least part of the Proterozoic, the Tuareg Shield basement-dominated terrains were probably separated by an oceanic tract (the hypothetical Laouni seaway, which could have been part of the Goiás–Pharusian ocean) from NOBO–BENI southward. As the West and Central Tuareg basement-dominated blocks are separated one from another and from the West African and Saharan paleocontinents by juvenile Neoproterozoic terrains (Tilemsi, Silet, Serouenout and Aouzegueur), they probably constituted isolated continental fragments during most of the Neoproterozoic, after hyperextension and detachment of the Greater São Francisco–Congo–(Saharan?) paleocontinental border (Figs. 5, 6 and 7).

A major, Pacific-type oceanic domain (the Goiás–Pharusian or Brasilides ocean) separated the West African–São Luís Craton from the Archean–Paleoproterozoic blocks of northern Borborema/ Benino–Nigerian Shield (NOBO–BENI) and the basement-dominated domains of the West Tuareg Shield (IOGU/IGU, Tirek, Kidal, Tassendjanet and Ahnet) during the early Neoproterozoic. On the opposed Borborema

margin, the RP–RdP–Se–Yaoundé–Central African belt bordering the northern São Francisco–Congo craton also presents components of complete plate tectonics cycles, including ophiolitic remnants of a former Neoproterozoic ocean (the Transnordestino–Central African ocean) that separated the São Francisco–Congo paleocontinent from the Archean–Paleoproterozoic blocks in the Central-southern Borborema Province (AP, AM, RC and PEAL) and AY (APAMCAPAY).

Thus, the West Gondwana Orogen seems to have evolved through the typical “extroversion” mechanism proposed by Murphy and Nance (2003), *i.e.*, through the closure of the Pacific-type Goiás–Pharusian ocean with development of extensive magmatic arc tracts during the Neoproterozoic, and finally a collision with the Rodinia-derived Amazonian craton. On the other hand, the Central African Orogen and its continuation in the orogenic belts that border the northern São Francisco–Congo craton margin seem to have developed through typical “introversion” processes, *i.e.*, the opening and closing of internal oceans through the classical Wilson Cycle of plate tectonics. This could reveal a pattern where transversal oceanic realms such as the Transnordestino–Central African ocean, PAB–WECA and Laouni seaways would represent internal oceans developed through introversion breakup processes of the Greater São Francisco–Congo paleocontinent and reagglutination of the detached fragments in a similar position due to closure of the major, external longitudinal Goiás–Pharusian ocean, giving rise to the West Gondwana Orogen to the west. West Gondwana seems, thus, to have been formed through a combination of extroversion and introversion processes acting through the major longitudinal Goiás–Pharusian realm and restricted transversal internal oceans generated due to the breakup and hyperextension of a Greater São Francisco–Congo-(Saharan?) paleocontinent margins.

An open issue and complicated correlation problem to solve is the definition of the geodynamic meaning of the 1000–920 Ma Cariris Velhos belt of metavolcanosedimentary and plutonic rocks that crosscuts the central portion of the Borborema Province in NE Brazil, whose correlatives are yet poorly constrained or undiscovered in NW Africa (maybe hiding below the Benue trough?). This belt is interpreted by some authors as representing a continental magmatic arc developed during the early Tonian, which would then lead to an interpretation that the NOBO-BENI and APACAMPAY portions of the Borborema Province were not joined until this point — or alternatively, that they rifted apart from each other before the onset of subduction. Other authors interpret it as a continental rift system, which would allow for NOBO-BENI and APAMCAPAY to be joined before the onset of Tonian rifting in the Borborema Province.

NOBO-BENI is separated from APAMCAPAY by the PAB metavolcanosedimentary belt and by the

Neoproterozoic-dominated Western Cameroon and Mayo Kebbi domains. Evidence for Neoproterozoic subduction (Kozuch 2003, Medeiros 2004, Bouyo Houketchang *et al.* 2015, Brito Neves *et al.* 2016, Caxito *et al.* 2019), continental collision in the form of retro-eclogites (Beurlen *et al.* 1992, Lages and Dantas 2016), and probable Neoproterozoic oceanic crust remnants (Lages *et al.* 2017) that support the development of a complete plate tectonics cycle, including the development of oceanic crust, subduction, and continental collision in the PAB area was presented in the past years, but is still preliminary and controversial (see discussion in Neves 2018).

The proposed connections of NOBO-BENI (and possibly the basement-dominated blocks of the Tuareg Shield) and of APAMCAPAY as two single Archean–Paleoproterozoic decratonized blocks generated from rifting and hyperextension of the margins of a major ca. 2.0 Ga paleocontinent (Greater São Francisco–Congo), drifted apart from each other during the Neoproterozoic, and then accreted, involved in continental collision and strongly reworked (*i.e.*, metacratonized) through introversion-style tectonics during the Pan-African/Brasiliano Orogeny remains to be tested; at this point, though, an alternative interpretation that each of these domains consisted of multiple fragmented blocks during the Proterozoic that drifted and were accreted to one another akin to exotic terranes is also possible. Further studies might help to recognize key rock units such as ophiolites, HP/UHP rocks and magmatic arcs within the Borborema Province, the Trans-Saharan, and the Central African orogens, and thus further refine and modify the proposed models.

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F.A.C. idealized and concretized the concept of the paper, the models and systematic maps and figures. L.S. and C.G. thoroughly discussed the models and Borborema Province’s geology, provided inputs and modifications to the text, concept, models, and figures. In addition, C.G. provided valuable input about the geology of the Benino-Nigerian Shield and Dahomeyides area. A.B. and E.F. provided valuable input about the geology of the Tuareg Shield, figures, and updated bibliography in the area. M.H.B. provided valuable input about the geology of Cameroon and adjacent areas, figures, and updated bibliography. The entire manuscript was revised, commented and corrected by all of the co-authors. Competing interests: The authors declare no competing interests.

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