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# Extruding the Borborema Province (NE-Brazil): a two-stage Neoproterozoic collision process

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## ABSTRACT

**We propose that the development of the Borborema Province from 620 to 570 Ma resulted from two discrete collisional events. Collision I, along the West Gondwana Orogen on the west side of the Province, took place at *c.* 620–610 Ma as the result of collision between the Parnaíba Block, as the forefront of the much larger Amazonian-West Africa Craton, and the old basement of the Borborema Province. The suture zone related to this collision was reactivated by a dextral transform zone (the Transbrasiliano Lineament), allowing the Borborema Province to approach and collide against the São Francisco Craton in the south at *c.* 590–580 Ma marking collision II along the Sergipano Orogen. The combined stresses related to eastward push from collision I and northward push from the cratonic indentation into a thickened lithosphere gave rise to an extensive network of strike-slip shear zones across the Province, forcing its northeastward extrusion.**

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## Introduction

Lateral escape of continental blocks occurs in many active collisional areas (e.g., Tapponier *et al.*, 1982; Sengör *et al.*, 1985). Extrusion tectonics has been suggested for the Borborema Province, in north-east Brazil (e.g., Brito Neves *et al.*, 2000; Alkmim *et al.*, 2001; Bueno *et al.*, 2009), but the relation to its large-scale tectonic evolution remains unclear. Here, we present the hypothesis that the evolution of the Province during the Neoproterozoic (620–570 Ma) results from interference between two collisions.

The Borborema Province is bounded to the west by the Parnaíba Block, which is inferred from geophysics and considered here as the forefront of the much larger Amazonian-West African Craton (Fig. 1). This boundary is adjacent to a set of dextral high-T shear zones collectively known as the Transbrasiliano Lineament (equivalent to the Kandi Lineament in Africa). To the south the Province is bounded by the São Francisco Craton. It is composed of large areas of Archean/Paleoproterozoic gneissic/migmatitic rocks, and restricted Mesoproterozoic/Early Neoproterozoic rocks of the Cariris Velhos Belt, which make up the basement of metamorphosed supracrustal rocks; there are also Neoproterozoic to Cambrian intrusions, and its well-known network of transcurrent shear zones (Caby, 1989; Vauchez *et al.*, 1995; Brito Neves *et al.*, 2000; Weinberg *et al.*, 2004; Neves *et al.*, 2012; Archanjo *et al.*, 2013). In our view, by the end of the Neoproterozoic, the Province constituted a coherent block of stable continental crust of pre-Neoproterozoic age, with small intracontinental basins in its central portion (Neves, 2003), which was highly remobilized during and after the collisional events described here.

In the Borborema Province, a number of crustal-scale shear zones branch out of the major Transbrasiliano shear system (Fig. 2). Continuity between high-strain zones, similar *P–T* conditions of deformation and kinematic coherence suggest that this network represents a single system (Vauchez *et al.*, 1995). The E–W trending Patos and Pernambuco dextral shear zones divide the province into Northern, Central and Southern sub-provinces (Brito Neves *et al.*, 2000; Neves, 2003). Dextral strike-slip shear zones trending NE–SW characterize the Northern sub-province. The Central sub-province is characterized by a network of conjugate shear zones, comprising a set of E–W trending dextral shear zones and a sinistral set trending NE–SW (Neves *et al.*, 2012). The Southern sub-province is bounded by the São Francisco Craton to the south and is characterized by south-verging thrusting with a small dextral component (Oliveira *et al.*, 2010). Geochronological (U-Pb) and thermochronological (Ar-Ar) data (Table 1 and Fig. 2) indicate that deformation along these shear zones peaked with associated magmatism from 590 to 560 Ma and extended into lower *T* conditions from 550 to 500 Ma in the Central sub-province (e.g., Monié *et al.*, 1997; Corsini *et al.*, 1998; Guimarães *et al.*, 2004; Neves *et al.*, 2008, 2012; Hollanda *et al.*, 2010; Archanjo *et al.*, 2013).

Regional deformation and metamorphism were synchronous throughout the Northern and Central sub-provinces, starting before *c.* 630 Ma, but are younger in the Southern sub-province, starting at *c.* 610–570 Ma (Arthaud *et al.*, 2008; Amaral *et al.*, 2010; Oliveira *et al.*, 2010; Neves *et al.*, 2012). High-*P*/high-*T* regional metamorphism prevails in the northern part, where eclogites have been found between the Transbrasiliano Lineament and the Santa Quitéria continental arc (Santos *et al.*, 2009). Low-*P*/high-*T* metamorphism characterizes the central part, dominated by migmatites and gneisses (Neves *et al.*, 2012), and lower *P*/*T* conditions (amphibolite to greenschist facies) are dominant in

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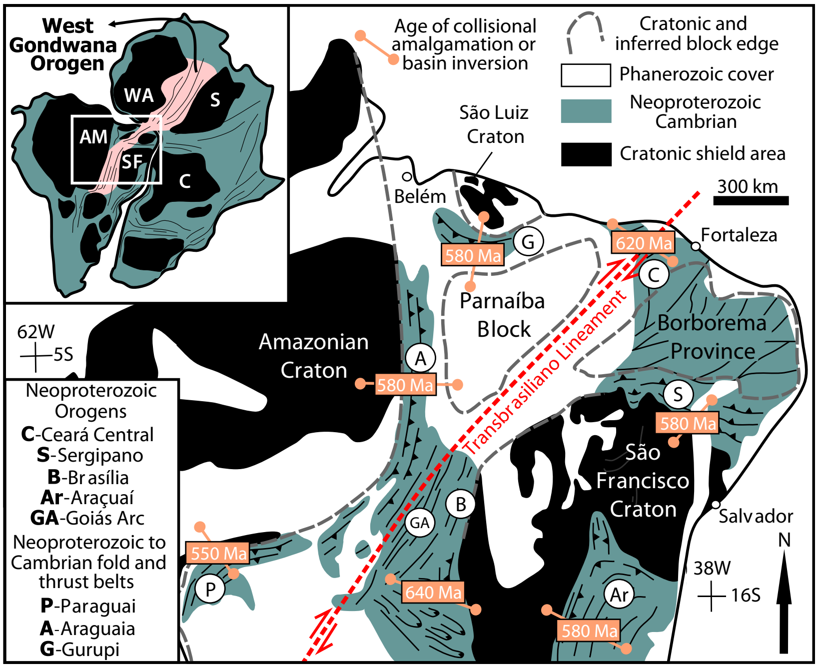


**Fig. 1** Positions of cratons, blocks, Brasiliano Neoproterozoic orogens and Neoproterozoic to Cambrian fold and thrust belts in Brazil (modified from Alkmim *et al.*, 2001). Cratons in the inset: AM, Amazonian; WA, West Africa; SF, São Francisco; C, Congo; S, Saharan 'metacraton'.

the Southern sub-province (Oliveira *et al.*, 2010). In this work, we use existing data on the temporal and spatial tectonothermal and magmatic evolution of the Borborema Province to propose a new integrated tectonic model for its evolution between 620 and 550 Ma resulting from two collisional events.

## The West Gondwana Orogen: the 620–600 Ma collision I

The Ceará Central Domain of the Northern sub-province is part of a large collisional belt (referred to here as the West Gondwana Orogen) that extends from Hoggar in Africa to Central Brazil (e.g., Caby, 1989; Trompette, 1994; Cordani *et al.*, 2013a). Due to continued post-collisional convergence and escape, this collisional belt was subsequently reactivated by dextral shear zones (Caby, 1989; Castaing *et al.*, 1994). In the Ceará Central Domain, relics of retrogressed eclogitic rocks (800 °C; 17 kbar) have been dated at *c.* 615 Ma (Amaral, 2010), although older ages of *c.* 650 Ma from related calcsilicate rocks have also been putatively attributed to high-P conditions. These rocks are roughly aligned with other HP and UHP rocks in Africa also dated at *c.* 620–610 Ma (Bernard-Griffiths *et al.*, 1991; Affaton *et al.*, 2000; Jahn *et al.*, 2001) defining a large Himalayan-scale collisional orogen.

Along this orogen, and pre-dating collision, there are older, 950–630 Ma magmatic and sedimentary assemblages, interpreted as remnants of intraoceanic or continental arcs (e.g., Pimentel and Fuck, 1992; Caby, 2003; Duclaux *et al.*, 2006; Berger *et al.*, 2011; Ganade de Araujo *et al.*, 2012a,b), related to subduction of the Pharusian-Goiás Ocean, consumed before collision (Kröner and Cordani, 2003; Cordani *et al.*, 2013b). This view of a large Pharusian-Goiás Ocean challenges the previously proposed Cambrian Clymene Ocean, where a younger suture is inferred along the Paraguay-Araguaia fold and thrust belts (Trindade *et al.*, 2006; Tohver *et al.*, 2012; Cordani *et al.*, 2013b).

The Tamboril-Santa Quitéria Complex in the Ceará Central Domain is a large igneous unit representing arc granitoids (Fetter *et al.*, 2003) emplaced slightly before high-*P* metamorphism at *c.* 650–630 Ma. These arc rocks, together with supracrustal rocks, were reworked and partially melted soon after the inferred collision at *c.* 620–600 Ma (Arthaud, 2007; Ganade de Araujo *et al.*, 2012a).

Throughout the Northern and Central sub-provinces, a gently dipping foliation associated with thrusting developed at the time of collision I (e.g. Caby and Arthaud, 1986;

**Fig. 2** Temporal and spatial distribution of granitoid rocks in the Borborema Province. The figure depicts a systematic younging of arc-related pre-collisional magmatism from north to south across the Province, as well as in the timing of metamorphism. Arc magmatism ends at *c.* 630 Ma in the NW-section of the province, but starts at *c.* 630 Ma in the south (Fetter *et al.*, 2003; Oliveira *et al.*, 2010). Whilst the most voluminous magmatism is centred around 580 Ma across the entire Province, the timing of collisional magmatism in each region varies: 620 Ma in the NW section of the Province, along the trend of the Transbrasiliano Lineament and 590–570 Ma in the south, along the Sergipano Orogen, contemporaneous with peak magmatism in the Province. Ar-Ar cooling ages show the same systematic decreasing age pattern from the site of collision I in the Ceará Central Domain to the site of collision II in the Sergipano Belt, but suggest that final cooling occurred only at *c.* 500 Ma, which is interpreted to indicate the end of collisional deformation. Voluminous magmatism during development of the shear zones at *c.* 590–560 Ma has dominant lithospheric mantle affinities (Neves *et al.*, 2000; Guimarães *et al.*, 2004) possibly related to delamination of the orogenic crustal root after thickening promoted by collision I (Ganade de Araujo, 2011). Ar-Ar ages also indicate slow cooling with continuous heat supply until the Cambrian (Monié *et al.*, 1997; Corsini *et al.*, 1998; Hollanda *et al.*, 2010). References for ages are listed in Table 1.

 

Neves *et al.*, 2012). In the Central sub-province, where detailed studies have been carried out, this foliation is associated with peak metamorphic conditions of 640–750 °C and 6–8 kbar, at *c.* 620 Ma (Neves *et al.*, 2012).

We argue that collision of the Borborema Province against the Parnaíba block, representing part of the Amazonian-West-African Craton, is marked in the Ceará Central Domain by the end of arc-related magmatism at *c.* 630 Ma and high-*P* metamorphism at *c.* 620–615 Ma, and was

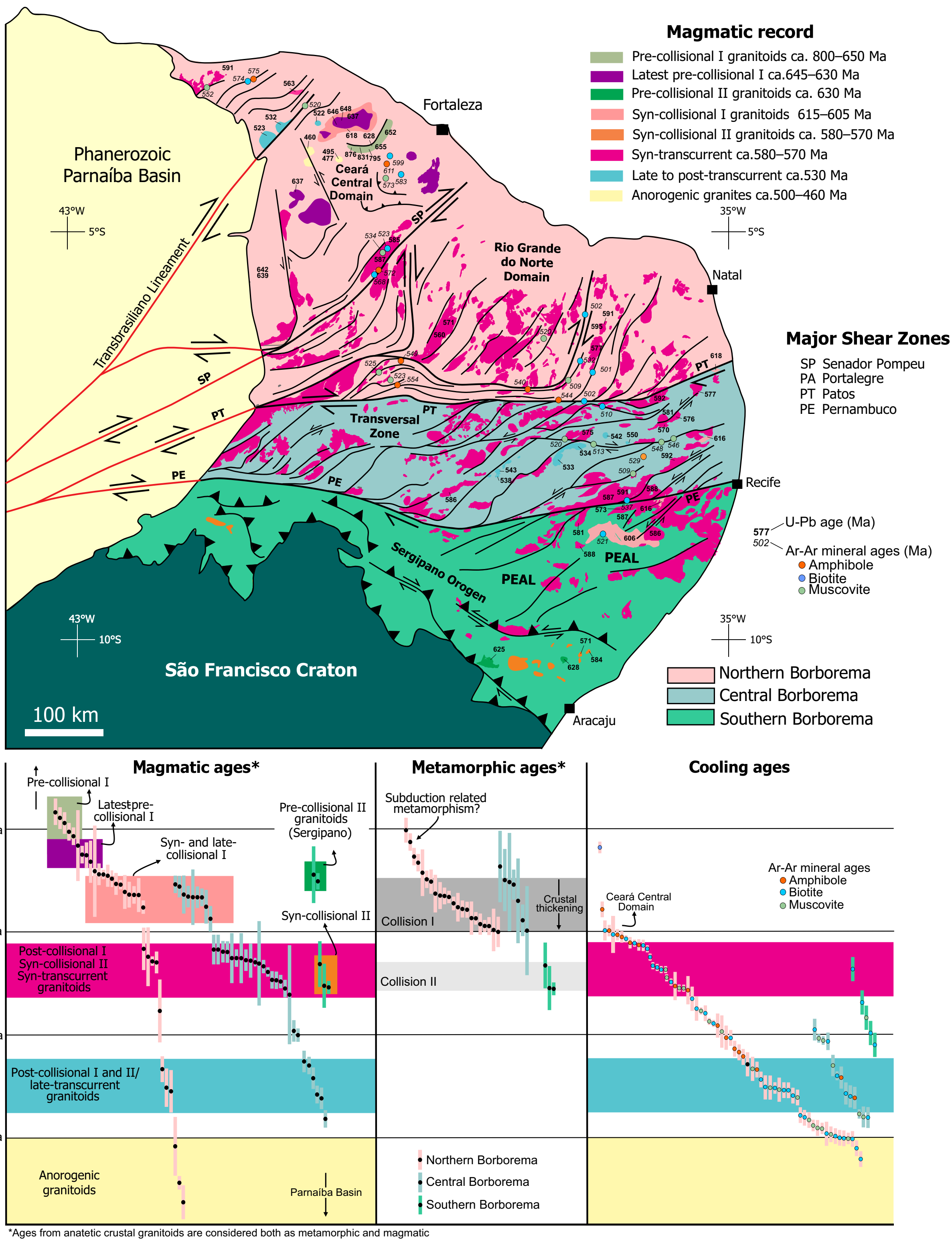

**Table 1** Summary of main U-Pb and Ar-Ar ages available for the Borborema Province

| | | Mineral | Technique | Reference |
|---|---|---|---|---|
| Northern Borborema Province | | | | |
| *Magmatic ages* | | | | |
| 876 ± 6 | Lagoa Caíçara Complex granodiorite | Zircon | SHRIMP | Ganade de Araujo *et al.* (2012a) |
| 831 ± 7 | Lagoa Caíçara Complex tonalite | Zircon | SHRIMP | Ganade de Araujo *et al.* (2012a) |
| 655 ± 5 | Tamboril Santa Quitéria Complex granodiorite | Zircon | SHRIMP | [Carlos Eduardo Ganade de Araujo (CEGA) unpublished] |
| 652 ± 5 | Tamboril Santa Quitéria Complex granodiorite | Zircon | SHRIMP | [Carlos Eduardo Ganade de Araujo (CEGA) unpublished] |
| 648 ± 4 | Tamboril Santa Quitéria Complex diorite | Zircon | SHRIMP | [Carlos Eduardo Ganade de Araujo (CEGA) unpublished] |
| 646 ± 5 | Tamboril Santa Quitéria Complex diorite | Zircon | SHRIMP | [Carlos Eduardo Ganade de Araujo (CEGA) unpublished] |
| 642 ± 15 | Novo Oriente granites | Zircon | Pb evaporation | Ganade de Araujo *et al.* (2012c) |
| 639 ± 3 | Novo Oriente granites | Zircon | Pb evaporation | Ganade de Araujo *et al.* (2012c) |
| 638 ± 3 | Novo Oriente granites | Zircon | LA-ICP-MS | Ganade de Araujo *et al.* (2010) |
| 637 ± 7 | Tamboril-Santa Quitéria Complex diorite | Zircon | ID-TIMS | Fetter (1999) |
| 637 ± 4 | Tamboril Santa Quitéria Complex monzogranite | Zircon | SHRIMP | [Carlos Eduardo Ganade de Araujo (CEGA) unpublished] |
| 629 ± 22* | Lagoa Caíçara Complex diatexite | Zircon | ID-TIMS | Castro (2004) |
| 628 ± 4 | Lagoa Caíçara Complex two-mica orthogneiss | Zircon | SHRIMP | [Carlos Eduardo Ganade de Araujo (CEGA) unpublished] |
| 627 ± 4 | Lagoa Caíçara Complex two-mica orthogneiss | Zircon | SHRIMP | [Carlos Eduardo Ganade de Araujo (CEGA) unpublished] |
| 625 ± 4.6 | Tamboril Santa Quitéria Complex diatexite | Zircon | SHRIMP | [Carlos Eduardo Ganade de Araujo (CEGA) unpublished] |
| 623 ± 6 | Gnaissic granodiorite | Zircon | ID-TIMS | Castro (2004) |
| 619 ± 6* | Tamboril Santa Quitéria Complex diatexite | Zircon | ID-TIMS | Castro (2004) |
| 618 ± 5* | Tamboril Santa Quitéria Complex diatexite | Zircon | SHRIMP | Ganade de Araujo *et al.* (2012a) |
| 618 ± 5* | Tamboril Santa Quitéria Complex diatexite | Zircon | SHRIMP | Ganade de Araujo *et al.* (2012a) |
| 618 ± 3* | Tamboril Santa Quitéria Complex diatexite | Zircon | ID-TIMS | Castro (2004) |
| 611 ± 3* | Tamboril Santa Quitéria Complex diatexite | Zircon | ID-TIMS | Castro (2004) |
| 597 ± 6 | Tororó diorite | Zircon | SHRIMP | Archanjo *et al.* (2013) |
| 595 ± 3 | Tororó gabbro norite | Zircon | SHRIMP | Archanjo *et al.* (2013) |
| 591 ± 4 | Tororó granite | Zircon | SHRIMP | Archanjo *et al.* (2013) |
| 591 ± 10 | Chaval granite | Zircon | ID-TIMS | Fetter (1999) |
| 587 ± 5 | Quixeramobim monzonite | Zircon | ID-TIMS | Nogueira (2004) |
| 585 ± 5 | Quixeramobim monzonite | Zircon | ID-TIMS | Nogueira (2004) |
| 577 ± 5 | Acarí porphiritic granite | Zircon | SHRIMP | Archanjo *et al.* (2013) |
| 572 ± 4 | Acarí leucogranite | Zircon | SHRIMP | Archanjo *et al.* (2013) |
| 571 ± 3 | Pereiro granite | Zircon | ID-TIMS | Magini (2001) |
| 563 ± 17 | Tucunduba monzonite | Zircon | ID-TIMS | Fetter (1999) |
| 560 ± 60 | Padre cosme granite | Zircon | ID-TIMS | Magini (2001) |
| 532 ± 7 | Mucambo syenite | Zircon | ID-TIMS | Fetter (1999) |
| 523 ± 5 | Meruoca monzosyenite | Zircon | U-Pb SHRIMP | Archanjo *et al.* (2009) |
| 522 ± 5 | Barriga granite | Titanite | ID-TIMS | Fetter (1999) |
| 495 ± 14 | Taperuaba granite | Zircon | U-Pb SHRIMP | Castro *et al.* (2012) |
| 467 ± 7 | Taperuaba granite | Zircon | ID-TIMS | Castro *et al.* (2012) |
| 460 ± 15 | Pajé granite | Zircon | ID-TIMS | Teixeira (2005) |
| *Metamorphic ages* | | | | |
| 650 ± 3 | Calcsilicate rock | Zircon | LA-ICP-MS | Amaral *et al.* (2010) |
| 644 ± 3 | Aluminous paragneiss | Monazite | U-Pb EPMA | Castro (2004) |
| 614 ± 4 | Mafic retro-eclogite | Zircon | LA-ICP-MS | Amaral (2010) |
| 629 ± 10 | Aluminous paragneiss | Monazite | U-Pb EPMA | Castro (2004) |
| 626 ± 19 | Aluminous paragneiss | Monazite | U-Pb EPMA | Castro (2004) |
| 617 ± 1.7 | Aluminous paragneiss | Zircon | ID-TIMS | Castro (2004) |
| 614 ± 2 | Aluminous paragneiss | Zircon | ID-TIMS | Castro (2004) |
| 612 ± 5.5 | Aluminous paragneiss | Zircon | SHRIMP | Arthaud (2007) |
| 612 ± 3.4 | Mafic granulite | Zircon | LA-ICP-MS | Amaral *et al.* (2012) |
| 607 ± 6.7 | Leucossome | Zircon | ID-TIMS | Arthaud (2007) |
| 607 ± 1.6 | Leucossome | Zircon | ID-TIMS | Arthaud (2007) |
| 604 ± 3.8 | Aluminous paragneiss | Zircon | ID-TIMS | Castro (2004) |
| 603 ± 3 | Diatexite | Zircon | ID-TIMS | Castro (2004) |
| 603 ± 1.5 | Aluminous paragneiss | Zircon | ID-TIMS | Castro (2004) |
| 601 ± 9 | Aluminous paragneiss | Monazite | U-Pb EPMA | Castro (2004) |
| 589 ± 10 | Mafic granulite | Zircon | LA-ICP-MS | Amaral *et al.* (2012) |
| 586 ± 1.6 | Aluminous granitoid | Zircon | ID-TIMS | Fetter (1999) |
| Central Borborema Province | | | | |
| *Magmatic ages* | | | | |

**Table 1** (Continued).

| | | Mineral | Technique | Reference |
|---|---|---|---|---|
| 618 ± 5 | Curral de Cima tonalite | Zircon | SHRIMP | Ferreira *et al.* (2011) |
| 616 ± 5 | Timbaúba pluton | Zircon | SHRIMP | Guimarães *et al.* (2011) |
| 616 ± 4 | Caruarú orthogneiss | Zircon | LA-ICP-MS | Neves *et al.* (2012) |
| 606 ± 8 | Jupi two-mica gneiss | Zircon | LA-ICP-MS | Neves *et al.* (2008) |
| 592 ± 7 | Bom Jardim granite | Zircon | ID-TIMS | Guimarães *et al.* (2004) |
| 592 ± 5 | Esperança pluton | Zircon | ID-TIMS | Archanjo and Fetter (2004) |
| 591 ± 5 | Caruaru Arco Verde batolith | Zircon | Pb evaporation | Neves *et al.* (2004) |
| 591 ± 5 | Texeira pluton | Zircon | SHRIMP | Archanjo *et al.* (2008) |
| 588 ± 12 | Caruaru Arco Verde batolith | Zircon | ID-TIMS | Guimarães *et al.* (2004) |
| 587 ± 8 | Cachoeirinha pluton | Zircon | LA-ICP-MS | Neves *et al.* (2008) |
| 587 ± 5 | Caruaru Arco Verde batolith | Zircon | Pb evaporation | Neves *et al.* (2004) |
| 586 ± 21 | Pajeú Complex | Zircon | ID-TIMS | Van Schmus *et al.* (1995) |
| 586 ± 2 | Panelas pluton | Zircon | LA-ICP-MS | Neves *et al.* (2012) |
| 581 ± 3 | Alagoinhas pluton | Zircon | ID-TIMS | Mariano *et al.* (2009) |
| 581 ± 2 | Campina Grande Complex | Zircon | ID-TIMS | Guimarães *et al.* (2004) |
| 577 ± 4 | Lourenço monzodiorite | Zircon | SHRIMP | Ferreira *et al.* (2011) |
| 576 ± 3 | Serra Redonda pluton | Zircon | SHRIMP | Archanjo *et al.* (2008) |
| 575 ± 14 | Serra Branca Complex | Zircon | ID-TIMS | Guimarães *et al.* (2004) |
| 573 ± 4 | Cabanas pluton | Zircon | LA-ICP-MS | Neves *et al.* (2008) |
| 570 ± 24 | Queimadas pluton | Zircon | ID-TIMS | Guimarães *et al.* (2004) |
| 564 ± 5 | Mamanguape pluton | Zircon | LA-ICP-MS | Ferreira *et al.* (2011) |
| 548 ± 4 | Sucuru dike | Zircon | SHRIMP | Hollanda *et al.* (2010) |
| 543 ± 7 | Pereiro pluton | Zircon | LA-ICP-MS | Guimarães *et al.* (2004) |
| 542 ± 5 | Uruçu gabbro | Zircon | SHRIMP | Hollanda *et al.* (2010) |
| 538 ± 23 | Serra do Vellho Zuza pluton | Zircon | LA-ICP-MS | Guimarães *et al.* (2004) |
| 537 ± 6 | Monteiro dike | Zircon | SHRIMP | Hollanda *et al.* (2010) |
| 534 ± 4 | Sumé pluton | Zircon | SHRIMP | Hollanda *et al.* (2010) |
| 533 ± 4 | Santa Catarina pluton | Zircon | SHRIMP | Hollanda *et al.* (2010) |
| *Metamorphic ages* | | | | |
| 626 ± 15 | Leucossome of migmatitic paragneiss | Zircon | LA-ICP-MS | Neves *et al.* (2006) |
| 625 ± 24 | Zircons from banded orthogneiss | Zircon | LA-ICP-MS | Neves *et al.* (2006) |
| 632 ± 17 | Alcantil orthogneiss | Zircon | LA-ICP-MS | Neves *et al.* (2012) |
| 623 ± 6 | Zircon overgrowth in a paragneiss | zircon | LA-ICP-MS | Neves *et al.* (2009) |
| 612 ± 54 | Metamorphic zircons in orthogneiss | Zircon | LA-ICP-MS | Neves *et al.* (2006) |
| 600 ± 22 | Metamorphic zircons in orthogneiss | Zircon | LA-ICP-MS | Neves *et al.* (2006) |
| Southern Borborema Province | | | | |
| *Magmatic ages* | | | | |
| 628 ± 12 | Pre-collision Camará tonalite | Zircon | SHRIMP | Bueno *et al.* (2009) |
| 625 ± 2 | Coronel Sá pre-collisoinal granodiorite | Zircon | ID-TIMS | Long *et al.* (2005) |
| 584 ± 10* | Angico syn-collisional granite | Titanite | ID-TIMS | Bueno *et al.* (2009) |
| 571 ± 9* | Pedra Furada syn-collisional granite | Titanite | ID-TIMS | Bueno *et al.* (2009) |
| *Metamorphic ages* | | | | |
| 573 ± 1 | Macururé garnet-mica schist | WR-garnet | Sm-Nd isochron | Oliveira *et al.* (2010) |
| Northern Borborema Province | | | | |
| *Cooling ages* | | | | |
| 641 ± 2 | Orthogneiss | Biotite | Ar-Ar | Castro (2004) |
| 611 ± 3 | Amphibolite | Amphibole | Ar-Ar | Castro (2004) |
| 601 ± 4 | Granja kinzigite | Biotite | Ar-Ar | Monié *et al.* (1997) |
| 601 ± 2 | Amphibolite | Amphibole | Ar-Ar | Castro (2004) |
| 599 ± 8 | Orthogneiss | Biotite | Ar-Ar | Castro (2004) |
| 599 ± 2 | Amphibolite | Amphibole | Ar-Ar | Castro (2004) |
| 598 ± 2 | Amphibolite | Amphibole | Ar-Ar | Castro (2004) |
| 597 ± 1 | Aluminous paragneiss | Biotite | Ar-Ar | Castro (2004) |
| 595 ± 2 | Amphibolite | Amphibole | Ar-Ar | Castro (2004) |
| 595 ± 1 | Orthogneiss | Biotite | Ar-Ar | Castro (2004) |
| 594 ± 2 | Amphibolite | Amphibole | Ar-Ar | Castro (2004) |
| 594 ± 2 | Orthogneiss | Biotite | Ar-Ar | Castro (2004) |
| 592 ± 1 | Aluminous paragneiss | Biotite | Ar-Ar | Castro (2004) |
| 588 ± 1 | Aluminous paragneiss | Biotite | Ar-Ar | Castro (2004) |
| 584 ± 1 | Aluminous paragneiss | Biotite | Ar-Ar | Castro (2004) |

 

**Table 1** (Continued).

| | | Mineral | Technique | Reference |
|---|---|---|---|---|
| 583 ± 1 | Aluminous paragneiss | Biotite | Ar-Ar | Castro (2004) |
| 582 ± 1 | Aluminous paragneiss | Biotite | Ar-Ar | Castro (2004) |
| 582 ± 1 | Aluminous paragneiss | Muscovite | Ar-Ar | Castro (2004) |
| 578 ± 1 | Aluminous paragneiss | Muscovite | Ar-Ar | Castro (2004) |
| 576 ± 1 | Aluminous paragneiss | Biotite | Ar-Ar | Castro (2004) |
| 574 ± 6 | Granja granuilte | Amphibole | Ar-Ar | Monié *et al.* (1997) |
| 573 ± 1 | Aluminous paragneiss | Muscovite | Ar-Ar | Castro (2004) |
| 573 ± 1 | Aluminous paragneiss | Muscovite | Ar-Ar | Castro (2004) |
| 572 ± 6 | Mombaca granulite | Amphibole | Ar-Ar | Monié *et al.* (1997) |
| 568 ± 5 | Mombaca granulite | Biotite | Ar-Ar | Monié *et al.* (1997) |
| 563 ± 5 | Granja granuilte | Biotite | Ar-Ar | Monié *et al.* (1997) |
| 562 ± 1 | Aluminous paragneiss | Muscovite | Ar-Ar | Castro (2004) |
| 561 ± 3 | Protomylonitic granite | Biotite | Ar-Ar | Corsini *et al.* (1998) |
| 557 ± 1 | Aluminous paragneiss | Muscovite | Ar-Ar | Castro (2004) |
| 556 ± 1 | Aluminous paragneiss | Biotite | Ar-Ar | Castro (2004) |
| 555 ± 5 | Pre-migmatitic tonalite | Amphibole | Ar-Ar | Monié *et al.* (1997) |
| 552 ± 7 | Chaval granite | Muscovite | Ar-Ar | Monié *et al.* (1997) |
| 549 ± 5 | Archean basement | Amphibole | Ar-Ar | Monié *et al.* (1997) |
| 549 ± 3 | Mylonitic tonalite | Biotite | Ar-Ar | Corsini *et al.* (1998) |
| 544 ± 3 | Mafic layer | Amphibole | Ar-Ar | Corsini *et al.* (1998) |
| 542 ± 3 | Biotite-rich dyke | Amphibole | Ar-Ar | Corsini *et al.* (1998) |
| 540 ± 3 | Mylonitic granite | Amphibole | Ar-Ar | Corsini *et al.* (1998) |
| 536 ± 5 | Oros schist | Phlogopite | Ar-Ar | Monié *et al.* (1997) |
| 534 ± 5 | Paragneiss (Ceara Central) | Muscovite | Ar-Ar | Monié *et al.* (1997) |
| 534 ± 3 | Mafic boudin | Amphibole | Ar-Ar | Corsini *et al.* (1998) |
| 529 ± 3 | Mafic boudin | Biotite | Ar-Ar | Corsini *et al.* (1998) |
| 525 ± 5 | Paragneiss (Ceara Central) | Biotite | Ar-Ar | Monié *et al.* (1997) |
| 525 ± 5 | Archean basement | Muscovite | Ar-Ar | Monié *et al.* (1997) |
| 525 ± 2 | Pegmatite | Biotite | Ar-Ar | Araújo *et al.* (2005) |
| 524 ± 5 | Proterozoic cover | Muscovite | Ar-Ar | Monié *et al.* (1997) |
| 524 ± 3 | Metapelite | Biotite | Ar-Ar | Corsini *et al.* (1998) |
| 524 ± 3 | Biotite-rich dyke | Biotite | Ar-Ar | Corsini *et al.* (1998) |
| 521 ± 3 | Mafic layer | Biotite | Ar-Ar | Corsini *et al.* (1998) |
| 520 ± 3 | Muscovite-quartz mylonite | Muscovite | Ar-Ar | Araújo *et al.* (2005) |
| 511 ± 3 | Metapelite | Biotite | Ar-Ar | Corsini *et al.* (1998) |
| 510 ± 3 | Mylonitic granite | Biotite | Ar-Ar | Corsini *et al.* (1998) |
| 509 ± 3 | Quartzite | Muscovite | Ar-Ar | Corsini *et al.* (1998) |
| 506 ± 2 | Hydrothermal muscovite | Muscovite | Ar-Ar | Araújo *et al.* (2005) |
| 505 ± 3 | Mylonitic orthogneiss | Muscovite | Ar-Ar | Corsini *et al.* (1998) |
| 505 ± 2 | Mylonitic schist | Muscovite | Ar-Ar | Araújo *et al.* (2005) |
| 502 ± 5 | Aluminous granitoid | Biotite | Ar-Ar | Corsini *et al.* (1998) |
| 502 ± 3 | Granite vein | Muscovite | Ar-Ar | Corsini *et al.* (1998) |
| 502 ± 3 | Mylonitic orthogneiss | Biotite | Ar-Ar | Corsini *et al.* (1998) |
| 501 ± 3 | Serido metapelite | Biotite | Ar-Ar | Corsini *et al.* (1998) |
| 500 ± 3 | Equador schist | Biotite | Ar-Ar | Corsini *et al.* (1998) |
| 500 ± 3 | Sheared granite | Muscovite | Ar-Ar | Corsini *et al.* (1998) |
| 500 ± 2 | Mylonitic schist | Biotite | Ar-Ar | Araújo *et al.* (2005) |
| 496 ± 3 | Equador schist | Biotite | Ar-Ar | Corsini *et al.* (1998) |
| 491 ± 3 | Sheared granite | Biotite | Ar-Ar | Corsini *et al.* (1998) |
| Central Borborema Province | | | | |
| *Cooling ages* | | | | |
| 552 ± 5 | Cachoeirinha pluton | Biotite | Ar-Ar | Neves *et al.* (2012) |
| 548 ± 2 | Coxixola mylonites | Muscovite | Ar-Ar | Neves *et al.* (2012) |
| 547 ± 4 | Coxixola mylonites | Muscovite | Ar-Ar | Neves *et al.* (2012) |
| 547 ± 2 | Prata mafic stock | Amphibole | Ar-Ar | Neves *et al.* (2012) |
| 535 ± 5 | Metagranodiorite | Biotite | Ar-Ar | Neves *et al.* (2012) |
| 530 ± 2 | Prata mafic stock | Biotite | Ar-Ar | Neves *et al.* (2012) |
| 529 ± 5 | Alcantil orthogneiss | Amphibole | Ar-Ar | Hollanda *et al.* (2010) |
| 521 ± 5 | Jupi orthogneiss | Biotite | Ar-Ar | Hollanda *et al.* (2010) |
| 520 ± 5 | Coxixola mylonites | Muscovite | Ar-Ar | Hollanda *et al.* (2010) |

**Table 1** (Continued).

| | | Mineral | Technique | Reference |
|---|---|---|---|---|
| 519 ± 5 | Alcantil orthogneiss | Biotite | Ar-Ar | Hollanda *et al.* (2010) |
| 511 ± 2 | Coxixola mylonites | Muscovite | Ar-Ar | Hollanda *et al.* (2010) |
| 510 ± 5 | Coxixola mylonites | Muscovite | Ar-Ar | Hollanda *et al.* (2010) |
| 509 ± 5 | Santa Cruz do Capibaribe pluton | Biotite | Ar-Ar | Hollanda *et al.* (2010) |
| Southern Borborema Province | | | | |
| *Cooling ages* | | | | |
| 544 ± 10 | Leucogranite Major Isidoro | Biotite | Ar-Ar | Brito *et al.* (2008) |
| 557 ± 10 | Leucossome Major Isidoro | Muscovite | Ar-Ar | Brito *et al.* (2008) |
| 551 ± 10 | Kinzigitic gneiss Rio Couripe | Biotite | Ar-Ar | Brito *et al.* (2008) |
| 579 ± 10 | Biotite gneiss Rio Couripe | Biotite | Ar-Ar | Brito *et al.* (2008) |
| 566 ± 10 | Leucossome Rio Couripe | Biotite | Ar-Ar | Brito *et al.* (2008) |

*Magmatic and metamorphic ages (melting ages).

followed by thickening of the crust, with the development of thrust-related foliation (Caby and Arthaud, 1986), and heating, reaching peak thermal conditions and widespread anatexis at *c*. 620–600 Ma.

### The Sergipano Orogen: the 590–570 Ma collision II

The Sergipano Orogen in the Southern sub-province is composed of supracrustal rocks related to the development of the Sergipano Basin that may have initiated before 900 Ma (Brito Neves *et al*., 2000; Oliveira *et al*., 2010). Rifting at *c*. 700 Ma is well documented in one of its domains (the Canindé Domain) and could have lasted until *c*. 640 Ma (Oliveira *et al*., 2010). Like in the Ceará Central Domain, early convergent magmatism has arc-related signatures dated at *c*. 630–625 Ma (Long *et al*., 2005; Bueno *et al*., 2009), which were generated during subduction of a restricted Sergipano Ocean between the São Francisco Craton and the Pernambuco-Alagoas Massif (PEAL) (Oliveira *et al*., 2010).

Three deformation events have been recognized in the Sergipano Orogen (Bueno *et al*., 2009; Oliveira *et al*., 2010): south-verging D1 nappes and thrust zones, which thrust the supracrustal rocks over the São Francisco Craton; reactivation of D1 structures during D2 transpression associated with significant vertical movements and emplacement of most granitoids; and brittle to ductile-brittle D3 structures associated with exhumation in response to continued compression. Peak amphibolite facies metamorphism occurred during D2 at *c*. 570 Ma (garnet/whole-rock Sm–Nd isochron, Oliveira *et al*., 2010); similar U–Pb titanite ages have been obtained from syn-D2 leucogranites, such as the 584 ± 10 Ma Angico and the 571 ± 9 Ma Pedra Furada leucogranites (Bueno *et al*., 2009).

Combining the nature of the deformation and the ages of the leucogranites, Bueno *et al*. (2009) concluded that peak metamorphism resulted from collision between the São Francisco Craton and the Pernambuco–Alagoas Massif (PEAL), thrusting the supracrustal rocks onto the craton during D2. The climax of this collision and associated granitic magma production can be reasonably bracketed to between 590 and 570 Ma (Bueno *et al*., 2009; Oliveira *et al*., 2010), sometime after peak temperatures in collision I.

### Extrusion Tectonics (*c*. 590–570 Ma)

Figure 3 summarizes the evolution of the two orogenies, starting with collision I closing the Pharusian-Goiás Ocean and creating the West Gondwana Orogen, followed by closure of the Sergipano Ocean and collision of the São Francisco Craton with the Borborema Province (collision II) at *c*. 590 Ma, creating the Sergipano Orogen. Interaction between the two collisions led to the extrusion of the Province between 590 and 560 Ma along a network of strike-slip shear zones accompanied by the intrusion of syn-kinematic granitoids. The *c*. 30 Ma time gap between collisions I and II (*c*. 620 and 590 Ma respectively) is reflected in the time gap between peak temperatures (620–600 Ma and 590–570 Ma respectively).

Structures developed during the interaction of the two orogenies change systematically from SE to NW across the Borborema Province (Fig. 4). In the Southern sub-province, south-verging thrusting of the Sergipano Belt with a small dextral component indicates dominant N–S shortening and crustal thickening (Bueno *et al*., 2009; Oliveira *et al*., 2010).

In contrast, the Central sub-province has an older (*c*. 620 Ma) penetrative foliation, possibly related to far-reaching stresses from collision I, overprinted by the conjugate sets of E–W dextral and NE–SW sinistral, subvertical, mylonitic belts that characterize its main deformation phase (Neves *et al*., 2012). Here, the 600–590 Ma time interval corresponds to transition from the contractional event to a transcurrent regime, which reached slightly lower *P–T* conditions of 690–730 °C and 4–6 kbar (Neves *et al*., 2012) between 590 and 570 Ma, as constrained by the ages of syn-transcurrent granitoids (e.g., Guimarães *et al*., 2004; Neves *et al*., 2008, 2012). This late deformational event defines a transpressional deformation with maximum shortening oriented NW–SE and strain taken up by the conjugate pairs of transcurrent shear zones with first-order dextral E-W shear zones associated with second order sinistral NE–SW shear zones (Fig. 4).

The Northern sub-province also has its early low-angle contractional

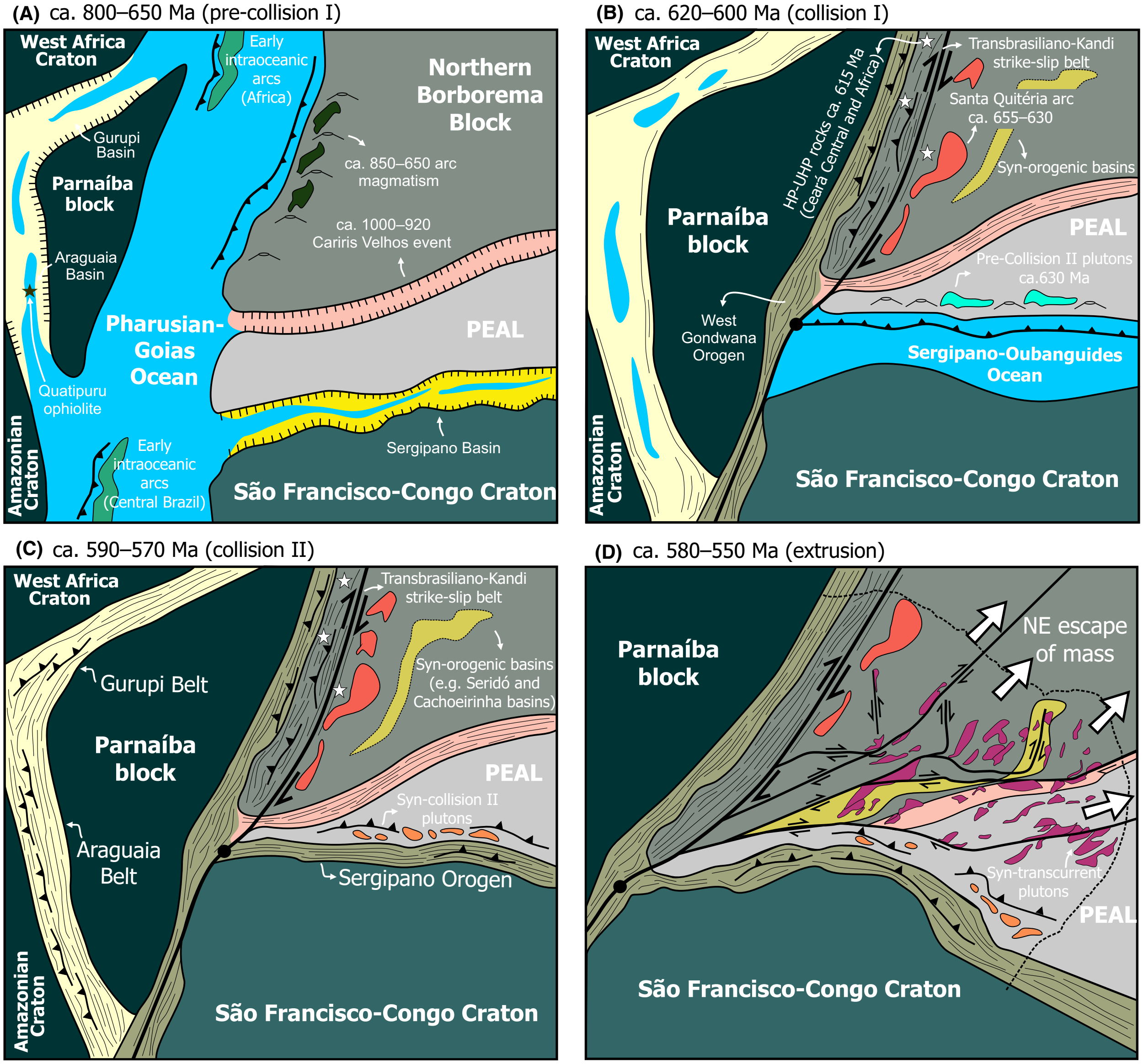


**Fig. 3** Simplified Neoproterozoic tectonic evolution of the Borborema Province and adjoining regions. (A) Position of the main tectonic components of the region in the pre-collision I stage (*c*. 800–650 Ma), based on Caby (1989), Pimentel and Fuck (1992), Brito Neves *et al*. (2000), Berger *et al*. (2011), Ganade de Araujo *et al*. (2012a,b), including the Cariris Velhos extensional event (Neves, 2003). The Parnaíba Block is inferred from geophysical evidence (de Castro *et al*., 2013) and is separated from the Amazonian-West-African Craton by the Gurupi and Araguaia volcano-sedimentary belts (Klein *et al*., 2005; Moura *et al*., 2008). Opening of the Sergipano Basin (>800 Ma) and continued rifting (*c*. 700–640 Ma) separate the PEAL from the rest of the São Francisco-Congo Craton (Oliveira *et al*., 2010). (B) Collision I (*c*. 620–610 Ma) in the west, leading to the West Gondwana Orogen marked by HP and UHP metamorphism and anatexis of continental crust (Bernard-Griffiths *et al*., 1991; Agbossoumondé *et al*., 2001; Jahn *et al*., 2001; Fetter *et al*., 2003; Santos *et al*., 2009) and arc magmatism in the south due to the initiation of subduction (Oliveira *et al*., 2010). (C) Collision II (*c*. 590–570 Ma) resulting from the closure of the Sergipano-Oubanguides Ocean and leading to thrusting of sedimentary rocks onto the craton, development of inboard orogenic basins in the Borborema Province (e.g., Van Schmus *et al*., 2003), and syn-collisional magmatism (Bueno *et al*., 2009; Oliveira *et al*., 2010). Inversion of the Gurupi and Araguaia basins (Klein *et al*., 2005; Moura *et al*., 2008). (D) Final craton indentation and northeastward extrusion stage (*c*. 580–550 Ma) with development of major shear zones (Neves *et al*., 2012; Archanjo *et al*., 2013) emanating from the main Transbrasiliano-Kandi Strike-Slip Belt. White arrows: direction of mass escape. Dashed line: shore line.

foliation overprinted by regional NE–SW trending dextral shear zones. Movement in these shear zones, dated by different methods, is bracketed to between 590 and 570 Ma (Fetter, 1999; Souza *et al*., 2006; Archanjo *et al*., 2013), extending into low-*T* conditions until the Cambrian period (530–500 Ma)

 

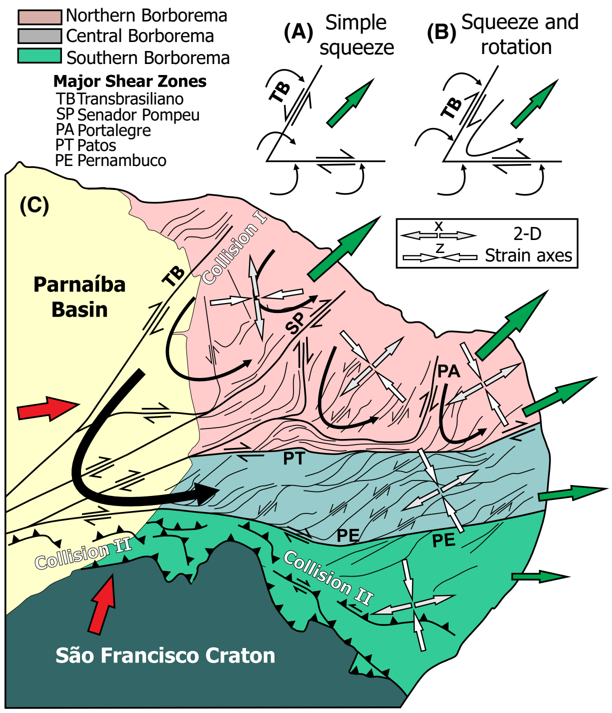


**Fig. 4** Extrusion of the Borborema Province. (A) Simple squeezing model that requires sinistral movement of the Transbrasiliano shear zone after collision II. (B) Squeezing and anticlockwise internal block rotation due to ductile deformation of the Borborema Province, allowing north-east escape and dextral movement on the Transbrasiliano shear zone. (C) Estimated orientations of 2-D strain axes for the different domains illustrating their anticlockwise rotation from southeast to northwest. Borborema Province scale block rotation (black thick arrow) and domain-scale rotations (solid black arrows) illustrate east and north-east mass escape. Straight red arrows: relative movement direction at *c*. 590–570 Ma. Straight green arrows: mass escape direction at *c*. 590–570 Ma.

(Corsini *et al*., 1998; Araújo *et al*., 2005; Hollanda *et al*., 2010). Unlike the Central sub-province, a lack of well-developed sinistral conjugate sets of shear zones in the Northern sub-province suggests a dominant simple shear transcurrent movement at 590–570 Ma, dominated by a NNE-directed block extrusion and characterized by an inferred maximum shortening strain axis trending approximately E–W (Fig. 4).

Accordingly, coeval *c*. 590–570 Ma regional structures indicate a large-scale anticlockwise rotation of the maximum shortening axis from N–S in the southeast to E–W in the northwest of the Province. This is accompanied by a change from thrusting with a small dextral component in the south and southeast, to pure shear expressed by a conjugate set of transcurrent shear zones in the centre, to dextral transcurrent movement and NNE block extrusion in the northwest (Fig. 4). It is important to notice that deformation was not simple rigid block rotation along faults, but consisted also of widespread internal ductile block deformation. Regional-scale rotation of strain axes is interpreted to be a result of superposition between a continued eastward push of the conjoined Parnaíba Block and Amazonian-West African Craton and the stresses generated by the northward push of the São Francisco Craton in the south. In this case, the axes' rotation reflects the relative impact of each collision: collision I dominating deformation in the northwest imposing NNE to NE escape, and collision II dominating in the southeast, causing south-verging thrusting. Deformation in the inter-collisional Central sub-province reflects an interaction between the two collisions leading to its conjugate transcurrent system.

Whilst our focus has been restricted to South America, the conclusions can be expanded to Africa. The São Francisco Craton was part of the much larger São Francisco-Congo Craton, and collision II with the Borborema Province was a result of the closure of the Sergipano-Oubanguides Ocean (e.g. Van Schmus *et al*., 2008). Likewise, collision I was part of a broader collisional belt, the West Gondwana Orogen, including the Dahomey and Hoggar in Africa, where magmatism, eclogitization, thrusting and later dextral reactivation follow the same overall timing as in the Ceará Central Domain (Caby, 1989, 2003; Bernard-Griffiths *et al*., 1991). Moreover, the large-scale shear zone system that resulted from the interaction between the two collisions can be correlated with large lineaments in the Benino-Nigerian Province and the E–W trending shear zones of Cameroon (Caby, 1989; Trompette, 1994; Van Schmus *et al*., 2008).

## Transbrasiliano-Kandi Strike-Slip Belt (TKSSB): A Neoproterozoic Transform Plate Boundary?

The dextral TKSSB formed as a result of relative movement obliquity during collision I (Fig. 3). This strike-slip belt reactivated the previous sutures (e.g. Caby, 1989; Castaign *et al*., 1994), and dextral movement along it started possibly as early as 615 Ma, soon after collision I. In our view, it may have functioned as a transform plate boundary, allowing approximation of the Borborema Province to the São Francisco Craton, and leading to closure of the Sergipano Ocean and collision II (Fig. 3).

Extrusion of the Borborema Province via a simple squeezing model after indentation of the São Francisco Craton requires a change from dextral to sinistral shear movement in the TKSSB (Fig. 4A). This movement switch at *c*. 590–580 Ma has not been documented, and therefore we suggest instead an anticlockwise block rotation of the Borborema Province relative to the São Francisco Craton, associated with internal ductile deformation of its tectonic domains, so as to maintain dextral shear along the TKSSB (Fig. 4B). It is this rotation resulting from collision interference and cratonic indentation that triggered the inferred northeastward extrusion of the Borborema Province.

## Conclusion

We present the first attempt to integrate the tectonothermal and magmatic history of the Borborema Province within the 650–550 Ma time span. Granitoid and migmatite ages indicate that its Neoproterozoic evolution started with an early collision associated with the closure of the large Pharusian-Goiás Ocean at 620–600 Ma and generalized crustal thickening, marked by the development of eclogites and high-*T* thrusting foliation defining the West Gondwana Orogen. The site of this collision was subsequently reactivated by a set of dextral shear zones, forming the Transbrasiliano-Kandi Strike-Slip Belt, which acted as a transform plate boundary, allowing the closure of the restricted Sergipano Ocean and collision with the São Francisco Craton at *c.* 590 Ma. Interaction between the two collisions between 590 and 570 Ma and continuous cratonic indentation led to the province-wide switch to transcurrent deformation and block escape generally to the NE, associated with province-wide magmatism and regional rotation of the maximum shortening axis.

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