Decratonization by Rifting followed by Orogeny and Transcurrent Dispersal of Old Terranes in NE Brazil: A Common Feature of Gondwana Amalgamation?

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Research Article

Keywords: decratonization, reworking, transpressional orogeny, terrane translation

Posted Date: December 7th, 2020

DOI: <https://doi.org/10.21203/rs.3.rs-117523/v1>

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Version of Record: A version of this preprint was published at Scientific Reports on March 11th, 2021. See the published version at <https://doi.org/10.1038/s41598-021-84703-x>.

Abstract

Dispersion and deformation of cratonic fragments within orogens in the periphery of cratons require weakening of the craton margins in a process of decratonization. The Borborema orogenic province, in NE Brazil, is one of several Brasiliano/Panafrican late Neoproterozoic orogens that led to the amalgamation of Gondwana. A common feature of these orogens is that a period of extension and opening of narrow oceans preceded inversion and collision. For the case of the Borborema Province, the São Francisco Craton was pulled away from its other half, the Benino-Nigerian Shield, during an extension event lasting between 1 Ga and 0.65 Ga. This was followed by inversion and a transpressional orogeny from c. 0.60 Ga onwards. Here we investigate the boundary region between the north São Francisco Craton and the Borborema Province and demonstrate how cratonic blocks became physically involved in the orogeny. We combine these results with a wide compilation of U-Pb and Nd-isotopic model ages to show that the BP consists of up to 65% of strongly sheared ancient rocks affiliated with the São Francisco/Benino-Nigerian Craton, separated by major transcurrent shear zones, with only ~ 15 % addition of juvenile material during the orogeny. This evolution is repeated across a number of Brasiliano/Panafrican orogens, with significant local variations, and indicate that extension weakened entire cratonic regions in a process of decratonization that prepared them for involvement in the orogenies that led to the amalgamation of Gondwana.

Background

Cratons are old, stable continental regions with thick buoyant keels that resist deformation, protecting them from tectonic reworking. Their thick and cold refractory lithospheric keel is taken to be responsible for their integrity¹. However, during continental collisions, colliding cratonic blocks can be partially reworked to generate continental tracts that are no longer cratons but that are not typical orogens either². Thus, understanding the origin of these old continental crust within orogenic areas must address the specific mechanisms for both the weakening of the craton lithosphere (*c.f.* decratonization) and their subsequent reworking. First order controls in the reworking of these strong lithospheres are temporal and spatial variations of their thermal state and pre-existing mechanical anisotropies or major compositional boundaries^{3–8}. The North China Craton is a classic example where lithospheric thinning, asthenospheric decompression and magmatism changed the thermal and chemical state of the cratonic lithosphere resulting in wholesale decratonization^{9–12}.

Here we describe the process of decratonization of the São Francisco Craton (SFC) during the Neoproterozoic in northeast Brazil. This craton is bound to the north by the late Neoproterozoic orogenic Borborema Province. In the province, pre-orogenic extension started as early as 1000–900 Ma and resulted in the development of intracontinental extensional basins¹³, passive margin basins flanking the SFC^{14–16}, and separation of the SFC from the African Benino-Nigerian Shield^{17,18}. Remarkably, this orogenic province includes a number of reworked and deformed Archean-Paleoproterozoic terranes among the Neoproterozoic sedimentary basins and granitic intrusions¹⁹. These old terranes are relatively small

(10,000 to 40,000 km²) and bounded by large-scale continental shear zones^{19,20} (**Fig. 1A and B**). Although no quantitative crustal growth curves of the orogenic Borborema Province have been reported, present models range from purely intracontinental reworking²¹, to juvenile arc accretion^{22,23} and docking followed by reworking of unrelated terranes²⁴, or even to questionable autochthonous accretion surrounding old small Archean crust²⁵.

The Borborema Orogen comprises two separate and interacting collisions: one on the west side as part of the vast West Gondwana Orogen (WGO)²⁶ and one in the south against the SFC and termed here Southern Borborema Orogen (SBO). These two collisions were partly contemporaneous and interacted involving the entire Borborema Province (BP). In this paper we will use the term BP to refer to the entire orogenic area. The current configuration of the Province seems to be controlled by these collisions as indicated by the record of UHP metamorphism and eclogites^{26,27}, marginal ophiolites^{28,29} and arc sequences^{16,23,30} that together suggest two separate but related collisions: an oceanic subduction followed by collision along the WGO^{19,26}, and a later but in part contemporaneous collision with the SFC. The two different orogens interacted in a complex collisional zone, giving rise to an intricate network of continental shear zones that controlled deformation¹⁹. In this context, the large Transbrasiliano-Kandi shear zone, that developed as a result of the WGO, acted as a dextrally transfer zone leading to collision and development of the Southern Borborema Orogen¹⁷.

In this paper, we compile large volumes of whole-rock Nd isotope data, zircon U-Pb geochronology data, as well as geological and geophysical data of the Borborema Province and northern part of the SFC and the Benino-Nigerian Shield. We use the data to first quantify the Neoproterozoic continental growth of the Borborema Province and establish the dominance of recycled cratonic material, and then to investigate how the decratonization allowed former cratonic Archean-Paleoproterozoic terranes to be entrained within the BP during the Neoproterozoic Orogeny.

Geological Setting Of The Borborema Province

The distribution of lithologies in the triangular wedge-shaped orogenic BP (**Fig. 1**) was ultimately controlled by a set of Neoproterozoic strike-slip shear zones^{19,20}. These shear zones bound the north, central and south sub-provinces and within them several other informal domains³¹. Shearing was accompanied by granitoids with intrusions concentrated at 585-565 Ma¹⁹. Archean and Paleoproterozoic lithologies are found as blocks all over the BP, always limited by Neoproterozoic shear zones (**Fig. 1**). Early Neoproterozoic extensional events starting as early as 1000-900 Ma are marked by granitoid intrusions, bimodal volcanism and deposition of immature terrigenous and minor carbonatic sediments in the so-called Cariris Velhos event¹³. In the southern BP this event culminated in the development of a passive margin sequence along the edge of the SFC associated to 900-800 Ma mafic-ultramafic intrusions, proximal margin-type ophiolites and A-type granites^{14,16,28,32}. In this region, extensional tectonics may have lasted most of the Neoproterozoic, with the last pulses of rifting recorded by the 720-680 Ma Canindé Group, a sequence of mafic-ultramafic rocks and subvolcanic A-type igneous rocks¹⁶.

Early Neoproterozoic passive margin and intracontinental sedimentation was overlain by orogenic sedimentary successions as young as 580 Ma¹⁶ contemporaneous with other basins within the central and north BP³³. The lithological boundary of the SFC and BP is defined in many geological maps (**Fig. 1A**), however seismic data indicate that the lithospheric cratonic signature at 100 km depth extend further north ending within the central portion of BP³⁴ (**Fig. 1C**).

During the Late Neoproterozoic, from 650 to 610 Ma, predating continental collisional events, continental magmatic arcs developed in the west²³ and south³⁵ parts of the province, closing intervening oceanic basins. During the collisions that ensued the province was squeezed between two impinging continents, one continent coming in from the west and the other, the São Francisco Craton, coming in from the south¹⁹. As a consequence, the BP “escaped” obliquely with the development of a throughgoing network of transcurrent shear zones^{19,20} that shear and limits Archean-Paleoproterozoic terranes of unknown origin^{36–38}, such as the Alto Moxotó Terrane²⁴ (**Fig. 1**). Just how these old terranes became involved in the orogen remains unclear.

Results

U-Pb ages, Nd isotopic spatial distribution and crustal growth

The U-Pb ages of igneous rocks in the northern SFC and Benino-Nigerian Shield show a similar pattern to those of the ancient basement terranes in the BP, recording similar episodes of crust production during the Archean and mostly the Paleoproterozoic (Figs. 2A). In the Neoproterozoic, U-Pb age of igneous rocks from the BP shows two intervals of crust production at 1.0-0.92 Ga and 0.67-0.52 Ga, with a few ages < 0.50 Ga (Fig. 2B). Both intervals are characterized by production of new juvenile crust combined with recycling of old pre-existing crust. The spatial distribution of the interpolated U-Pb ages and $\epsilon\text{Nd}_{(t)}$ values (Fig. 1D and E), excluding the areas covered by sedimentary and metasedimentary rocks, was used to estimate the crustal growth during the Borborema Province Orogen (see methods and supplementary figure S1).

The gridded values resulted in a map with 46,426 pixels with a pixel size of 3.2 x 3.2 km (pixel area=10.24 km²). These pixels were clipped to the crystalline basement area of the Borborema Province, excluding the Neoproterozoic metasedimentary belts, Phanerozoic basins and more recent cover, resulting in a map with 17,235 pixels with a total area of 176,486 km². Pixel values of Nd model ages (Fig. 1B) were binned into 100 m.yr. interval, from 500 to 3400 Ma, and so were the U-Pb crystallization ages from individual rock samples. Positive $\epsilon\text{Nd}_{(t)}$ values were used to distinguish juvenile addition of new crust to the Borborema Province through time.

The results based on the exposed surface area, incorporating both zircon U-Pb and Nd isotopes, indicate that 65-60% of the province was already formed by the end of the Paleoproterozoic, with a rapid growth

rate between 2.3 to 2.0 Ga, when 55-50% of the continental crust of the Borborema Province formed (Fig. 2C). During the Early Neoproterozoic, from 1.0 to 0.7 Ga, new juvenile additions accounts for ~ 20% of the crust. This period includes the early stages of the Santa Quitéria arc at c. 0.85 Ga²³ and magmatism related to the Cariris Velhos event from c. 1.0 to 0.92 Ga³⁹. The production of new continental crust during the main Neoproterozoic orogenic period, between 0.67 and 0.52 Ga, accounts for only ~ 15% of the new continental crust in the province, suggesting the orogeny was characterized by whole-sale lithospheric reworking with minor juvenile magma input.

Transpression and correlation of terranes

Another aspect revealed by our data compilation and geophysical image investigation is the link between old Paleoproterozoic and Archean terranes across the province. The Southern Borborema Orogen (Figs. 1A, 1B and 3), is split into the Sergipano and Riacho do Pontal fold-and-thrust belts by a promontory of the São Francisco Craton, well-defined in the Nd isotopic model age map (Fig. 1B) and geological maps³⁷. This promontory forms the Entremontes block and may mark an inherited feature of the paleocontinental passive margin inverted during onset of the Southern Borborema Orogen. It comprises mainly Archean gneisses and migmatites and Paleoproterozoic gneisses and supracrustal rocks³⁷.

The combination of our field data and available geological maps, isotopic data and geophysical images show that the Entremontes Block is bound by the Pernambuco shear zone in the north and the Boa Vista shear zone in the south (Fig. 3A). Movement on these shear zones forced block rotation and internal deformation of the block under a transpressive regime (Fig. 3B) leading to the folds documented in the aeromagnetic images at wavelengths of 5 to 20 km with 2D axial planes subparallel to the shear zones (block diagram in Fig. 3B). In outcrop, folds are tight and fold a previous foliation (Sn), generating a steep axial plane (Sn+1) permeated by leucosomes indicative of syn-tectonic partial melting (Fig. 3B). Stretching lineation has low rake and is commonly parallel to the fold axes plunging at low angles to WSW or ENE. Kinematic indicators on Sn+1 planes indicate consistent top-to-NE or E transport in the Entremontes block (Fig. 3A). This direction could either be a result of rotation of early-formed shear zones, or formed contemporaneously with transcurrent movement, defining a constrictional transpressional belt. The metasedimentary Riacho do Pontal fold-and-thrust belt, west of the Entremontes block, includes the Afeição domain comprising Tonian metasedimentary rocks. In contrast to the Entremontes, the direction of tectonic transport for the entire Riacho do Pontal belt is dominantly top-to-SW, thrusting the belt over the SFC¹⁵ (Fig. 3A).

The geophysical and Nd isotopic characteristics of the ancient Entremontes block and the Tonian-age Afeição domain can be recognized in the central Borborema province, north of the Pernambuco shear zone, displaced dextrally by ≈ 200 km and deformed into sigmoidal terranes characteristic of the BP (Fig. 3 and supplementary figure S1). U-Pb ages and Eps Nd(t), as well as K-Th-U contents, as recorded in the radiometric images (supplementary figure S1), show that the Afeição domain can be linked with the contemporaneous Alto Pajeú domain¹³, and the Entremontes block can be tracked into the Alto Moxotó

domain, also composed of Paleoproterozoic and Archean gneisses and migmatites^{24,37}. The Alto Moxotó terrane includes high-grade Late Neoproterozoic metasedimentary rocks of the Surubim Complex that can be correlated to the lower-grade equivalents of the Riacho do Pontal fold-and-thrust belt and of the Cabrobó Complex overthrusting the Entremontes block. The Surubim Complex and these lower grade-rocks share similar detrital zircon age signatures^{40–42}.

In summary, much of the Borborema province has old Nd model ages and zircon population signatures similar to the São Francisco Craton/Benino-Nigerian Shield (Fig. 1 and 2A), suggesting direct or indirect derivation from these areas. The stepwise process of breakdown and involvement of cratonic blocks is preserved at the margin of the craton, where increased deformation of cratonic blocks is recorded across the Pernambuco shear zone and associated with a dextral displacement of ≈ 200 km.

Discussion: Decratonization, Terrane Dispersion And Reworking

We suggest that Tonian extension, recorded by bimodal magmatism and rift-related sedimentation followed by passive margin sedimentation, would have opened a narrow ocean recorded by marginal ophiolites dated at ca. 0.82 Ga, breaking apart the greater São Francisco Craton/Benino-Nigerian Shield¹⁸ (**Fig. 4A**). This process pulled out crustal ribbons, such as the Pernambuco-Alagoas terrane (PEAL, **Fig. 4A**), from the cratonic margin by ca. 0.82 Ga¹⁵ and continued to 0.72-0.68 Ga with the last pulses of rifting recorded by the mafic-ultramafic intrusive rocks of the Canindé Group in the Southern Borborema Province¹⁶.

The break-up of the conjoined São Francisco Craton/Benino-Nigerian Shield during extension indicates that decratonization started already in the Early Neoproterozoic, in a manner akin to the Mesozoic decratonization of the North China Craton⁹, where extension associated with metasomatism¹⁰ transferred continental lithospheric mantle to the asthenosphere⁴³ and facilitated continental breakup⁴⁴. This hypothesis is supported by alkaline volcanism (e.g. kimberlites) in the northern SFC from 1150 to 680 Ma^{45,46}.

The long-term effect of extension on lithospheric strength depends on the relative thinning of the crust in relation to the sub-continental lithospheric mantle (SCLM)^{47,48}. Starting from a thick Archean lithosphere, as for the SFC^{49,50}. Tonian thinning and refertilization of the SCLM (indicated by the alkaline volcanism), would have led to weakening that persisted long-after extension ended. Thus, the Tonian extensional event would have made sections of the cratonic paleocontinent amenable to subsequent reworking within the orogenic realm.

This weakened, decratonized lithosphere between the Benino-Nigerian Shield and the São Francisco Craton was reworked in two steps during the construction of the Borborema Province Orogen. The first step was a result of oblique continental collision with the West African Craton being thrust under the Benino-Nigerian Shield^{17,26,51,52}. This was preceded by oceanic lithosphere subduction and magmatism in the aforementioned Santa Quiteria arc, and terminal collision led to the development of the dextral

Transbrasiliano-Kandi strike-slip belt (**Fig. 4B and C**). The second step was a result of dextral movement on the Transbrasiliano-Kandi strike-slip belt. This movement brought the Benino-Nigerian Shield closer to the São Francisco Craton deforming the weakened decratonized area in between these two stiffer lithospheric domains leading to the transpressional Borborema Province Orogeny (see cross section in **Fig. 4D**).

The transcurrent shear zones that characterize the Borborema Province splayed out of the Transbrasiliano-Kandi shear zone²³ and deformed the weakened cratonic margin. Deformation was a result of these two quasi-contemporaneous collisions^{23,26} (**Fig. 4D**). In the north part of the Borborema Province, old Paleoproterozoic and minor volumes of Archean rocks dominate and represent the southern continuation of the Benino-Nigerian Shield¹⁷ (north of the Patos shear zone in **Figure 1B**). To the south, the Borborema Province record the interaction of the decratonized lithosphere and the São Francisco Craton. In this region, the transcurrent shear zones wrenched the blocks of the northern margin of the São Francisco Craton that had been previously weakened by the Cariris Velho extension. Deformation included a number of continental ribbons (e.g. PEAL terrane) pulled away from the craton and the intervening Tonian sedimentary basins (**Fig. 4C and D**).

The exact geometry of the decratonized terrane at the start of wrenching, and the source region of individual blocks now embedded in the BP are generally unknown. However, using rock ages, isotopic and geophysical signatures, we have linked the Tonian-aged Afeição domain and the ancient Entremontes block south of the Pernambuco shear zone, with the Tonian-age Alto Pajeú and the ancient Alto Moxotó terranes, north of the shear zone. This implies a ≈ 200 km dextral wrenching across the Pernambuco shear zone (**Fig. 3**). The rocks south of the shear zone record only incipient deformation, whereas those to the north are intensely strained into sigmoidal terranes, in harmony with the regional transcurrent deformation and geological-geophysical structure of this region.

It is also possible to recognize signatures of specific sections of the SFC in the old blocks now within the BP. For example, the geological features of the Gavião Block in the SFC can be found in blocks within the Central and Northern Borborema Province^{36,38,53}. These features include rare occurrences of Paleoarchean rocks (>3.4 Ga) embedded in Neoarchean (2.8-2.6 Ga) to Paleoproterozoic (2.1-2.0 Ga) rocks imprinted by ca. 2.0 Ga high-grade metamorphism^{53,54}. We conclude that deformation of craton margin blocks, such as the Entremontes block, into the sigmoidal-shaped Alto Moxotó terrane within the Borborema Province, illustrates how a number of other Archean-Paleoproterozoic blocks may have been pulled away from the original craton to form inliers within the orogeny. It is important to note, however, that dispersal of São Francisco Craton decratonized blocks was more effective along the southern and central zones of the Borborema Province, where evidence for Cariris Velhos extensional events has been better defined. The Benino-Nigerian Shield also comprises Paleoarchean rocks of ca. 3.5 Ga such as the Kaduna Massif⁵⁵ that could be linked to the São José do Campestre Massif³⁶ of the northern Borborema Province, unrelated to the orogenic dispersal of former cratonic fragments documented in the province's southern and central zones.

Decratonization related to early to late Neoproterozoic extension and juvenile magmatism could have been widespread throughout West Gondwana, related to the break-up of Rodinia. For example, it might account for thinning of the cratonic lithosphere in the Ribeira and Araçuaí belts of southeastern Brazil⁵⁶, decratonizing the eastern margin of the SFC, preparing it for later involvement in the transcurrent Brasiliano tectonics⁵⁷. In the Araçuaí Belt fissural mafic magmatism preceded the opening of the Adamastor Ocean starting at 1.0 Ga^{58,59} with subsequent Tonian rift-related, A-type continental plutonism, dated at c. 0.87 Ga³⁰. Further south, in the Dom Feliciano-Kaoko belt, rift-related siliciclastic and bimodal volcanic rocks preserved in the Neoproterozoic schist belts from both the Rio de la Plata/Paranapanema and Congo/Kalahari cratonic margins suggest a continental rifting phase between 0.9 and 0.78 Ga⁶⁰. In the African side of these orogens (e.g. Gariep, Kaoko and Damara-Lufilian belts) extensional tectonics and breakup of surrounding cratons are also constrained to between 0.85 to 0.77 Ga^{61–63}. These protracted extensional events preceding the Brasiliano/Panafrican orogens of coastal South America and their African equivalents, disrupted and weakened the surrounding cratons enabling orogenic reworking and transcurrent dispersal of old terranes such as the São Luiz, Curitiba, and Cabo Frio terranes^{64,65}. The same could account for Archean/Paleoproterozoic lithosphere in the West Gondwana Orogen in Africa where c. 1.1-1.0 Ga extension in the Tuareg Shield allowed reworking during the Pan-African Orogeny².

Global estimates for the construction of Gondwana between 0.5-0.6 Ga indicate only a minor mantle addition⁶⁶, in accordance to our observations. This final stage of reworking and transcurrent tectonics was accompanied by abundant syn-transcurrent magmatism with dominant lithospheric mantle affinities^{67,68} from 590 to 560 Ma, but peaking at c. 580 Ma¹⁹. The orogenic collisional period of BP resulted in crustal thickening (>80 km), especially along the West Gondwana Orogen²⁶, however, Rayleigh wave tomography indicate that this orogen are marked by thinner lithosphere⁶⁹, thus suggesting that the orogenic roots have been delaminated after collision. The lithospheric mantle signatures of the 590 to 560 Ma syn-transcurrent and post-collisional magmatism may reflect the delamination of the orogenic lithosphere, resulting in low-viscosity zones that would facilitate lateral crustal flow⁷⁰ leading to the processes of scape tectonics and terrane dispersion in the Borborema Province¹⁹ (cross section in **Figure 4B**). Finally, Ar-Ar cooling ages and emplacement of poorly deformed to isotropic granitoids indicate slow cooling rates with continuous heat supply by the delamination process until the Cambrian (530-500 Ma)¹⁹.

We conclude that the cratonic roots of the São Francisco Craton/Benino-Nigerian Shield, responsible for craton integrity, were weakened by Tonian-age extension, similar to the evolution of the North China Craton where extension and alkaline magmatism provided a mechanism for decratonization. This created the conditions required for the involvement and dispersal of decratonized inliers within the Brasiliano orogen. We suggest that this may have been the general sequence of events for many of the Brasiliano/Panafrican orogens, where extension related to the break-up of cratonic masses and opening

of oceanic realms with varying degrees of maturity were followed by convergence and wrench tectonics during Gondwana amalgamation.

Methods

Nd isotopic maps.

In order to discriminate terranes with similar signatures, a large compilation comprising 360 zircon U-Pb ages and 1331 Sm-Nd whole-rock isotope analyses of samples from the BP and the northern SFC were used (Fig. 1B). Sm-Nd isotope distribution of a large number of samples is suitable to identify correlated terranes due to resistance of the Sm-Nd isotope system to post-crystallization thermal disturbance⁷¹. Data were downloaded from the open sources DateView⁷² and the Geological Survey of Brazil database (<http://geosgb.cprm.gov.br>). Due to the scarcity of the U-Pb crystallization ages from the Benino-Nigerian Shield, for this region we use the individual zircon ages for dated metaigneous rocks available in the global zircon compilation of reference [73]. The compilation was augmented with data from the literature. Most of the data is from (meta)igneous rocks with subordinated input from metasedimentary rocks.

In general, Nd model ages (TDM) do not correspond to a specific crust-formation event but instead reflect mixing of material derived from the mantle at different times and are determined by calculating the time when a sample had an isotopic composition identical to that of its source⁷⁴, so they can be understood as minimum ages of crust formation. For figure 1B we used Sm-Nd TDM ages as originally reported by different authors (Table 1 of supplementary material). The Sm-Nd TDM ages were gridded in the ArcGIS software using the Inverse-Distance-Weighted Interpolation (IDW). Since significant discontinuities modify the surrounding geological environment, we define the major shear zones as interpolation barriers. We also applied the Gaussian low-pass filter to attenuate high frequencies due to variable spacing between samples. We compared compiled U-Pb zircon crystallization ages and freely available geological maps (<http://geosgb.cprm.gov.br>) of the Northern SFC and BP to cross-check terrane affinity based on the Sm-Nd TDM map, to identify old terranes within the Borborema orogenic province. From the compiled Sm-Nd dataset only data with reported ppm content of Nd, Sm and $^{143}\text{Nd}/^{144}\text{Nd}$ ratio associated with reliable reported U-Pb ages for the magmatic crystallization were considered for building the $\text{eNd}_{(t)}$ maps and further crustal growth curve for the Borborema Province. This resulted in 889 data points with assigned geographical position and recalculated $^{147}\text{Sm}/^{144}\text{Nd}$ ratio. A new screening was applied to eliminate unreliable $^{147}\text{Sm}/^{144}\text{Nd}$ resulting in the 837 data points that were used for further gridding of $\text{eNd}_{(t)}$ values, as described above (Fig. 3). The gridded values resulted in a map with 46,426 pixels with a pixel size of 3.2 x 3.2 km (pixel area=10.24 km²). These pixels were clipped to the igneous crystalline area of the Borborema Province, excluding the Neoproterozoic metasedimentary belts, Phanerozoic basins and more recent cover, resulting in a map with 17,235 pixels with a total area of 176,486 km². Pixel values were further binned to 100 m.yr. interval, from 500 to 3400 Ma, along with U-Pb crystallization ages from individual rock samples. The $\text{eNd}_{(t)}$ cut-off value of zero was used to distinguish juvenile addition of new crust from reworked crust in the Borborema Province through time.

The pixels with $eNd > 0$ were binned to 100 m.yr. and the cumulative percentage area covered by juvenile rocks was used to infer the crustal growth of Borborema Province from 3.4 to 0.5 Ga. Figure S1 (supplementary material) show the data distribution used to grid the Sm-Nd TDM ages.

Magnetic maps.

The airborne magnetic database comprises data from seven surveys between 2001 and 2010, with 500 m flight-line spacing in the N-S direction and flight height of 100 m (<http://geosgb.cprm.gov.br>). The Total Magnetic Intensity map (TMI) was created by interpolating the magnetic data into a 125 m grid cell size using the bi-directional method and subsequently filtered by a Gaussian low-pass filter. To highlight the regional tectonic framework, we calculated the first vertical derivative of TMI (1VD).

Declarations

ACKNOWLEDGMENTS

This research was supported by the Serrapilheira Institute (grant # Serra – 1709-21887). C.E.G acknowledges the CAPES Higher Education Improvement Coordination 88881.363575/2019-01 for supporting the author's research visiting at the University of Bern during the writing of the paper. We appreciate the critical reading of Daniela Rubatto and Jörg Herrmann that contributed to the improvement of the early version of the manuscript.

AUTHOR CONTRIBUTIONS

C.E.G. and R.F.W. conceived the idea and wrote the paper. F.A.C. contributed to the discussion and revised the paper. C.E.G., R.F.W., L.B.L.L., L.R.T. conducted the field investigation and image interpretation. C.E.G, L.B.L.L. and I.C compiled the isotopic data and conducted the 2-D gridding of the data into isotopic maps.

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Figures

Figure 1

Age of lithological units and distribution of model ages in the Borborema Province A. Geological-age map of the Borborema Province, labels correspond to names of shear zones. B. Sm-Nd TDM age map of the Borborema Province and northern São Francisco Craton with magnetic first derivative image as background (see Fig. S1 for location data points). Note the Entremontes Promontory (labelled E), a part of the SFC separating two fold-and-thrust belts of the Southern Borborema Orogen. SP: Senador Pompeo shear zone; PA: Portalegre shear zone; PT: Patos shear zone; PE: Pernambuco shear zone; Boa Vista shear zone; SQ: Santa Quitéria arc; TP: Tróia-Pedra Branca terrane; NBB: Northern Borborema block; SC: São José do Campeste terrane; AM: Alto Moxotó terrane; E: Entremontes block; SBO: Southern Borborema Orogen; RP: Riacho do Pontal fold-and-thrust belt; SER: Sergipano fold-and-thrust belt; C: Cachoeirinha Belt, B: Seridó Belt. C. P-wave tomography model for the BP at 100 km depth³⁴ (Simões Neto et al., 2019) showing a markedly high velocity under the Alto Moxotó Terrane. D. Spatial distribution of zircon U-Pb crystallization ages of igneous and metaigneous rocks of the Borborema Province. E. Spatial distribution of $\epsilon Nd(t)$ values calculated for the time of crystallization shown in (D).

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Figure 2

Zircon U-Pb, Nd whole-rock data and crustal growth. A. Similarity of zircon U-Pb crystallization age distribution for the North São Francisco Craton, Benino-Nigerian Shield and Borborema Province (see Methods for explanations on data compilation). B. Zircon U-Pb crystallization ages for Neoproterozoic magmatism in the Borborema Province and their $\epsilon\text{Nd}(t)$ values and TDM (given by the colour of the circles). Data show increased involvement of old crust during the Brasiliano Orogen, as oceanic basins closed, and collision progressed (see Methods for data compilation). C. Continental growth for the Borborema Province using data from samples of igneous and metaigneous rocks (solid lines) and exposed area of igneous and metaigneous rocks based on pixel values from the maps in figures 1D and E (dashed lines). Colour of the lines represent cumulative U-Pb ages (red), $\epsilon\text{Nd}(t) < 0$ (black) and Nd model ages (green), binned for each 100 m.yr interval from 3400 to 500 Ma. Growth is estimated from the cumulative proportion of juvenile crustal addition using the $\epsilon\text{Nd}(t)$ cut-off value of zero from the igneous and metaigneous rock samples and gridded pixels for the crystalline igneous and metaigneous areas from the maps of figures 1D and E (see Methods).

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Figure 3

A. Sm-Nd TDM age map of the south Borborema Province and northern edge of the São Francisco Craton with magnetic first derivative image as background. Inset illustrates the dextral displacements of the 1 to 0.8 Ga and the older 2.8-2.0 Ga terrane across the Pernambuco shear zone, resulting from transcurrent tectonics. BV: Boa Vista shear zone; PE: Pernambuco shear zone; E: Entremontes Block; AF: Afeição domain; RP: Riacho do Pontal fold-and-thrust belt; AP: Alto Pajeú terrane; AM: Alto Moxotó terrane; SFC: São Francisco Craton. B. Block diagram illustrating the transpressive regime in the Entremontes Block with progressive displacement and increased deformation from the craton to the Entremontes Block and to the Alto Moxotó terrane across the Boa Vista (BV) and the Pernambuco (PE) shear zones. Note how the Tonian rocks follow the same pattern from the Afeição (AF) domain to the Alto Pajeú (AP) terrane. Together, they indicate a dextral displacement across the PE shear zone of at least 200 km.

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Figure 4

Neoproterozoic decratonization, transcurrent tectonics and terrane dispersion in NE Brazil. A. Overall extension of the São Francisco Craton/Benino-Nigerian Shield (SFC and BNS), following intrusion of intraplate Cariris Velhos granitoids (1000-920 Ma in orange) and leading to development of Tonian rift basins in restricted oceanic realms at 850-700 Ma (c.f. Sergipano Ocean recorded by the ca. 800 Ma Monte Orebe ophiolite²⁸ (blue star in C) and aulacogens such as the 900-500 Ma Paramirim. Inception of peripheral intraoceanic and transitional arcs in the west along the Goiás-Pharusian Ocean. The Gavião Block (GB) is the old Archean cratonic nucleus of the co-joined São Francisco Craton (SFC), Congo Craton (CC) and the Benino-Nigerian Shield (BNS). The Pernambuco-Alagoas terrane (PEAL) represents a continental ribbon of SFC rocks within the rift, that was extensively intruded by Brasiliano-age granitoids. Note the Entremontes (E) promontory on the paleomargin of the SFC. B. Subduction stage marked by intrusion of continental arc related granitoids such as the Santa Quitéria and Major Isidoro/Betania arcs in the western and southern Borborema Province, respectively. This panel also shows the Archean domains of Kanuda (K), Campo Grande (C) and Sao José do Campestre (SJ) and the Nigerian schist belts of the Benino-Nigerian Shield. C. Overall shortening of the interior basins (Tonian rift + Ediacaran orogenic-related basins) as a response to the oblique continental collision along the West Gondwana

Orogen (WGO) marked by ultra-high-pressure (UHP) metamorphism, and nucleation of the dextral Transbrasiliano-Kandi shear zone (TK)23,26 as a result of continental collision in the west. This stage is also marked by continental arc magmatism (630-600 Ma) in the Southern Borborema Orogen16 and shearing along the inactive Santa Quitéria arc17. D. Zooming on NE Brazil and NW Africa illustrating final shortening resulting in closure of rift basins and development of the Borborema transcurrent shear zone system as a consequence of the double cratonic indentation associated with continued convergence of the West African Craton against the greater São Francisco-Saharan paleocontinent in the west and a counterclockwise rotation of the São Francisco Craton in the south. Transpression deformed and dispersed terranes A-type sourced from the SFC within the Borborema Province. Transcurrent shear zones are associated with magmatism and crustal heating associated with delamination of the lithospheric mantle. Arrows and their size indicate direction and relative magnitude of the stresses, respectively. Shear zones: TK-Transbrasiliano-Kandi, PE-Pernambuco, PT: Patos, SP: Senador Pompeo, BV: Boa Vista. Disrupted Tonian and cratonic domains: Afeição (AF), Alto Pajeú (AP), Alto Moxotó (AM), Tróia (T), Granjeiro (G), Cristalândia do Piauí (PI). PM: Partial melting.

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