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## Review Article

# The Borborema Strike-Slip Shear Zone System (NE Brazil): Large-Scale Intracontinental Strain Localization in a Heterogeneous Plate

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Large-scale strike-slip faults are fundamental tectonic elements of the continental lithosphere. They constitute plate boundaries (continental transforms), separate terranes with contrasting geological histories within accretionary orogens, or accommodate heterogeneous deformation in intracontinental settings. In ancient orogens, where deeper levels of the crust are exposed, these faults are expressed as shear zones materialized by up to tens of km-wide mylonitic belts. The Borborema shear zone system in northeastern Brazil is one of the largest and best-exposed intracontinental strike-slip shear zone systems in the world, cropping out over 250,000 km<sup>2</sup>. Here, we review its main geophysical, structural, petrologic, and geochronologic characteristics and discuss the factors controlling its development. This complex continental scale shear zone system is composed of a set of NE- to NNE-trending dextral shear zones from which there are two major E-trending dextral shear zones with horse-tail terminations into the transpressional belt branch, as well as several smaller E-trending dextral and NE-trending dextral and sinistral shear zones. The major shear zones are marked by extensive linear or curvilinear magnetic gradients, implying their continuation at depth. The major shear zones are materialized by migmatite to amphibolite-facies mylonites, but the entire system shows evidence of late deformation at lower temperatures. The system developed during the late stages of the Neoproterozoic Brasiliano (Pan-African) orogeny (mainly from 590 to 560 Ma), postdating by more than 20 Ma the main stage of contractional deformation. Localization of strike-slip shearing in this intraplate setting was controlled by rheological contrasts between blocks with distinct Paleoproterozoic histories, the presence of preorogenic Neoproterozoic rifts, the craton geometry, and zones of enhanced magmatic activity, highlighting the importance of rheological heterogeneity in controlling shear zone nucleation and evolution.

## 1. Introduction

Large-scale strike-slip faults and shear zones are prominent features of many orogenic belts. The major ones are rooted in the lithospheric mantle, as supported by geophysical surveys, such as seismic and magnetotelluric anisotropy measurements (see [1] and the references therein). In some cases, these faults/shear zones juxtapose terranes with disparate geological evolution. Such faults may correspond to continental transform boundaries like the San Andreas Fault (e.g., [2]), which separates the North America Plate from the Pacific Plate; the Alpine Fault in New Zealand (e.g., [3]),

which separates the Pacific Plate from the Australia Plate; and the North Anatolian Fault (e.g., [4]), which separates the Eurasian Plate from the Anatolian Plate and connects the East Anatolian zone of convergence to the Hellenic Trench. Large-scale strike-slip faults also often overprint previous terrane boundaries, as the shear zones delimiting terrane boundaries in the North America Cordillera (e.g., [5]) and in the Tuareg Shield (e.g., [6] and the references therein). However, in many cases, large-scale strike-slip shear zones accommodate relative displacement of blocks that share similar geological characteristics, as exemplified by the shear zones in Central Asia (e.g., [7]). These intraplate

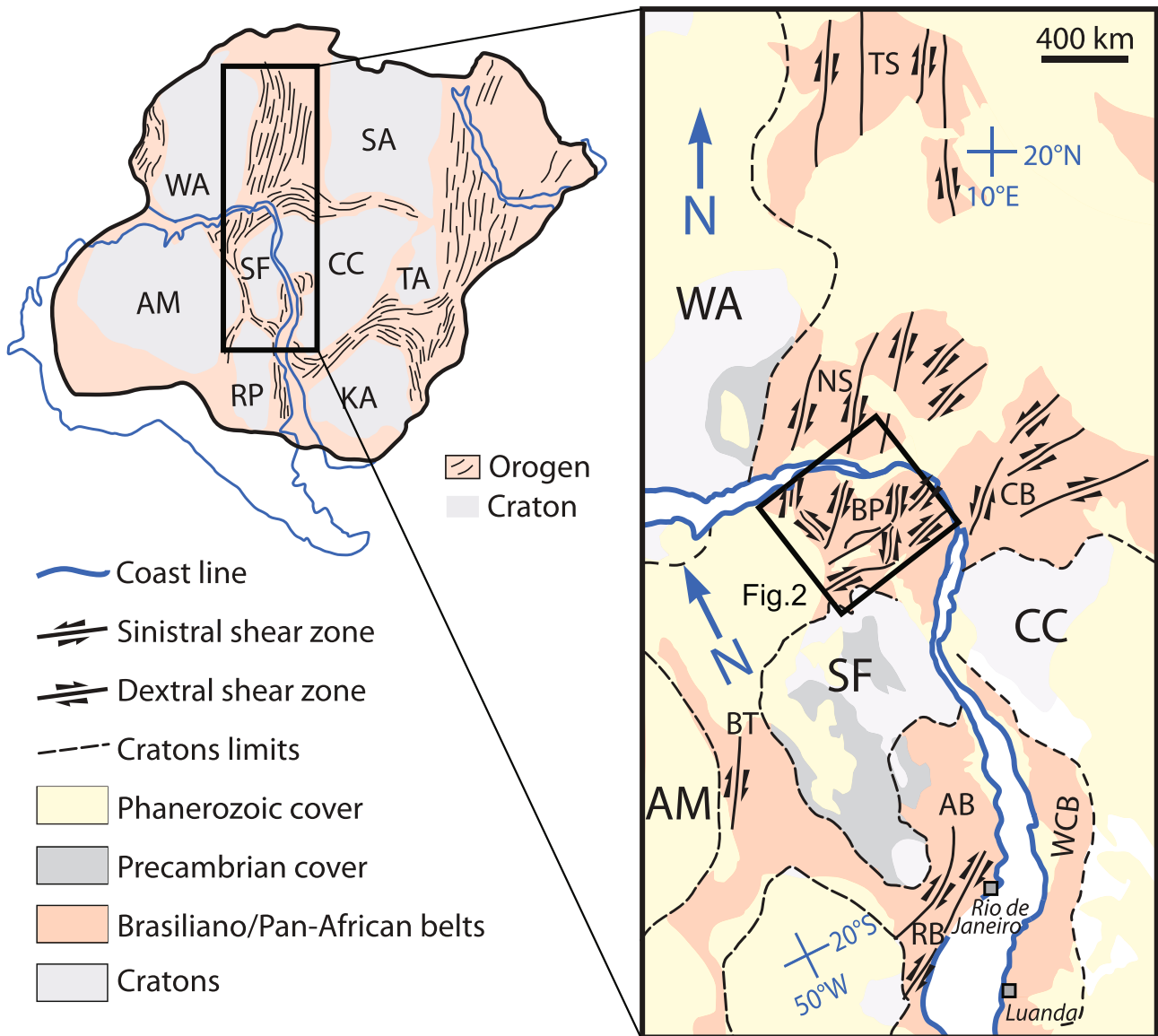


FIGURE 1: Schematic map of the West Gondwana continent after the Brasiliano-Pan-African orogeny, at ca. 500 Ma. Thin blue lines are the present-day contours of South America and Africa. Cratons—AM: Amazonian; CC: Congo; KA: Kalahari; RP: Rio de la Plata; SA: Sahara; SF: São Francisco; TA: Tanzania; WA: West Africa. Enlargement shows the main strike-slip shear zones in the Neoproterozoic belts—AB: Araçuaí; BP: Borborema; BT: Brasília-Tocantins; CB: Cameroon; NS: Nigeria; RB: Ribeira; TS: Tuareg; WCB: West Congo.

shear zones commonly develop following a period of crustal thickening related to continental collision and their location is strongly influenced or even determined by the presence of large-scale heterogeneities such as craton margins or aborted rifts within the original lithosphere. This is, for instance, the case of the Altyn Tagh fault in the Himalayas [8, 9], which separates the Tibetan Plateau from the Tarim Craton, the Além Paraíba shear zone in the Araçuaí belt (southeast Brazil), which records a shift from the orogen-normal to orogen-transverse tectonic flow linked to the southern termination of the São Francisco Craton [10, 11], and the Great Slave Lake shear zone in Canada, which accommodated the relative motion of the Slave Craton and the Churchill Province [12].

Numerous syn- to postcollisional, transcontinental-scale strike-slip shear zones developed during and following the assembly of West Gondwana during the Brasiliano/Pan-African orogeny (Figure 1). Along the Atlantic coast, tens to hundreds of kilometers-long shear zones run in an N-S to NE-SW orientation in the Araçuaí-Ribeira-Dom Feliciano orogenic system on the South American side (e.g., [11, 13, 14]) and in the Kaoko-Gariep system on the African side (e.g., [15]). Thousands of kilometers-long N-S striking shear zones extend between Nigeria and the Hoggar in NW Africa (e.g., [16]) and major NE-SW striking shear zones are present in Central Africa ([17] and the references therein).

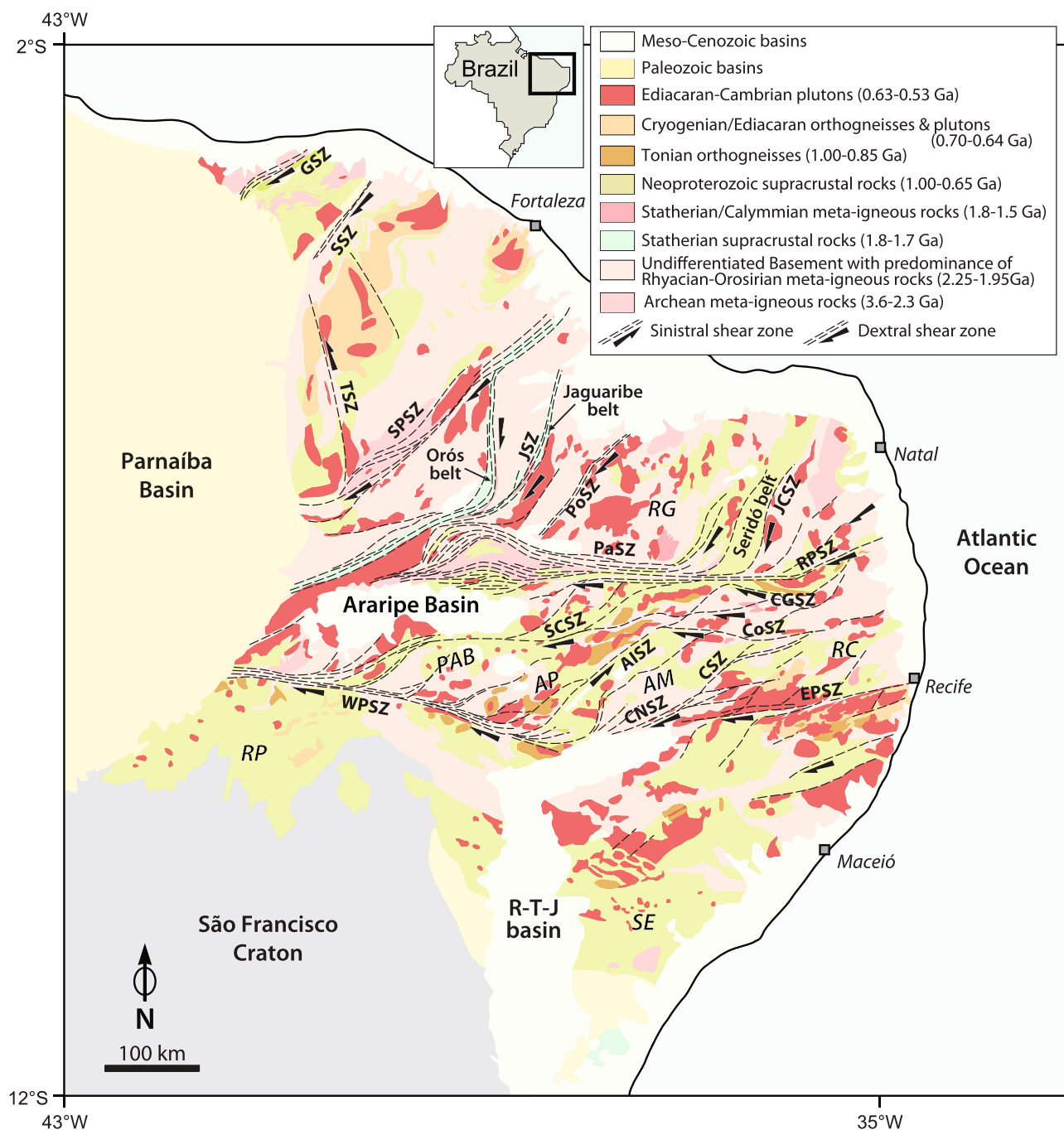


FIGURE 2: Simplified geological map of the Borborema province displaying the Borborema shear zone system (BSZS) and the alternation of metaigneous domains and metasedimentary belts of variable ages that characterizes the province. Main shear zones of the BSZS (black dashed lines): AISZ: Afogados da Ingazeira; CSZ: Congo; CNSZ: Cruzeiro do Nordeste; CoSZ: Coxixola; CGSZ: Campina Grande; EPSZ: East Pernambuco; GSZ: Granja; JSZ: Jaguaribe; JCSZ: Picuí-João Câmara; PaSZ: Patos; PoSZ: Portalegre; RPSZ: Remígio Pocinhos; SSZ: Sobral; SPSZ: Senador Pompeu; SCSZ: Serra do Caboclo; TSZ: Tauá; WPSZ: West Pernambuco. The Patos/Remígio-Pocinhos and West Pernambuco/East Pernambuco shear zones divide the province in three subprovinces: northern, central, and southern, which are further subdivided in domains, most of which are also delimited by shear zones of the BSZS. The domains cited in the text are as follows: AM: Alto Moxotó; AP: Alto Pajeú; PAB: Piancó-Alto Brígida; RC: Rio Capibaribe; RG: Rio Grande do Norte; RP: Riacho do Pontal; SE: Sergipano; R-T-J: Recôncavo-Tucano-Jatobá sedimentary basin.

Neoproterozoic to early Paleozoic strike-slip shear zones, hundreds of km long and up to 25 km wide, are particularly well exposed in NE Brazil, where they constitute the Borborema shear zone system (BSZS), which associates anastomosing

high-temperature (HT) strike-slip shear zones and transpressional belts ([18]; Figures 2 and 3). This complex shear zone system crops out over >250,000 km<sup>2</sup> between the Atlantic coast and the Parnaíba Basin to the west.

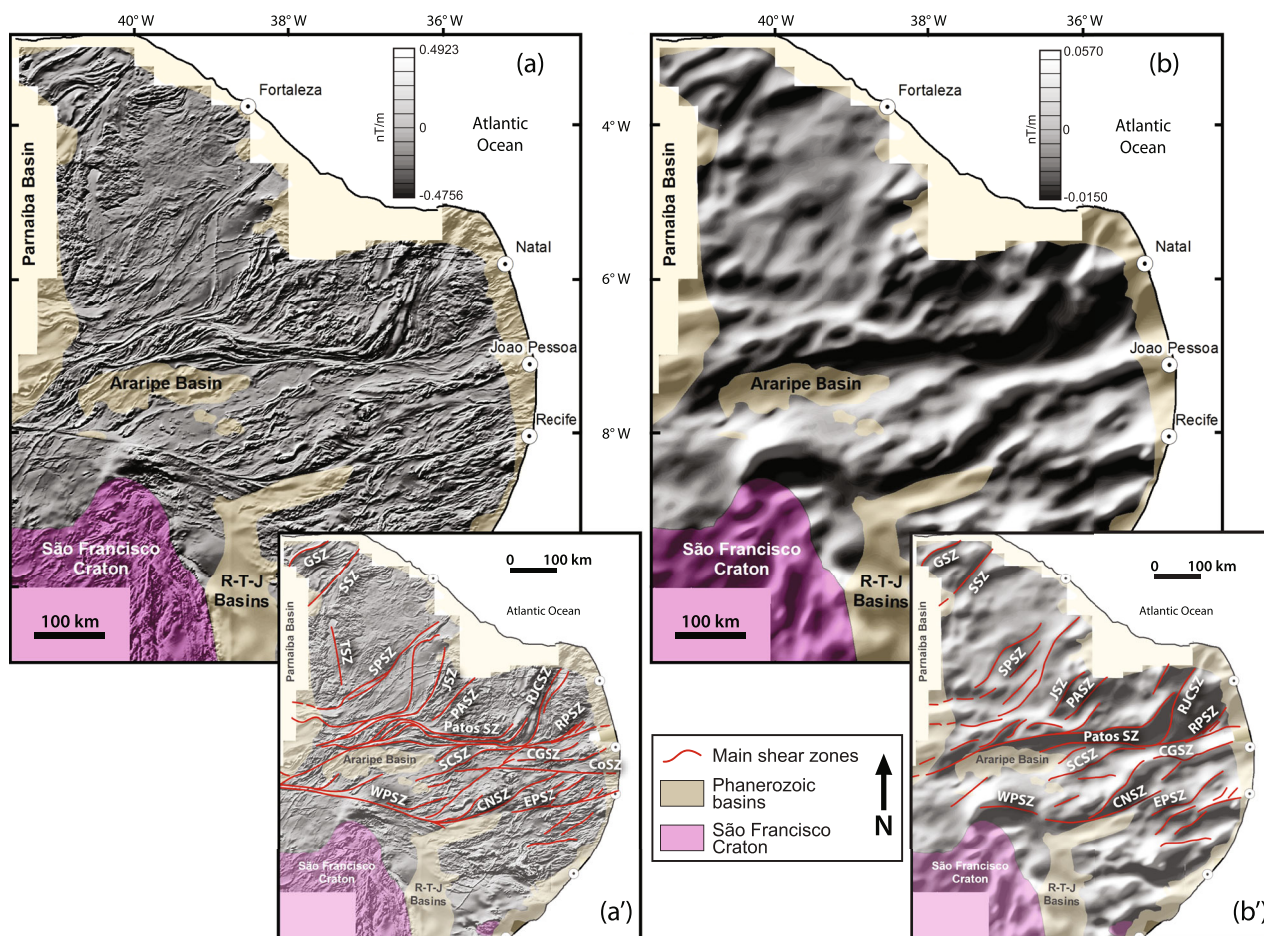


FIGURE 3: (a) First-order derivative map from the Borborema province upward continued to 1,000 m. (b) First-order vertical derivative map upward continued to 15,000 m. (a') and (b') shear zones that may be related to the major magnetic lineaments in (a) and (b). Abbreviations as in Figure 2.

Geophysical surveys suggest continuity of the main shear zones beneath the basin and their probable connection with the Transbrasiliano lineament, a major NNE-trending dextral shear zone that crosscuts a large part of the South American continent and has been correlated with the Kandi fault and the  $4^{\circ}50'$  shear zone in Africa (e.g., [19–21] and the references therein).

Since the definition of the BSZS more than 25 years ago [18], a large amount of data has been accumulated justifying a new synthesis. In addition to traditional field-based structural work, analytical and geophysical data, which were scarce or unavailable at that time, became increasingly abundant. These new data include (1) gamma ray spectrometry and magnetic surveys conducted by the Brazilian Geological Survey (CPRM) that cover the whole Borborema province, (2) regional gravimetric and magnetic data ([22] and the references therein), (3) seismic refraction [23] and magnetotelluric lines [24] as well as seismic tomography and anisotropy data [25, 26], which provide hints on the structures at depth, and (4) petrological and geochronological studies in several shear zones. The work aims at presenting a comprehensive overview of the literature related to the BSZS, reanalyzing aeromagnetic data to deduce the continuation at depth of

the shear zones, synthesizing structural, petrological, and isotopic data, and discussing the processes controlling the nucleation and development of intraplate shear zones.

## 2. Geological Setting

The Borborema province is a key region to understand the Neoproterozoic tectonic evolution of West Gondwana because of its location between the West Africa-Amazonian and São Francisco-Congo cratons (Figure 1). Recent overviews of its main geological features are provided by Caxito et al. [27] and Neves [28]. The Borborema province is classically divided into three subprovinces (Northern, Central, and Southern) separated by the dextral Patos and Pernambuco shear zone systems and further subdivided into several domains (Figures 2 and 3). These subdivisions record the alternation of metaigneous domains and metasedimentary belts of variable ages that characterize the province (Figure 2).

The metaigneous domains comprise scattered Archean blocks, but they are mainly composed of Paleoproterozoic (mostly 2.25–2.05 Ga old) orthogneisses and migmatites (Figure 2), considered to result from the amalgamation of

microcontinents and island arcs during a major accretionary/collisional episode terminated around 2 Ga ago (see [28] and the references therein). This great orogenic event was followed by an extended period (ca. 1 Ga) of tectonic stability. Igneous activity in the Neoproterozoic produced a ~50 km wide NE-trending belt of dominantly coarse-grained granites to granodiorites and subordinate volcanosedimentary sequences between 1000 and 920 Ma ([29–31] and the references therein) and more restricted episodes of intraplate magmatism at 900–850 Ma [32, 33] and 700–640 Ma [34, 35] in the central and southern subprovinces. Between 670 and 640 Ma, a large batholith, interpreted as a magmatic arc, was emplaced in the western part of the northern subprovince [36, 37]. Finally, in the late Neoproterozoic and Cambrian (640–530 Ma), the entire province was affected by extensive granitic magmatism; this event comprises abundant synkinematic magmatism in the BSZS (e.g., [38] and the references therein).

Metasedimentary belts, sometimes with a subordinate volcanic component, cover large areas of the Borborema province (Figure 2). Late Paleoproterozoic volcanosedimentary successions (ca. 1.7 Ga old) are present in the Northern subprovince [39]. A small fraction of the metasedimentary sequences in the central and southern subprovinces has early Tonian (1000–920 Ma) ages [31, 40]. However, most of the precursor sedimentary basins were formed in the mid/late Neoproterozoic (<800–700 Ma), with sedimentation ending just before or at the onset of the Brasiliano orogeny (e.g., [41–43]).

The Borborema province was extensively reworked and metamorphosed during the Neoproterozoic-early Paleozoic Brasiliano orogeny. The initial phase of this event, between 640 and 600 Ma, as determined by zircon U-Pb dating of orthogneisses and plutons with shallow dipping foliations and down-dip lineations, resulted in contractional deformation and metamorphism in the northwestern, central, and southern sectors of the Borborema province (see the review in [28]). In the northwestern Borborema province, nappe tectonics with NW to WNW tectonic transport are associated with extensive migmatization of metasedimentary sequences and mafic granulites and eclogites retrogressed to garnet amphibolites with equilibrium pressures > 1.2–1.4 GPa [44–48]. In most of the central/eastern sector of the central subprovince, W- to NW-directed tectonic transport is recorded by shallow dipping foliations associated with dominantly high-temperature (500°C–750°C), medium-pressure (500–900 MPa) metamorphism and intrusion of synorogenic plutons bearing flat-lying magmatic to solid-state foliation [49–54]. However, in the Piancó-Alto Brígida domain of the western portion of the central subprovince (Figure 2), the deformation is weaker, with local preservation of sedimentary structures, and occurred under low to moderate greenschist facies conditions [55]. The eastern part of the northern subprovince remained largely undeformed during the initial phases of the Brasiliano event. The available geochronological data indicate that deformation in the Seridó belt (Figure 2) started later than in other metasedimentary belts. Deformation in this belt is associated with U-Pb monazite ages between 626 and 500 Ma with a

cluster at 550–570 Ma in the west and 520–540 Ma in the east [56–60]. The southernmost part of the Borborema province—the Riacho do Pontal and Sergipano belts (Figure 2)—is characterized by a different kinematics during the Brasiliano orogeny, recorded by thrusts with tectonic transport towards the south onto the northern boundary of the São Francisco craton [32, 34].

Contrasting models were proposed to explain the first stage of the Brasiliano orogeny, ranging from amalgamation of continental magmatic arcs to intracontinental orogenic thickening (see [27, 38] for comprehensive overviews). However, an emerging consensus is that the BSZS developed after ca. 600 Ma in an intracontinental postcollisional setting [21, 27, 38, 51, 61].

At the end of the Brasiliano orogeny, reactivation of the BSZS controlled the formation of small Cambrian-Ordovician molassic basins in the northwestern Borborema province [62]. This late deformation was followed by a quiescence period marked by regional subsidence and formation of the Parnaíba Basin on the westernmost part of the BSZS (Figure 2). The depositional history of the Parnaíba Basin extends from the Silurian until the Cretaceous, over the westernmost part of the BSZS. Reactivation of the BSZS played again a key role in the Mesozoic during the continental rifting that led to the opening of the Atlantic Ocean, as indicated by the geometry of the Cretaceous sedimentary basins (e.g., Araripe, Jatobá, and Potiguar; Figure 2) [63].

### 3. Geometry and Kinematics of the BSZS

The BSZS has a complex geometry: it is composed of interconnected shear zones with dominantly NE-SW or E-W orientations and N-S to NE-SW transpressional belts (Figure 2). From west to east, the BSZS is composed by a set of NE- to NNE-trending dextral shear zones from which two major E-trending dextral shear zones branch. These E-trending shear zones have horse-tail terminations and branch into transpressional belts. In between and east of these two major E-trending dextral shear zones, the BSZS is characterized by minor E-trending dextral and NE-trending dominantly sinistral shear zones, which form a sigmoidal array with a dominant NE-trend (Figures 2 and 3). The main NE- and E-trending dextral shear zones (Sobral, Senador Pompeu, Patos, and West Pernambuco) are hundreds of kilometers long and up to 25 km wide, but their width varies along the length due to multiple branching secondary shear zones. The smaller shear zones are typically 1–2 km wide. Most sinistral shear zones have shorter lengths, but the WNW-trending Tauá and NE-trending Afogados da Ingazeira shear zones are >150 km long.

**3.1. Geophysical Characteristics.** The outcropping geometry of the BSZS may be compared with that inferred at depth from aeromagnetic data. The first-order vertical derivative of the total magnetic intensity (TMI) upward continued to 1,000 m (Figure 3(a); see Supplementary Material for methods description (available here)) is characterized by

strong and extensive magnetic gradients that define NE-SW- and ENE-WSW-trending linear to curvilinear magnetic zones (magnetic lineaments), as indicated in Figures 3(a) and 3(b). In the northern subprovince, these lineaments coincide with the major NE-SW and N-S-trending shear zones but the Senador Pompeu shear zone shows a weaker, more discontinuous magnetic gradient than the others (Figure 3(a)). The E-trending Patos and West Pernambuco shear zones are also delineated by major linear and curvilinear magnetic zones, whereas the smaller shear zones in-between and east of their termination are associated with an anastomosed network of sigmoidal magnetic gradients with a general NE trend.

The first-order vertical derivative of the total magnetic intensity (TMI) upward continued to 15,000 m (Figure 3(b); see Supplementary Material for methods description (available here)), which maps the structural framework into deeper levels of the crust [64], preserves the same anastomosed pattern of magnetic lineaments (Figure 3(b)). The strongest magnetic lineaments at depth are associated with the Granja and Sobral shear zones in the northwestern part of the BSZS and with the Patos, West Pernambuco, and associated branching shear zones. The westernmost part of the West Pernambuco shear zone shows, however, a much weaker magnetic signature at depth.

Despite its importance in the crust, continuation of the BSZS in the mantle is not clear. A NW-SE trending refraction profile across the Patos and East Pernambuco shear zones did not unravel any significant present-day variation in the Moho depth [23]. N-S-oriented magneto-telluric profiles show a resistive anomaly associated with the West Pernambuco shear zone, but no clear signal beneath the Patos shear zone [65]. Anisotropic receiver functions show consistent fast polarization directions in the crust and mantle beneath most of the Borborema province, with a predominance of NE to E-W fast polarization, but no systematic parallelism between individual measurements and the neighboring shear zones [26]. Teleseismic shear wave splitting shows a complex pattern [25]. NE fast polarization directions are observed beneath the Sobral shear zone, in the Seridó belt, and beneath the Remigio-Pocinhos shear zone. However, elsewhere, there is no clear relation between the orientation of the fast SKS polarization and the trend of the shear zones. Delay times are also extremely variable across the Borborema province, without any clear pattern.

**3.2. Kinematics and Metamorphic Conditions of Mylonitization.** Quantitative thermobarometric studies and measurement of quartz and feldspar crystallographic preferred orientations (CPO), which may be used to estimate synkinematic temperature conditions, have been conducted only in a few shear zones. Figure 4 displays the available  $P-T$  estimates for the metamorphism associated with the BSZS and for the metamorphism associated with shallowly dipping foliations recording the earlier stages of the Brazilian orogeny in the Borborema province. Temperature conditions during strike-slip shearing have mainly been assessed by the mesoscopic characteristics of the mylonites (e.g., intensity of grain size reduction), the occurrence (or not) of

syn-shearing anatexis, and thin section observations of the dominant deformation mechanisms and stable mineral assemblages during shearing. We classify shear zones as being of high-T type if the inferred temperature of mylonitization is  $>500$ – $550^{\circ}\text{C}$ , conditions under which feldspars may deform by dislocation creep and recrystallize by subgrain rotation or be subjected to syn-kinematic myrmekitization, quartz recrystallizes dominantly by grain boundary migration, not accompanied by prominent grain size reduction, and hornblende is stable. Still higher temperature conditions ( $>600^{\circ}\text{C}$ ) are recorded by lineations marked by sillimanite and evidence for synkinematic migmatitization, recorded by asymmetric sigmoidal partial melting lenses and melt collection in  $C'$  shear bands. Medium-grade conditions ( $400$ – $450^{\circ}\text{C}$  to  $500$ – $550^{\circ}\text{C}$ ) are recorded by ductile deformation of feldspar associated with quartz recrystallization by subgrain rotation leading to moderate grain size reduction. In low-T mylonites ( $300^{\circ}\text{C}$  to  $400$ – $450^{\circ}\text{C}$ ), feldspar has dominant brittle behavior and dynamic recrystallization of quartz resulting in major grain size reduction.

**3.2.1. Shear Zones from the Western Part of the Northern Subprovince (Ceará Domain).** The major NE-trending shear zones from the western part of the northern subprovince (Granja, Sobral, and Senador Pompeu) comprise HT mylonitic belts up to 15 km wide with dextral shear kinematic criteria (S-C fabrics, asymmetric porphyroclasts of K-feldspar, garnet, amphibole, and mica fish; Figure 5) [18, 46, 79, 80]. Dextral shear is also recorded by entrainment features observable at a map scale. In this section of the BSZS, solely the NNW-trending Tauá shear zone displays a sinistral sense of shear [81].

The Granja shear zone displays a curved trend, transitioning from NNE to ENE, which is similar to the trace of the thrusts in this region (Figure 2). This shear zone has indeed been interpreted as recording the reactivation in dextral strike-slip shearing of a previous thrust zone [79]. In contrast, the Sobral shear zone is characterized by a linear NE-trend; this straight pattern may nevertheless result from its reactivation to form the Cambrian-Ordovician Jaibara basin, which now covers most of the mylonitic belt (Figure 2). The Senador Pompeu shear zone displays a  $>300$  km long NE-trending segment, but it curves into an E-trending orientation at its southern termination, after branching with the sinistral Tauá shear zone ([80] (Figures 2 and 3). This E-trending segment has been, similarly to the Sobral shear zone, reactivated as a graben, hosting another Cambrian-Ordovician molassic basin (Figure 2).

In the Granja and Sobral shear zones, plastically deformed orthopyroxene and sillimanite in felsic granulites and symplectites of clinopyroxene and plagioclase crystallized between clinopyroxene and garnet along S-C surfaces in mafic granulites attest that transcurrent shearing started under granulite facies conditions ( $>c. 750^{\circ}\text{C}$ ) [18, 46, 48, 79]. In the Tauá and Senador Pompeu shear zones, stability of amphibole, quartz recrystallization by grain boundary migration, and feldspar recrystallization by subgrain rotation in gneissic and granitic mylonites indicate deformation under

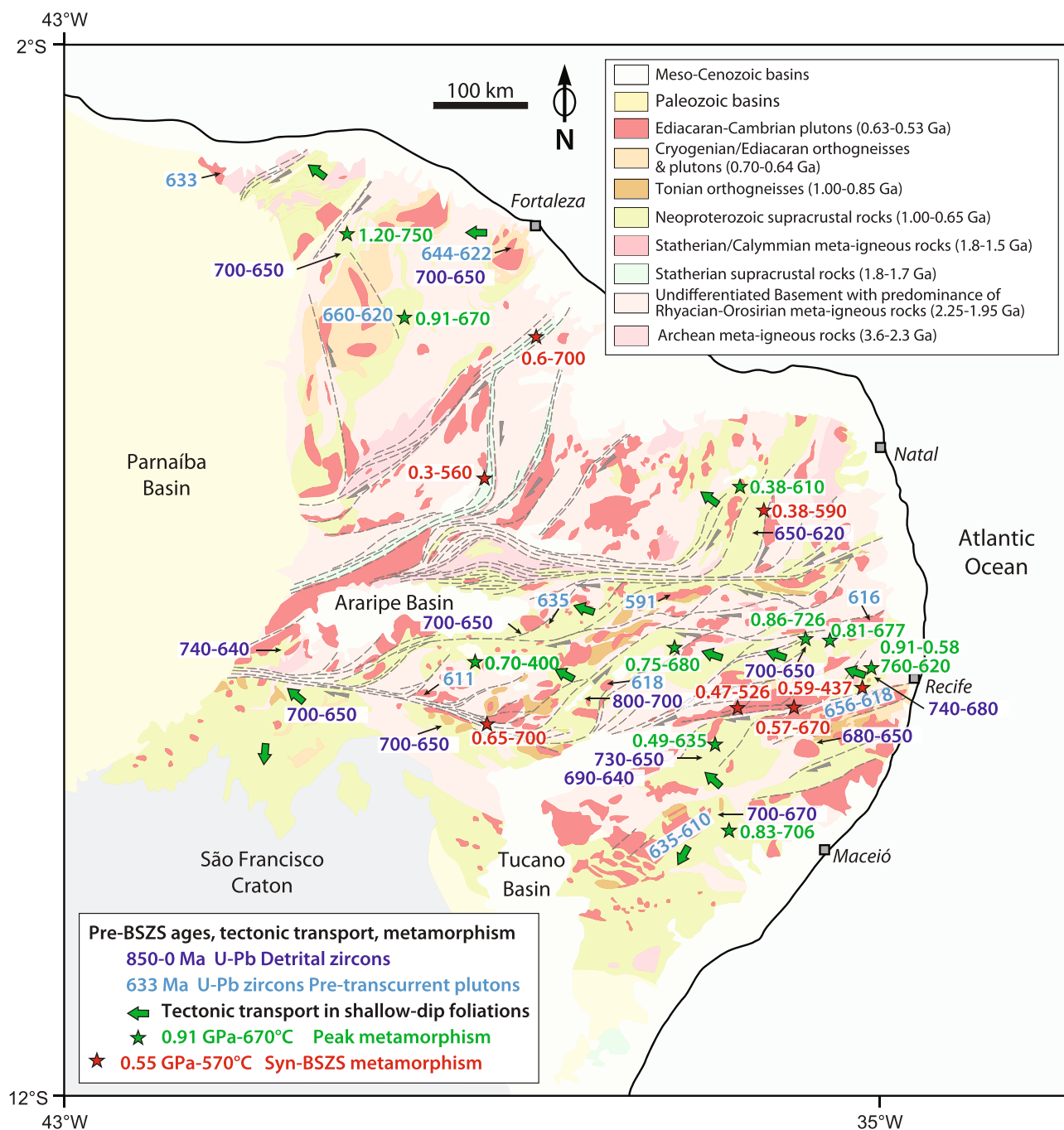


FIGURE 4: U-Pb ages of pretranscurrent plutons and of youngest detrital zircon fractions in metasedimentary units, kinematics, and  $P-T$  estimates associated with shallowly dipping foliations, and synkinematic  $P-T$  conditions in the BSZS. Pressures are indicated in GPa and temperatures in °C. U-Pb zircon ages of pretranscurrent plutons are from [35, 37, 66–70]. Detrital zircon ages are based on compilations by Neves [38] and Caxito et al. [71].  $P-T$  estimates are from [45, 48, 60, 72–77]. Transport directions are from [44, 46, 48, 50, 51, 54, 78].

amphibolite facies conditions [80, 81]. The Sobral shear zone was reworked at low temperature in a 1.5 km wide mylonitic belt and sinistrally reactivated under brittle/ductile conditions [83]. The Senador Pompeu and Tauá shear zones also show localized superimposition of low-temperature deformation.

East of the Senador Pompeu shear zone, the BSZS acquires a more complex geometry. It is characterized by several arcuate anastomosing shear zones that separate domains less or not affected by strike-slip shearing, forming

a duplex-like structure but with strike-slip kinematics [84]. The major E-trending dextral Patos shear zone (PaSZ) and several NE-trending dextral shear zones branch from the northern strand of the duplex. The NE-trending shear zones link the duplex to the N- to NNE-trending Orós and Jaguaribe metasedimentary belts, which record the inversion of Late Paleoproterozoic basins in dextral transpression [18, 56] (Figure 2). To the west, this structure continues as ENE-trending dextral shear zones partially covered by the

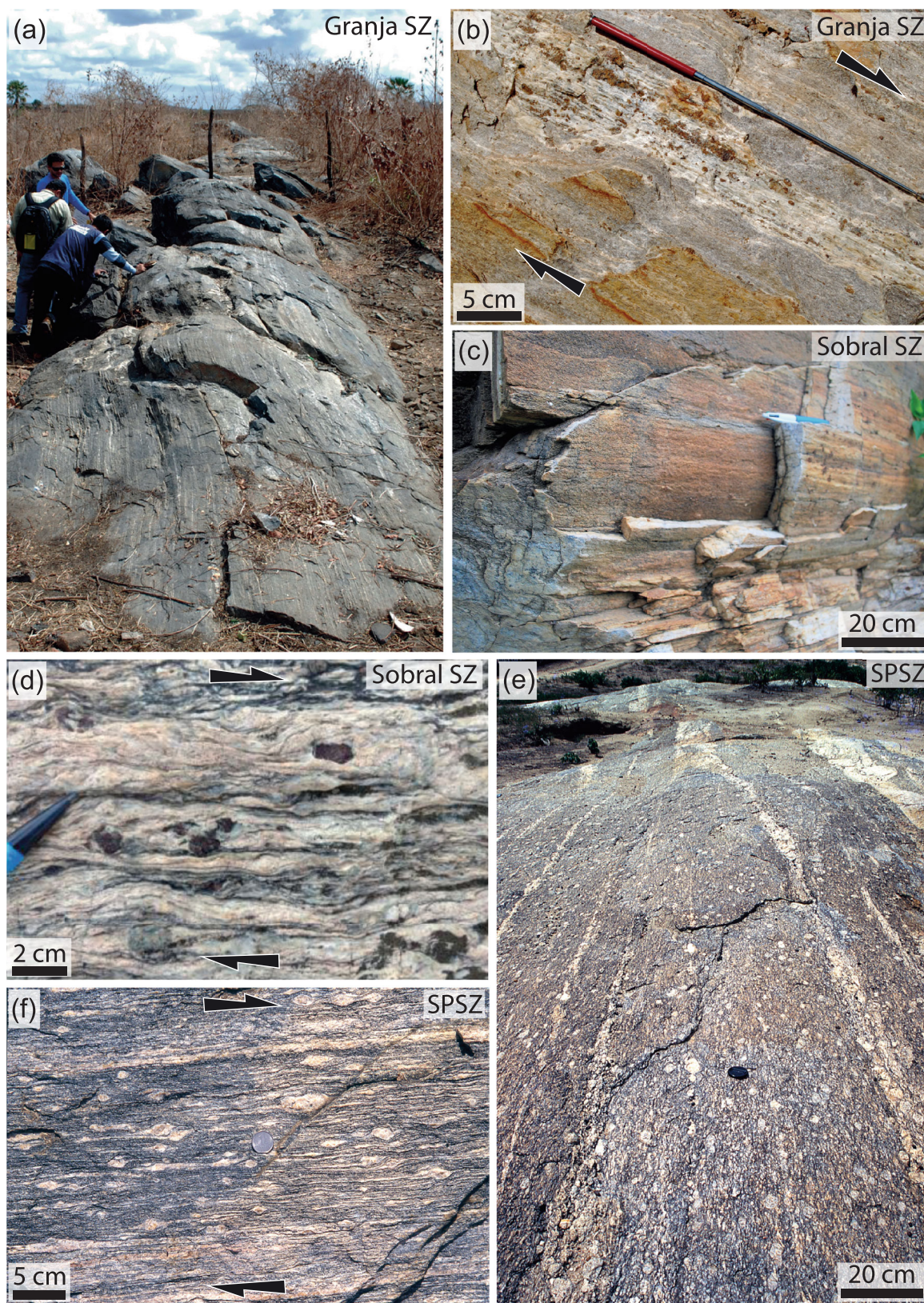


FIGURE 5: Field images of high-temperature mylonites in the dextral (a, b) Granja, (c, d) Sobral, and (e, f) Senador Pompeu shear zones. (a) Mylonite resulting from shearing of migmatized grey orthogneiss from the Paleoproterozoic basement. (b) Mylonitic kinzigite with syn-shearing anatexis. (c) Synkinematic granitic sheet with strong subhorizontal stretching lineation. (d) Mylonitic kinzigite, Sobral shear zone north of Cariré, CE from [82]. (e, f) Synkinematic porphyritic granite (Quixeramobim) intrusive in the Senador Pompeu shear zone, with strong solid-state (postcrystallization) deformation in (f). Photos (a–c) courtesy of P. Gorayeb.

Parnaíba basin. The northern termination of the Orós belt branches with the Senador Pompeu shear zone (Figure 2). Synkinematic metamorphic conditions increase along the strike of the Orós belt from greenschist to amphibolite (560°C, 0.3 GPa) to granulite facies in the northern part of the belt (700°C, 0.6 GPa; [56]). The southern strand of the duplex borders the Araripe Basin and the magnetic fabrics hint for its continuation beneath the western part of the basin (Figure 3).

**3.2.2. Patos Shear Zone System.** East of the duplex, the 150 km-long Patos shear zone (PaSZ) consists of an E-trending mylonitic belt up to 25 km wide from which a few NE-trending dextral shear zones branch off, forming horsetail-like structures (Figures 2, 3, and 6). The PaSZ is essentially composed of migmatites and HT coarse-grained mylonites (650–700°C) with subvertical mylonitic foliations bearing subhorizontal mineral stretching lineations and common dextral shear criteria (Figures 6(d) and 6(e)) [18]. The mylonites are mainly derived from orthogneisses. Mylonitic metasedimentary rocks are more common in the eastern part of the PaSZ where quartzites, metapelites, and amphibolites from the Seridó belt, interlayered with anatectic leucogranites, have been sheared into the PaSZ (Figure 6(c)).

The northern boundary of the PaSZ is marked by a sharp rotation of the dominantly NNE-trending foliation of the orthogneisses of the Rio Grande do Norte domain into parallelism with the mylonitic foliation (Figures 2 and 6(c)). The southern limit of the PaSZ is defined by a narrow (<1 km wide) low-temperature (LT) mylonitic belt, which reworked the HT mylonites [18, 85] (Figures 6(c), 6(f), and 6(h)). Dextral shear criteria in the low-temperature mylonites support a similar kinematics for the successive episodes of shearing that affected the PaSZ. The NE-trending dextral shear zones that branch off from the central section of the PaSZ display evidence of deformation under amphibolite or greenschist facies conditions. Microstructures and thermodynamic conditions estimated for granitoids deformed in the Portalegre shear zone, the most important of these NE-trending shear zones, suggest that the main deformation in the outcropping section occurred at 350–450°C [78].

The eastern termination of the PaSZ displays a complex geometry. The mylonitic foliation curves, forming a horsetail structure that connects the shear zone with the dextral transpressional deformation of the NE-trending Seridó Belt [18, 58, 86–88]. The connection between the two structures is clearly recorded by anatexites delimited by metasedimentary formations in the southern Seridó belt, which are dragged over several km into the PaSZ, with clear boudinage of the stiffer layers (quartzites). The transpressional nature of the deformation in the Seridó belt is attested by the association of dextral NE-trending shear zones with shallowly plunging lineations and isoclinal folds with NE-trending axial planes.

Only the narrow, LT mylonitic belt that reworks the southern limit of the PaSZ continues east of the Seridó belt towards a network of HT ENE-trending shear zones, collectively called the Remígio-Pocinhos shear zone [89, 90]

(Figures 2 and 6). South of it, the similar E-trending, but more arcuate, Campina Grande dextral HT shear zone forms an extensional relay with the PaSZ, curving towards a NE-SW direction and connecting with NE-trending shear zones of the central subprovince south of the Seridó belt [18, 66] (Figures 2 and 3). The magnetic gradient at depth associated with this shear zone is, however, less marked than that of the PaSZ (Figure 3(b)).

Extensive synkinematic partial melting characterizes the central portion of the PaSZ. Orthogneisses unaffected or slightly affected by partial melting show dynamic recrystallization of feldspars, chessboard extinction in large quartz grains, lobate contacts between quartz grains, abundant synkinematic myrmekite, and activation of the prism  $\langle a \rangle$  slip system in quartz and of the (0 1 0)[0 0 1] and (0 1 0)[1 0 0] slip systems in plagioclase [18, 84, 85, 91]. These features attest for deformation in the PaSZ at temperatures near to or above the granite solidus. In contrast, the southern margin of the central portion of the shear zone and its narrow eastern extension that connects with the Remígio-Pocinhos shear zone comprise fine-grained low-T mylonites and ultramylonites containing fractured K-feldspar porphyroclasts [18, 85, 87].

In the Picuí-João Câmara shear zone, which delimits the eastern border of the Seridó belt,  $P$ – $T$  estimates of 0.38 GPa and 590°C in mylonitic mica schists attest for deformation under upper amphibolite facies conditions but the presence of synkinematic sillimanite in the central part of the Seridó belt [60] implies even higher syn-transpressional  $P$ – $T$  conditions (up to 650°C and 0.5 GPa). In the southern branch of the Remígio-Pocinhos shear zone, metapelites, marbles, and orthogneisses also record deformation under upper amphibolite and even granulite facies conditions (e.g., cordierite + garnet + prismatic sillimanite + mesoperthitic K – feldspar in metapelites), coeval with extensive migmatization [89]. In contrast, the northern branch of this shear zone comprises mylonitized metapelites with stable staurolite-andaluzite assemblages, indicative of shearing deformation under lower amphibolite facies conditions.

**3.2.3. Pernambuco Shear Zone System.** The Pernambuco shear zone system (previously called Pernambuco lineament) was initially interpreted as a continuous 700 km-long shear zone (see [92] and the references therein) and is still shown in this way in several recent regional maps. However, more detailed works show that it is composed of two distinct, nonconnected segments: the up to ten km wide ESE-trending HT West Pernambuco shear zone (WPSZ) [93] and the narrower ENE-trending East Pernambuco shear zone (EPSZ) [94] (Figure 3).

The WPSZ has striking similarities with the PaSZ: the large dimensions, dextral motion, deformation under anatexis conditions, and eastward termination in a transpressional horsetail structure (Figures 7 and 8). However, the WPSZ is thinner (<10 km) and generates weaker linear magnetic gradients, particularly at depth (Figures 3(a) and 3(b)). Horse-tail structures are observed along the entire WPSZ (Figure 2). Radiometric mapping (Figure 7) highlights that, similarly to the PaSZ, the northern boundary of the WPSZ

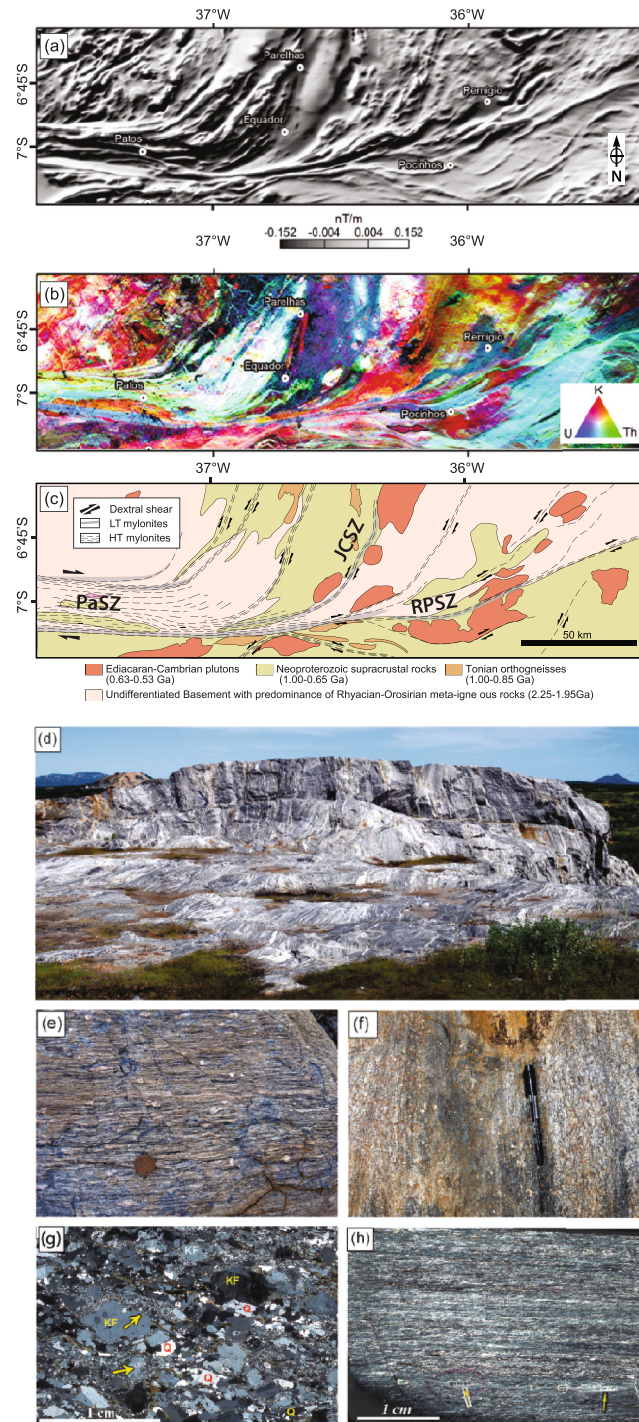


FIGURE 6: Central/eastern Patos (PaSZ), Remígio-Pocinhos (RPSZ), and Picuí-João Câmara (PJCSZ) shear zones. (a) First-order vertical derivative upward continued to 1,000 m. (b) RGB composite image of K, Th, and U. (c) Simplified geological map. (d–f) Representative field photographs of (d, e) HT synkinematic migmatitic mylonites and (f) LT mylonites of the PaSZ. (d) Anatectic domain characterized by interlayered leucogranites, partially melted metasedimentary rocks, and lenses of amphibolite, all of them showing a steeply dipping to vertical foliation (either magmatic or solid state). The width of the picture is ~50 m. (e)  $\sigma$ - and  $\delta$ -type porphyroclasts indicating dextral shear. The coin diameter is 2 cm. (f) Low-temperature mylonites to ultramylonites (darkest zone) from the southern boundary of the PaSZ supporting reactivation of the PaSZ during cooling. (g) Photomicrograph of HT mylonite displaying K-feldspar (KF) grains partially replaced by syn-kinematic myrmekite (yellow arrows); shearing of the myrmekites produces the quartz-plagioclase fine-grained matrix that composes most of the rock. Quartz (Q) is coarse grained, showing evidence for grain boundary migration and a tendency to form “platten-quartz” in ribbons. (h) Photomicrograph of LT mylonite. The fine-grained quartzofeldspathic matrix contains elongated, fractured, and partially retrogressed large crystals of sillimanite (yellow arrows) inherited from the original high-temperature mylonitization. Muscovite crystallized in the pressure shadows and fractures of the sillimanite crystals.

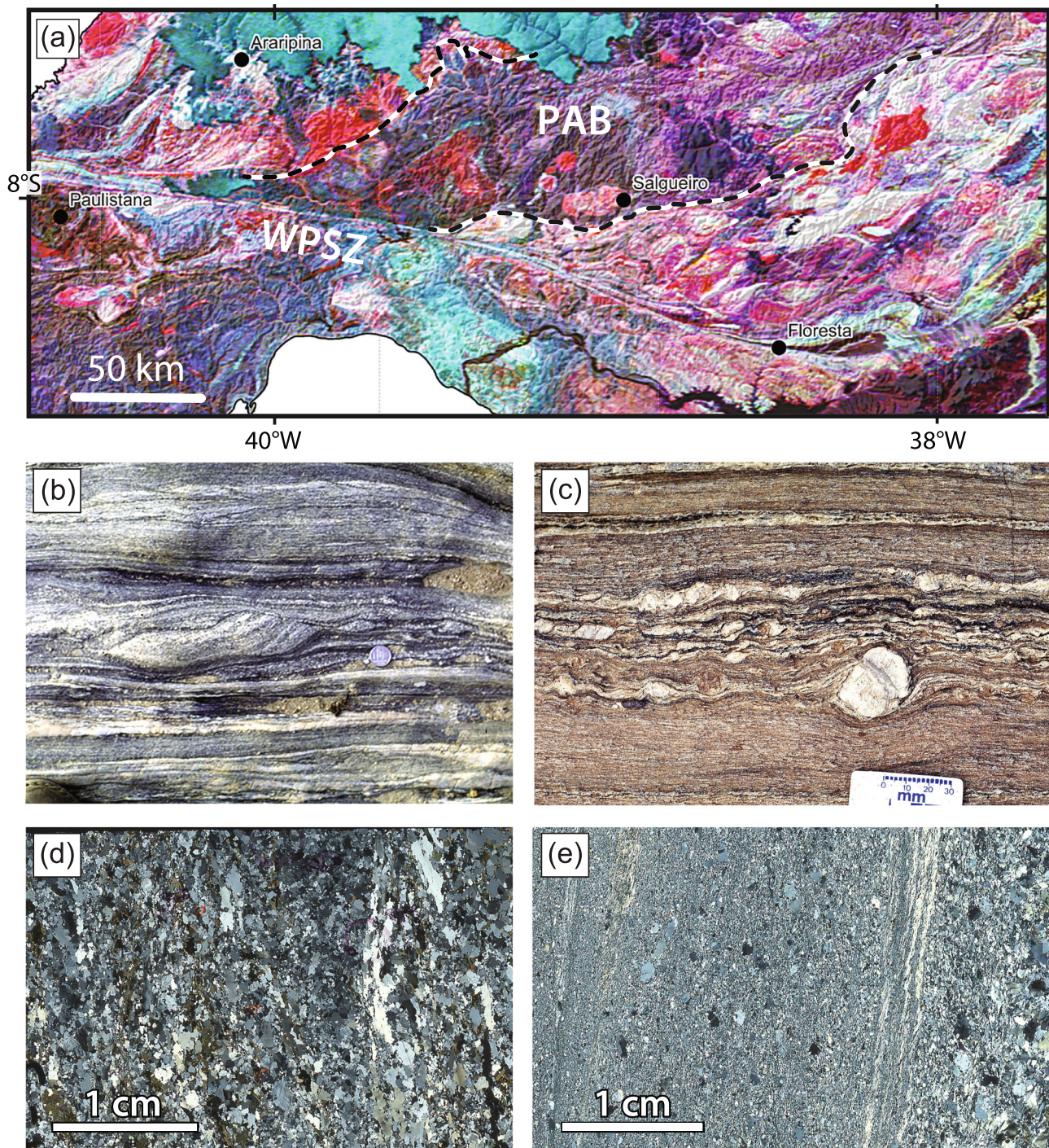


FIGURE 7: (a) Radiometric RGB composed image of K, Th, and U of the central and eastern section the West Pernambuco shear zone (WPSZ). On both sides of the Pianco-Alto Brigida (PAB) domain, the southern tips of the units that compose the central subprovince are dragged into the shear zone. The drag structures are less developed and the WPSZ is significantly narrower along the southern limit of the PAB. (b, c) Representative field photographs of HT mylonites. (b) Asymmetric boudins indicating a dextral sense of shear. Layers of anatectic granite parallel to the foliation support syn-kinematic partial melting. The coin diameter is 2 cm. (c)  $\sigma$ - and  $\delta$ -type K-feldspar porphyroclasts indicating dextral shear in a mylonitic paragneiss. (d, e) Photomicrographs of (d) HT and (e) LT mylonites. (d) Amphibolite facies quartz-feldspathic mylonite. Quartz crystals form ribbons up to 1 mm long, which contain small inclusions of biotite and K-feldspar elongated parallel to the foliation, pointing to effective synkinematic grain growth through grain boundary migration. (e) Thin section showing the reworking of an originally coarse-grained HT mylonite (at the right) to form a LT mylonite composed by a quartz-feldspathic fine-grained matrix, small K-feldspar porphyroclasts, and thin quartz ribbons.

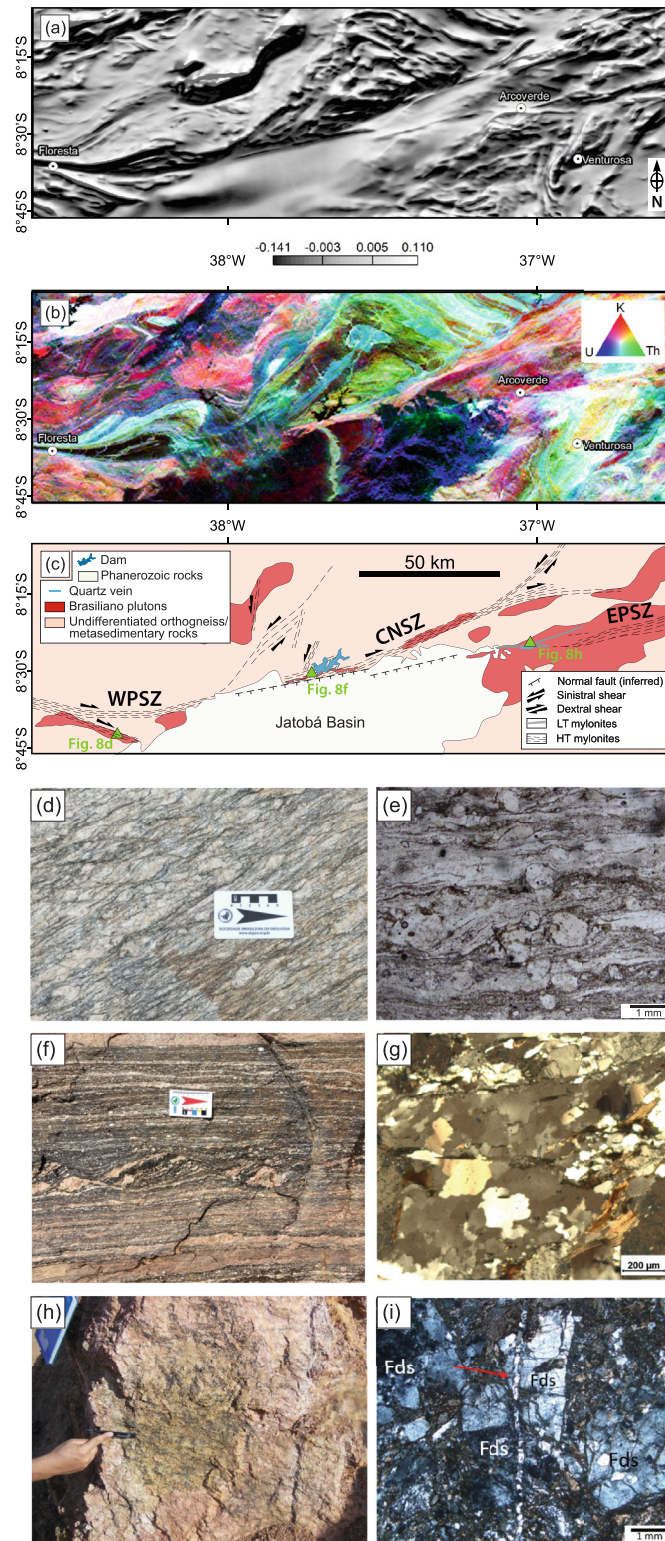


FIGURE 8: Eastern sector of the West Pernambuco (WPSZ), Cruzeiro do Nordeste (CNSZ), and western sector of the East Pernambuco (EPSZ) shear zones. (a) First-order vertical derivative upward continued to 1,000 m. (b) RGB composite image of K, Th, and U. (c) Simplified geological map. Stars show the location of field photographs (d–i) illustrating kinematic criteria (d, f, h) and microstructural features (d, e, i) in mylonites from the WPSZ (d, e), the CNSZ (f, g), and the western sector of the EPSZ (h, i). (d, e) S-C fabric at mesoscopic and microscopic (plane-polarized light photomicrograph) scales indicating dextral shear. (f) Asymmetric boudins in mylonitic banded gneiss. (g) Large quartz ribbons displaying recrystallization by grain boundary migration (crosspolarized light photomicrograph). (h) Cataclasite with steps indicating dextral shear and (i) extensive fracturing of feldspar (Fds) (crosspolarized light photomicrograph).

is characterized by a sharp rotation of the NE-trending fabric of the central subprovince, which is dragged and stretched into the WPSZ. The exception to this behavior is the section of the WPSZ south of the Piancó-Alto Brigida late Neoproterozoic metasedimentary belt (PAB) (Figure 7); there, the WPSZ is thinner and shows no horsetail departures. The PAB, which displays a contrasted radiometric signature relative to the surrounding domains (Figure 7), underwent LT metamorphism and moderate deformation during the Brasiliano event [55]. Its metasedimentary units are, however, deformed in a few NE- to ENE-trending shear zones, such as the dextral ENE-trending Serra do Caboclo shear zone that delimits its eastern border and the NE-trending sinistral Boqueirão dos Cochos shear zone in the west, and the Patos shear zone in the north [55]. The sediments of the Parnaíba Basin cover the westernmost section of the WPSZ but analysis of aeromagnetic data suggests that it connects to a NE-trending magnetic lineament running along the NW margin of the São Francisco craton.

The horsetail-like eastern termination of the WPSZ was first described based on field work, aerial photographs, and Landsat images [18, 93]. This structure, which is delimited by the NE-trending sinistral Afogados da Ingazeira and dextral Cruzeiro do Nordeste shear zones (Figure 8), defines a domain deformed in transpression, with shortening accommodated by macroscopic folds [95–97] (Figure 8). Although the easternmost section of the HT WPSZ is covered by sedimentary rocks of the Jatobá Basin, geophysical images support that it progressively curves to an ENE trend and connects with the dextral Cruzeiro do Nordeste shear zone, not with the E-trending East Pernambuco shear zone (Figures 2 and 8). As in the PaSZ, only the LT mylonites that rework the southern border of the WPSZ maintain an ESE trending. In this branch, HT mylonites are solely observed within a synkinematic pluton.

Mylonitization under high-temperature conditions in the WPSZ is supported by partial melting and growth of synkinematic prismatic sillimanite in metasedimentary rocks [18, 93]. Preliminary  $P$ – $T$  estimates suggest metamorphic conditions around 700°C and 600–700 MPa [18]. In the Cruzeiro do Nordeste shear zone, Miranda et al. [97], based on microstructural observations, documented a continuous transition from high- to low-temperature ductile fabrics, followed by the development of conjugate brittle-ductile faults.

The EPSZ shows marked variations in deformation conditions along its length and can be divided into two structural domains [94] (Figure 9). In the western sector, high-temperature mylonitization occurred along the southern margin of a large granitic batholith, where the granitoids were converted to typical coarse-grained S-C mylonites indicating dextral shear (Figures 9(d)–9(f)). The mylonitic belt attains its maximum width (c. 4 km) in the central portion of the batholith [94] and decreases steadily westward, fading away before reaching the Jatobá Basin (Figure 8). A sample of mylonitized sillimanite-bearing schist yielded  $P$ – $T$  conditions of 575 MPa and 670°C [72]. These values are somewhat higher than the pressure of  $475 \pm 25$  MPa and

temperature of  $526 \pm 9^\circ\text{C}$  estimated by Castellan et al. [73] through thermodynamic modelling of a granitic mylonite. In the eastern sector, the mylonitic belt is 1–2 km wide, affecting dominantly granitic plutons, and occurred at low temperature, producing fine-grained mylonites and ultramylonites [35, 72, 73]. These are characterized by retrogression of hornblende to actinolite and epidote in mafic/intermediate protoliths and, in all protolith types, by recrystallization leading to grain size reduction in quartz and fracturing of feldspars [94] (Figures 9(g)–9(i)). EBSD analysis of a granitic mylonite shows dominance of activity of the basal  $\langle a \rangle$  slip system in quartz, and thermodynamic modelling yielded  $P$ – $T$  conditions of  $590 \pm 100$  MPa and  $437 \pm 17^\circ\text{C}$  [73].

**3.2.4. Shear Zones in the Central Subprovince.** The central subprovince and the northeastern sector of the southern subprovince, i.e., the domain between and to the east of PaSZ and WPSZ, contain numerous anastomosed shear zones with orientations varying from ESE to NNE and a dominant NE trend, which form a sigmoidal pattern mimicking a S-C pattern at the regional scale (Figure 3). However, most NNE- to NE-trending shear zones are sinistral, not dextral (Figures 2, 8, and 9). Only a few, like the Serra do Caboclo shear zone [54], at the eastern boundary of the PAB metasedimentary belt, are dextral. E- to ENE-trending shear zones are dextral. These shear zones are usually <100 km long and <1–2 km wide. The dextral Coxixola shear zone [98–100] and the sinistral Afogados da Ingazeira shear zone [101] are longer (>250 km) but have sinuous trends. The NE-trending shear zones are curved and usually merge with the dextral E-trending shear zones. They often display evidence for a transpressional regime [52]. In general, there is no noticeable offset at the junction between NE- and E-trending shear zones, indicating that they are broadly contemporaneous. However, the NE-trending Afogados da Ingazeira and Serra do Caboclo shear zones show a small offset (c. 5 km) by the dextral E-trending Coxixola shear zone (Figure 3).

Amongst the sinistral shear zones, evidence of synkinematic partial melting is only reported for the Igaraci shear zone, a small shear zone located close to the eastern border of the Araripe Basin [102]. In the Afogados da Ingazeira shear zone and in the Fazenda Nova shear zone (a 40 km long shear zone that merges with the EPSZ; Figure 9), feldspar recrystallization by subgrain rotation and activation of prismatic and basal  $\langle a \rangle$  slip in quartz suggest that deformation started at temperatures above c. 550°C and later declined to low-amphibolite/upper-greenschist facies conditions (c. 450°C) [97, 101, 103]. Even lower temperature conditions (low-greenschist facies conditions) accompanied deformation in most shear zones within the PAB metasedimentary belt [55].

## 4. Timing

The timing of strike-slip activity has been determined through U-Pb dating of zircon from syn-shear leucosomes and of zircon and monazite grains inferred to have grown during shear deformation, by lower intercept ages

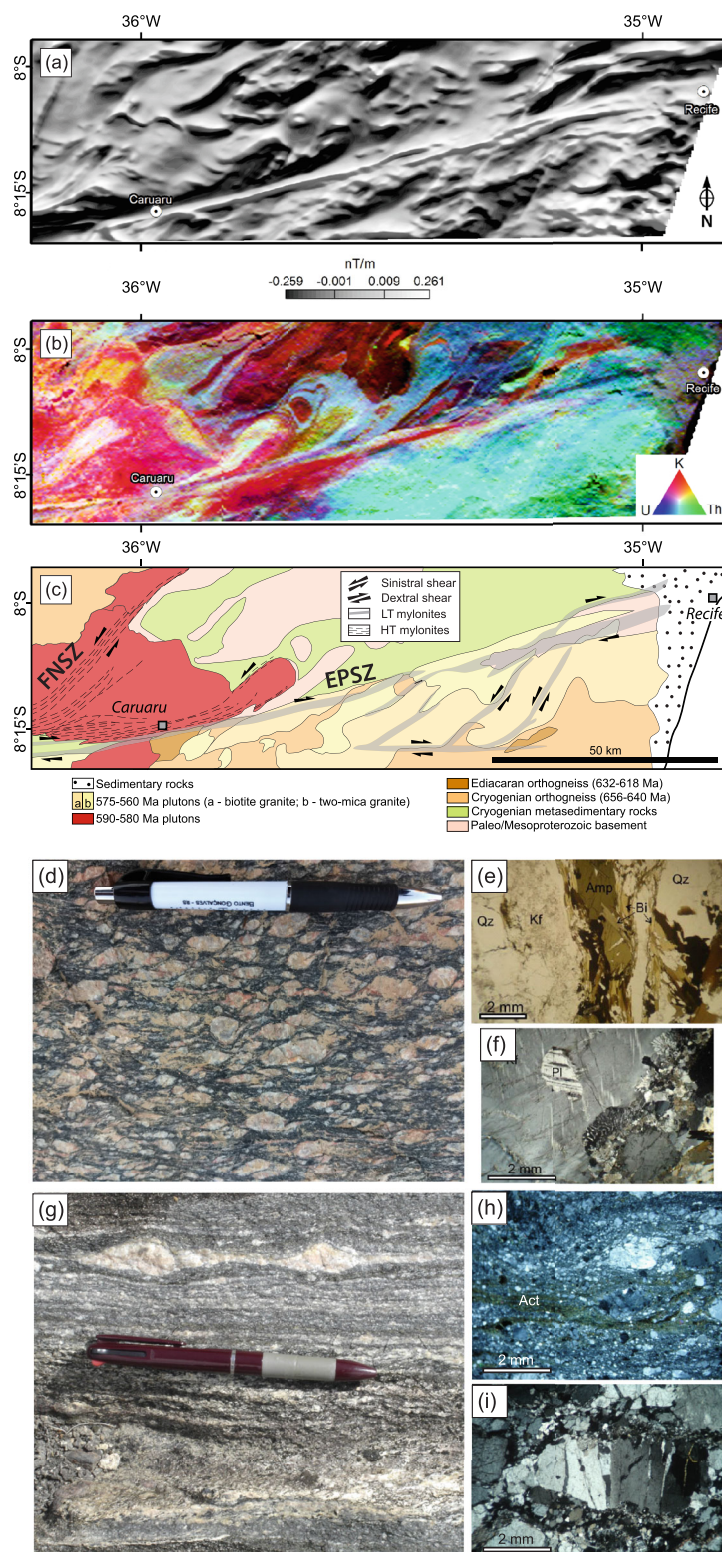


FIGURE 9: Central/eastern sector of the East Pernambuco shear zone (EPSZ) and the connection of the HT mylonites with the sinistral Fazenda Nova shear zone (FNSZ). (a) First-order vertical derivative upward continued to 1,000 m. (b) RGB composite image of K, Th, and U. (c) Simplified geological map. (d–i). Field and microstructural aspects of (d–f) HT and (g–i) LT mylonites. (d) S-C fabric in coarse-grained granitic mylonite indicating dextral shear. (e, f) HT mylonitic microstructures characterized by (e) the stability of hornblende (plane polarized light) and (f) abundant myrmekite around K-feldspar porphyroclast (crossed polarized light). Amp: amphibole; Bi: biotite; Kf: K-feldspar; Pl: plagioclase; Qz: quartz. The photographs representative of high-T (left) and low-T (right) mylonites. (g) Ultramylonite with quartz-feldspathic asymmetric boudins indicating dextral shear. (h, i) LT mylonitic microstructures in crosspolarized light characterized by (h) development of fibrous actinolite (Act) and (i) fracturing of feldspar porphyroclast.

in concordia diagrams from mylonitized metamorphic rocks and, indirectly, by dating of synkinematic plutons (Figure 10(a)). These plutons are elongated with their long axes parallel to the nearby shear zones or have en cornue shapes. Several have been studied through field and anisotropy of magnetic susceptibility mapping [51, 66, 72, 80, 87, 102, 104–106]. They have magmatic/magnetic foliation parallel to mylonitic foliation in the host rock and shallowly plunging magnetic lineation, indicating syn-shear intrusion and progressive fabric development during cooling and crystallization. In contrast, pretranscurrent plutons (Figure 4) have fabrics inconsistent with the kinematics of strike-slip shear zones and are partly deformed in the solid state, displaying gently dipping foliations. Cooling ages and rates have been assessed by combining U-Pb ages with  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  dating of amphibole, biotite, and muscovite. Figure 10(b) summarizes the available geochronological data.

**4.1. U-Pb Geochronology.** The Granja shear zone bounds the southeastern border of a prekinematic granite, which was emplaced at ca. 633 Ma (U-Pb zircon age; [107]) and deformed in strike-slip shearing at ca. 591 Ma (U-Pb monazite age; [46]). The last stages of strike-slip deformation occurred at ca. 563 Ma, the age of a small late kinematic pluton (U-Pb zircon age; [46]).

Synkinematic plutons associated with the Tauá and Senador Pompeu shear zones yielded U-Pb zircon crystallization ages of ca. 585 Ma [80, 108]. Near the junction of the two shear zones, U-Pb ages of 576 and 571 Ma of plutons unaffected or only slightly affected by shearing indicate emplacement during the waning stages of shear zone development [104].

Average crystallization ages of zircon rims from leucosomes of melt-bearing mylonites and of synkinematic plutons from the middle portion of the PaSZ suggest an interval of 566–558 Ma for the high-grade syn-shear metamorphism [85, 109]. Slightly older average ages of 575–573 Ma were obtained in zircon overgrowths and lower intercept ages in migmatites at the junction of the PaSZ with the Seridó belt [58]. These latter ages are similar to U-Pb ages of granitic plutons from the Seridó belt interpreted as coeval with strike-slip shearing [58, 110].

In the Remígio-Pocinhos shear zone, a syntectonic granitic pluton was dated at 588–566 Ma [111, 112] and U-Pb monazite ages from leucosomes range from 563 to 555 Ma [60]. U-Pb dating of monazite grains from the Picuí-João Câmara shear zone yielded dominantly younger ages of 530–525 Ma [60].

The timing of shear zone activity in the central section of the EPSZ is constrained by conventional U-Pb and evaporation Pb-Pb ages (591–587 Ma) of a large syntectonic batholith [113, 114] and by a U-Pb monazite age ( $591 \pm 4$  Ma) from a mylonitized Paleoproterozoic orthogneiss [115]. Plutons mylonitized at medium-/low-T conditions in the eastern section of the EPSZ yielded U-Pb ages in the 573–562 Ma interval [35, 116, 117]. U-Pb ages are not available for the WPSZ, but contemporaneous activity with the central EPSZ is suggested by the U-Pb age of 590 Ma of a syntectonic pluton from the Cruzeiro do Nordeste shear zone [118].

In the central subprovince, ages ranging from 592 to 583 Ma were obtained in synkinematic plutons associated with sinistral shear zones [40, 49, 67, 119, 120]. These ages are similar to those (592–581 Ma) of syntectonic plutons related to the E-trending Campina Grande shear zone [49, 105, 121]. Similarly, within the northeastern portion of the southern subprovince, several syn-transcurrent plutons provided U-Pb ages in the 592–581 Ma interval [68, 106, 116]. Dike swarms in the Coxixola shear zone yielded an age of 545 Ma [120], and late tectonic plutons at its western termination were dated at 560–533 Ma [98, 122].

**4.2.  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  Geochronology.** In the Granja and Senador Pompeu shear zones,  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  amphibole and biotite ages (in the ranges, respectively, of 570–575 Ma and 559–569 Ma) imply fast cooling rates of c.  $20^\circ\text{C}/\text{Ma}$  [104, 123]. Slower cooling during the final steps of exhumation is supported by the 536 Ma U-Pb ages of magmatic rocks crosscutting the units of the molassic basins formed by reworking of these shear zones [124, 125].

$^{40}\text{Ar}$ - $^{39}\text{Ar}$  data support variable cooling rates along the PaSZ.  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  ages of amphibole (544–533 Ma) and of biotite and muscovite (510–500 Ma) support slow cooling from c.  $500^\circ\text{C}$  to c.  $350$ – $300^\circ\text{C}$  in the central and eastern sections [126] whereas amphibole and muscovite ages of 565–547 Ma and 540–525 Ma, respectively, support faster cooling in the western section [109, 123, 126].

$^{40}\text{Ar}$ - $^{39}\text{Ar}$  amphibole (577–555 Ma) and biotite (545–533 Ma) ages from the EPSZ and a subsidiary NE-trending sinistral shear zone imply slow cooling [72]. In the Campina Grande shear zone,  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  amphibole and biotite ages of ca. 540 Ma and 520 Ma, respectively, are available [126]. In the Coxixola shear zone,  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  muscovite ages are older (ca. 547 Ma) in the eastern portion than in the western portion (ca. 510 Ma) [98].

## 5. Discussion

The following observations need to be accounted for in any model aiming to interpret the geometry, kinematics, and temporal evolution of the Borborema shear zone system: (1) the system developed in a highly heterogeneous lithosphere formed and transformed by a series of events during the Proterozoic, (2) there is a variation in the geometry of the shear zones, from west to east, (3) the high-temperature shear zones in the western part are NE-trending dextral (with exception of Tauá), (4) in the east, the high-temperature Patos and West Pernambuco dextral shear zones have complex geometries and finite lateral extents, terminating in NE-trending transpressional belts, (5) the domain between the Patos/Campina Grande and West and East Pernambuco shear zones is crosscut by minor, lower-temperature E-trending dextral shear zones linked to NE-trending sinistral shear zones forming a sigmoidal shear pattern, (6) the large NE-trending dextral shear zones in the west cooled faster than the shear zones in the east, and (7) faster cooling in the west relative to the east is also recorded in the E-trending Patos shear zone.

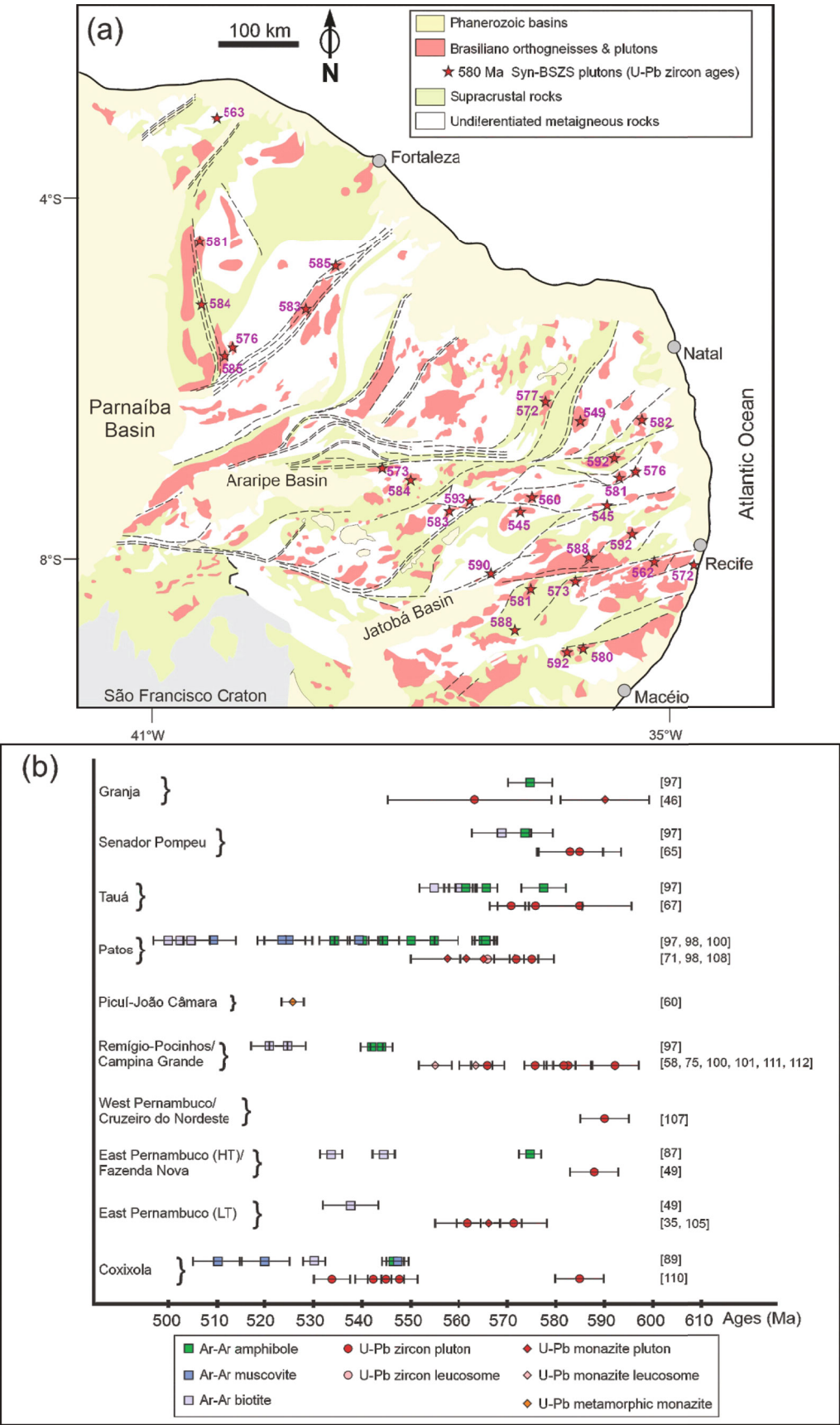


FIGURE 10: (a) U-Pb zircon ages of syn-transcurrent plutons of the BSZS. (b) Synthesis of available geochronological data for the BSZS.

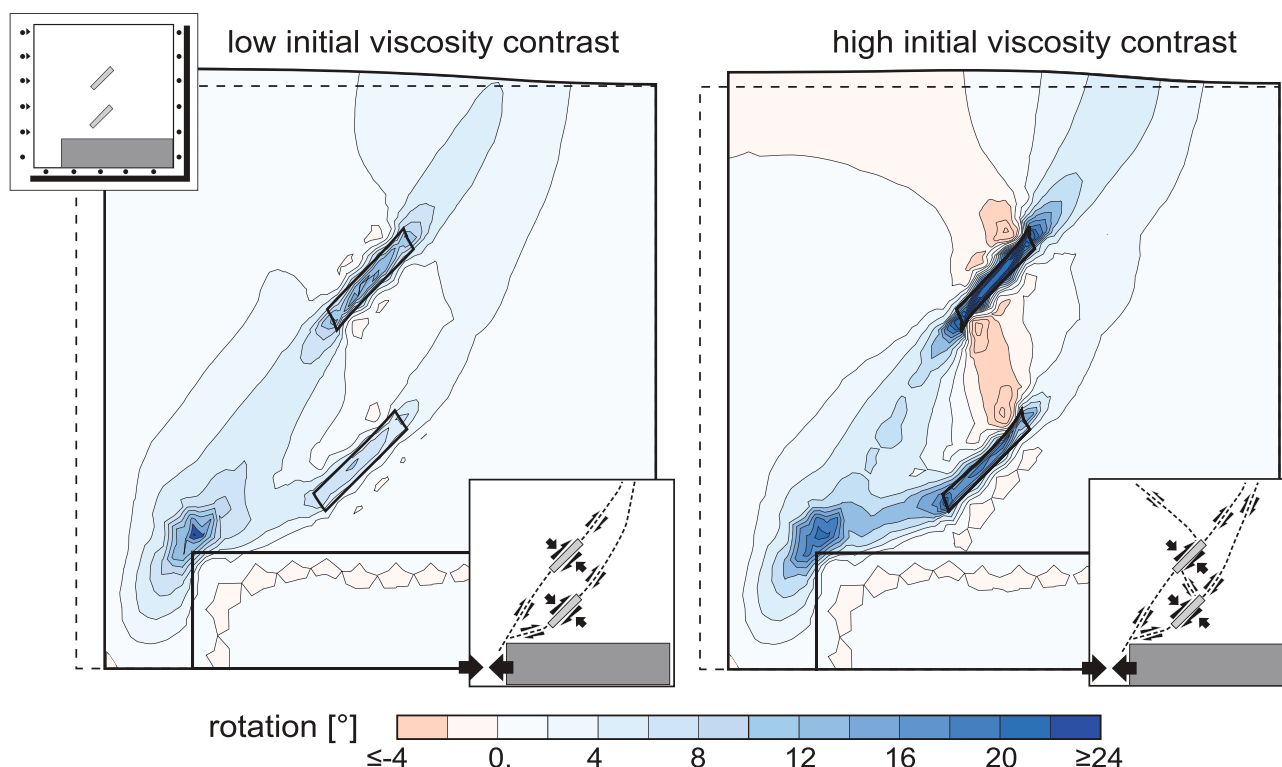


FIGURE 11: Two-dimensional plane stress numerical models testing the effect on the strain distribution of domains with contrasting rheological behaviors due to variations in the geotherm and crust thickness in the strain repartition within a continental plate subjected to compression [128]. (a, b) Display the finite rotation after 120 km of convergence applied to the western boundary of the model for simulations in which the weak domains (medium gray in the top left inset) have a weak (surface heat flow higher by  $5 \text{ mW}\cdot\text{m}^{-2}$ ) and strong (surface heat flow higher by  $30 \text{ mW}\cdot\text{m}^{-2}$ ) contrast in strength relative to the surrounding plate. Top left inset shows the geometry and boundary conditions for the two models; the darker block has a higher strength, representing a cratonic block. Bottom right insets show an interpretative sketch of the strike-slip shear zones (dashed lines) and transpressive belts (direction of shortening is indicated by solid arrows) developed in each model; the sizes of the arrows and thickness of the lines represent schematically the relative strain intensity.

**5.1. Nucleation and Development of the BSZS: Strain Localization in a Heterogeneous Plate.** Numerical models were successful in reproducing some features of the BSZS ([127, 128]; Figure 11). In these 2D plane stress models, a plate comprising a stiff block (aimed at simulating the cold São Francisco cratonic lithosphere) and lower strength blocks with variable orientations (representing preorogenic basins with hotter geotherms) was subjected to E-W compression. The models showed development of a major NE-trending dextral shear zone nucleated at the tip of the stiff heterogeneity. Strain localization in the low-strength blocks resulted in the development of strain transfer zones. These strain transfer zones are dextral shear zones, either branching from the major NE-trending shear zone formed at the tip of the stiff block or linking low-strength domains (Figure 11). In some simulations, depending on the arrangement of the low-strength domains, minor conjugate sinistral shear zones form (Figure 11). To a first approximation, the major shear zones in these models could be compared with the NE-trending dextral shear zones of northwest Borborema and the West Pernambuco and Patos shear zones. The secondary shear zones with opposite shear sense accommodating the deformation between the major ones may compare with the NW-trending Tauá or the NE

to NNE sinistral shear zones in the central and southern subprovinces.

The qualitative agreement between the strain fields in the models and the geometry and kinematics of the BSZS is consistent with the fact that Borborema province is a mosaic of domains of different tectonic ages, from Archean to Neoproterozoic (Figure 2), which, at the Neoproterozoic, may have had lateral variations in lithosphere thickness and stiffness. Some heterogeneities might have been inherited from the Paleoproterozoic Transamazonian/Eburnean event, which was probably responsible for the amalgamation of the Borborema province (see the review in [28]). Although it is expected that rheological heterogeneities of thermal origin may be eliminated in timescales  $> 1 \text{ Ga}$ , it is probable that the Rio Grande do Norte domain behaved as a stronger block throughout most of the Proterozoic since it was not affected by Neoproterozoic extension and only became involved in the Brasiliano Orogeny at ca. 600 Ma, much later than other domains of Borborema province. The lower temperature of mylonitization and the smaller width of the Portalegre and Picuí-João Câmara shear zones relative to other shear zones in northwestern Borborema Province also point to a colder geotherm in the Rio Grande do Norte domain.

The geometry of the northwestern part of BSZS is simple, suggesting a relatively homogeneous behavior of the plate. However, the Sobral and Senador Pompeu shear zones delimit crustal blocks with different basement ages (Figure 2). Northwestward of the Sobral shear zone, the basement comprises juvenile orthogneisses of the Siderian age (2.35–2.30 Ga; [129]), whereas southeastward ages mostly range from 2.19 to 2.13 Ga [130–132]. The southern portion of the Senador Pompeu shear zone juxtaposes Archean and Paleoproterozoic rocks [130] whereas its northern portion juxtaposes Paleoproterozoic orthogneisses with different ages (2.19–2.10 Ga vs. 2.25–2.17 Ga) [110, 131–133] (Figure 2). Furthermore, the Paleoproterozoic basement between the Sobral and Senador Pompeu shear zones is dominantly juvenile (positive  $\varepsilon_{\text{ND}}$  values) whereas east of Senador Pompeu, reworking of older crustal rocks is indicated by negative  $\varepsilon_{\text{ND}}$  values and Archean Nd model ages [110, 132, 133] (Figure 2). These contrasting geochronological and isotopic signatures suggest that the Sobral and Senador Pompeu shear zones may have overprinted previous terrane boundaries formed during the assembly of distinct crustal blocks during the Paleoproterozoic Transamazonian orogeny.

The multiple metasedimentary belts in the Borborema province record local rifting episodes that represent another source of heterogeneity. The earlier supracrustal belts, Orós and Jaguaribe (Figure 2), formed between 1.8 and 1.7 Ga [39]. Despite the large time span since their formation, both have been extensively reactivated in transpression during the formation of the BSZS [18, 56]. Extensional events also occurred in the Early Neoproterozoic. In the central subprovince, early Tonian rocks (1000–920 Ma) comprising granitic orthogneisses and bimodal metavolcanic rocks are distributed along a narrow and elongate NE–SW sigmoidal belt roughly 700 km long and 70 km wide [29, 30, 40]. This belt is delimited by some of the most important NE-trending sinistral shear zones of the central subprovince: the Afogados da Ingazeira and Serra do Caboclo shear zones (Figure 2). Similarly, the West Pernambuco shear zone bounds a belt comprising several Tonian granitic augen gneiss whose protoliths were probably emplaced during continental rifting (Figure 2) [96]. However, the most important extensional episode, which promoted the deposition of supracrustal sequences across the entire Borborema province, occurred during the Cryogenian (0.70–0.64 Ga; Figure 2) (see reviews in [28, 38]). In the Seridó basin, extension continued even during the early stages of the Brasiliano orogeny (0.6 Ga), since the sediments contain detrital zircons with U–Pb ages of 650–620 Ma [41, 134]. The Cryogenian extensional episode probably produced the most effective lateral variations in the mechanical behavior of the plate during the Brasiliano orogeny. The metasedimentary belts formed during this period show markedly different behaviors during the formation of the BSZS. The Seridó belt was extensively deformed in transpression and probably played a major role in the formation of the PaSZ, representing a softer domain within the Rio Grande do Norte block. In contrast, the Piancó-Alto Brígida domain in the western portion of the central subprovince is characterized by much

weaker deformation and low-temperature metamorphism during the Brasiliano orogeny [55], suggesting that it was stiffer than the remainder of the province and behaved like a plateau surrounded by belts with higher topography. Such a contrast in stiffness between the two domains might have resulted from the earlier stop of the extension and partial thermal reequilibration in the PAB but also from a more effective extension, leading to higher crustal thinning and, possibly, incipient oceanization in the PAB relative to Seridó.

The sinistral NE-trending shear zones in the central subprovince [50, 72, 100, 103] may be explained as conjugate shear zones [135] accommodating internal deformation of the block between the Patos-Remígio Pocinhos and West Pernambuco-East Pernambuco shear zone systems. Internal deformation of the block between these two major shear zones may also explain the coeval development of shear zones and NE-trending upright to steeply inclined folds recorded in this domain [50, 53, 95]. The presence of the stiffer PAB domain might have exacerbated this behavior by concentrating the deformation east of it, with growth and interlinkage of the shear zones occurring between ca. 580 and 560 Ma.

The formation of the BSZS was probably also influenced by other potential sources of heterogeneity in the mechanical response of the plate. The change in geometry and magnetic signature of the West Pernambuco shear zone north of the promontory of the São Francisco craton separating the Riacho do Pontal and Sergipano belts (Figure 2) points to a nonnegligible role of the geometry of the craton on the strain repartition in the southern part of the BSZS. Concentration of stresses at the northwestern tip of the São Francisco craton may also have played an essential role in triggering the formation of the large NE-trending dextral shear zones of the northwestern part of the BSZS, as substantiated by the numerical models (Figure 11).

The extensive magmatism associated with the Brasiliano orogeny (Figure 2) also certainly played a role in the development of the BSZS, by producing lateral variations in the thermal structure and strength in the crust. Mylonites along the central and western portions of the East Pernambuco shear zone are essentially restricted to the southern border of a large granitic batholith, country rocks being hardly affected by strike-slip shearing. Neves and Vauchez [103] and Neves et al. [136] showed that deformation of the still incompletely crystallized batholith by the shear zone postdated an early evolution of the magma chamber. They proposed that in the EPSZ and in other smaller shear zones from the Borborema province, strain localization may have been triggered by the existence of local rheological instabilities associated with magma chambers in the crust, with deformation localized in the high-temperature crystal mush during the last stages of crystallization.

Geochronological data show that the main period of shear zone activity under high- to medium-temperature conditions lasted from 590 to 560 Ma (Figure 10). The Patos shear zone seems anomalous since the ages of syn-kinematic leucosomes and plutons mostly cluster in the 570–560 Ma interval [85, 109], suggesting a later development as compared with the other large shear zones. However, slow

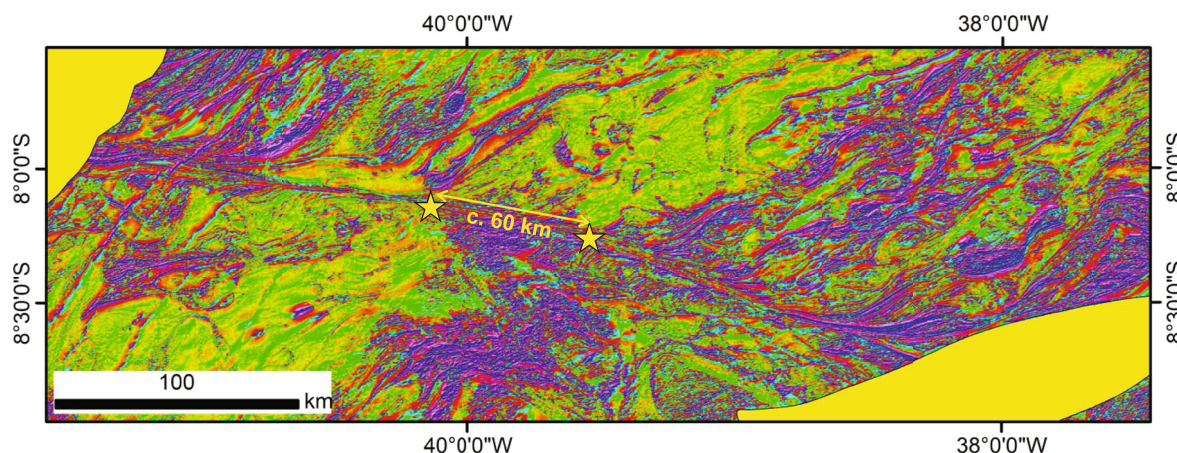


FIGURE 12: First-order vertical derivative image showing an estimated offset of c. 60 km across the central portion of the WPSZ.

cooling rates along the PaSZ, as suggested by  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  dates (Figure 10), may have allowed the persistence of near solidus conditions and zircon crystallization over a long time span. The U-Pb ages may therefore reflect the average zircon crystallization age, not the beginning of strike-slip motion. A similar relation between deformation and U-Pb zircon ages in granitoids and anatexis products has been proposed for the Araçuaí belt, southeastern Brazil [137].

**5.2. Displacement Estimates.** Markers allowing to quantify the displacement across the main shear zones are disputable. The Sobral and Senador Pompeu shear zones mostly juxtapose units with different ages and compositions (Figure 2). However, the correlation of two plutons of synkinematic porphyritic granite across the Senador Pompeu shear zone might constrain the displacement in this shear zone after 583 Ma (age U-Pb of the northern pluton [108]) to ~60 km. Similar units outcrop on both sides of the Granja shear zone, but no clear correlation can be made. Deflected structures imply a displacement of 30–35 km in the Tauá shear zone [80, 81]. Ávila et al. [80] estimated a pure shear component around 50% for the Tauá and Senador Pompeu shear zones based on the fabric of synkinematic granitoids. Given that the stretching lineations have consistent shallow plunges, the pure shear component was likely accommodated by enhanced horizontal stretching, which is consistent with the  $L > S$  fabric observed in several outcrops of the Tauá shear zone [81].

Melt-induced weakening leading to widely distributed deformation may account for a striking feature of the BSZS, which is the large width of the Patos and, to a lesser extent, West Pernambuco shear zones, >25 and 10 km wide, respectively, relative to the limited displacement that they may have accommodated. Their finite extent implies that the displacement cannot be higher than the shortening component in the transpressional belts into which they terminate. The maximum width of the Seridó belt is c. 80 km (Figure 2). If we assume that it resulted from 50% shortening due to eastward movement of the basement block along the PaSZ, a similar displacement can be inferred for the shear zone. Alternatively, if we consider that sediments in the Piancó-

Alto Brígida and Seridó belts were initially deposited in a single basin, the offset and difference in thickness between the two may constrain the maximum displacement along Patos to c. 100 km in the eastern termination plus c. 80 km shortening in the Seridó belt, amounting to c. 180 km, which seems consistent with the high stretching of Archean units in the duplex.

For the WPSZ, Ganade et al. [61] estimated a displacement of c. 200 km by correlating Tonian-age rocks in the Alto Pajeú and Riacho do Pontal domains (see Figure 2). However, rocks of the Tonian age are not restricted to these two domains; they also occur south of the entire length of the WPSZ (Figure 2) [96]. Although interpretation of the shear zone offset from a magnetic map, such as the first-order vertical derivative (Figure 12), is not straightforward, the offset of c. 60–100 km obtained by correlating zones of high and low magnetic gradients on both sides of the WPSZ is an alternative estimate for the dextral displacement in the WPSZ.

**5.3. Summary.** The formation of the BSZS records the transition of a homogeneous accommodation of the convergence between the West Africa-African and possibly the smaller Parnaíba block and the South American protocontinent, recorded by the shallow dipping foliations with NW to WNW tectonic transport (Figure 5), to a localized deformation regime. This transition was triggered, and its evolution is controlled, by the mechanical heterogeneity of the plate. Strain localization started therefore in multiple locations within the Borborema province, and as the shear zones developed, they interacted with each other, forming the present complex interlinked system, which then fully accommodated the convergence, producing bulk WNW shortening and NE stretching. The initial high-pressure deformation conditions, simpler geometry, and faster cooling of the northwestern domain record its proximity to the collision zone and a stronger eastward push of the Amazonian-West Africa cratons relative to the northward push of the São Francisco craton. In the more distal intraplate setting (the remainder of the Borborema province), strain localization was fully controlled by the rheological heterogeneities

inherited from the previous history of the plate or formed in response to the convergence (like the Brasiliano magmatism). Strain localization is initiated therefore at multiple locations producing a more complex pattern. The importance of geological expression and the geophysical signature of the Patos and West Pernambuco shear zones indicates nevertheless that they played a major role in transferring the deformation towards the interior of the plate.

Given the importance of the BSZS in the accommodation of the Brasiliano convergence and its preeminent role in controlling the location of the initial stages of the Mesozoic rifting, as indicated by the geometry of the Cretaceous sedimentary basins (e.g., Araripe, Jatobá, and Potiguar; Figure 2) [63], the poor evidence for its continuation in the lithospheric mantle is rather surprising. The absence of a clear signature of the BSZS in the lithospheric mantle might be associated with the high geothermal gradient prevailing in the Borborema province during the Brasiliano orogeny, but a clear physical explanation is still to be found.

## 6. Conclusions

The Borborema shear zone system is composed of two main domains: HT dextral NE-trending shear zones predominate in the west, whereas dextral E-trending shear zones and N- to NE-trending transpressional belts predominate in the east. The main E-trending Patos and West Pernambuco shear zones terminate in a horsetail structure that marks their connection with the dextral transpressional Seridó belt and a complex deformation zone in the Central subprovince (Alto Pajeú, Alto Moxotó and Rio do Capibaribe domains), respectively, associating contractional deformation, E-trending dextral, and dominantly NE-trending sinistral shear zones.

The development of the shear zone system was progressive and long lasting. The Borborema province is a mosaic of domains of different ages, from Archean to Neoproterozoic. This complex tectonic history, which involved, in particular, multiple extension episodes, likely produced significant lateral stiffness variations. This rheological heterogeneity is at the origin of the partitioned deformation that led to strain localization and development of the shear zone system. Strain localization is controlled by stress concentrations at tips of the stiff São Francisco craton, the presence of weak domains like the Seridó pre-orogenic rift, or large batholiths like those associated with the East Pernambuco shear zone, and reactivation of structures formed in previous deformation episodes. The location and geometry of the shear zones forming the BSZS were also influenced by the repartition of stiff blocks like the Rio Grande do Norte or the Piancó-Alto Brígida domains. Differential deformation required the development of large shear zones, like Patos and West Pernambuco, which worked as strain transfer zones. The main period of shear zone activity under high- to medium-temperature conditions lasted from 590 to 560 Ma, but it continued or was followed by one or several reactivations under decreasing temperature conditions. Once formed, the BSZS constituted a major feature in the structuration

of the plate, controlling its further deformation, in particular during the early episodes of rifting in the Mesozoic.

## Data Availability

The data supporting the conclusions of the study are available in published papers cited in the references list.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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## Supplementary Materials

Supplementary material describes the acquisition and processing of airborne geophysical (magnetic and gamma ray) data. (*Supplementary Materials*)

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