Journal of the Geological Survey of Brazil

Description and hierarchy of ductile deformation events in the Camalaú region, state of Paraíba, central portion of the Alto Moxotó Terrane, Borborema Province, Brazil

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Abstract

The Borborema Province (NE Brazil) has a long history of deformation, magmatism and metamorphism during the Precambrian Eon. Thus, it represents a natural laboratory to investigate widely developed ductile-deformation markers, such as major fold belts and large-scale shear zones. This paper describes the structural evolution of a complex folded area of the Alto Moxotó Terrane, Central Borborema Province. In this region, para-derived rocks of the Sertânia Complex are intruded by orthogneisses and migmatitic orthogneisses. The Geophysical magnetometric expressions of the Borberma Province are characterized by strong aligned and folded magnetic lineaments and integrated structural analysis, allowed us to identify three ductile deformation episodes. Brittle tectonics is also present, but not described. D_1 stage represents the basement structural framework restricted to local structural windows of ancient orthogneisses and migmatites that are not mappable at the work scale. D_2 deformation is widespread throughout the Central Borborema Province, producing nappes that mark top-to-NW tectonic vergence. Foliation and lineation attitudes are compatible with progressive deformation from tangential to strike-slip tectonics (i.e. D_2 to D_3). The latter is associated with the NE-SW Xinxó and Congo-Cruzeiro do Nordeste sinistral strike-slip shear zones, producing refold patterns that resemble Type-3 interference geometry. Based on airborne magnetic geophysical imaging interpretations and mesoscopic observations, we suggest that progressive deformation strongly affected the region and overprinted at large-scale early formed rocks.

Article Information

Publication type: Research paper
Submitted: 31 December 2019
Accept: 12 March 2020
On line pub: 6 April 2020
Editor: Vladimir Medeiros

Keywords:
Ductile deformation in Camalaú,
Moxotó Terrane,
Borborema Province

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1. Introduction

Lithospheric processes have played a major role in evolution of the Earth since early Archean times. Strain nucleation and crust deformation depend on a number of aspects including tectonic setting, rock assemblage, deformation/metamorphic P-T-t conditions and the extent of fluid-rock interaction (Ramsay and Huber 1984). Despite shallow conditions of deformation controlled by brittle tectonics, ductile rheology is mostly developed in deep-seated settings, especially during plate convergence such as the Andean and Himalayan chains (e.g. Buffett and Rowley 2006; Schellart et al. 2007; Cawood et al. 2009).

The Borborema Province in NE Brazil represents a natural laboratory to investigate widely developed ductile-deformation markers, such as major fold belts and large-scale shear zones that are interpreted by some authors as remnants of continental sutures (Cordani et al. 2013; Ganade de Araujo et al. 2014; Santos et al. 2015b). This province has a long history of deformation, magmatism and metamorphism spanning the Precambrian, originally defined by Almeida et al. (1981). The

ISSN: 2595-1939
https://doi.org/10.29396/jgsb.2020.v3.n1.2
Open access at jgsb.cprm.gov.br

major record of crustal recycling is related to the Brasiliano/Pan African orogeny that strongly affected the region (0.6-0.5 Ga, Brito Neves et al. 2014 and references therein). Within the central part of the province, i.e. Central Subprovince, the Alto Moxotó Terrane represents an Archean-Paleoproterozoic quasi-rigid block, interpreted as a basement inlier or a crustal exotic fragment, probably dismembered by the neighboring coeval cratons (Santos et al. 2017a and references therein). Despite the abundant basement units of this terrane, it preserves a complex deformational overprint, including thrust nappes/duplexes; strike-slip corridors and complex folding arrays, which have been recognized as reliable markers of late Neoproterozoic crustal shortening (Vauchez et al. 1995; Archanjo et al. 2008; Viegas et al. 2014; Santos et al. 2017a).

The main mechanisms that produced complex fold patterns within the region have been only recently identified (Neves et al. 2018). According to these authors, tectonic-induced interference fold patterns are mostly recorded in high-grade supracrustal metamorphic complexes that are closely related to conjugated pairs of transcurrent shear zones. Nevertheless, the extent of these events is still poorly explored and other areas might be explored.

In this contribution, we present a structural study focused on ductile deformation of the area surrounding Camalaú city in Paraíba State, covering a small area in the central part of the Alto Moxotó Terrane. We integrate airborne magnetic geophysical images and mesoscopic observations in order to describe the main deformation-folding patterns overprinted in an ancient block of the Borborema Province.

2. Geological Setting

The Borborema Province is divided into northern, central and southern subprovinces by regional scale E-W trending shear zones (Fig. 1a; Van Schmus et al. 1995). The studied area is located in the central portion of the Alto Moxotó Terrane, which is part of a crustal fragment mosaic that is bounded by E-W regional scale shear zones marking major subdivision of the Central Subprovince (Santos and Medeiros 1999; Brito Neves et al. 2000; Fig. 1b). This terrane is composed by metaplutonic units including metagranites, orthogneisses, migmatites and metamafic-ultramafic rocks that are interleaved with high-grade metamorphic supracrustal sequences (i.e. Sertânia Complex). The latter is interpreted by some authors as Paleoproterozoic in age (2.15-2.0 Ga; Santos et al. 2004), but a deposition age of ca. 700 Ma has been recently proposed (Neves et al. 2017). Despite the abundance of Rhyacian crust (2.2-2.15 Ga), early Paleoproterozoic and Archean rocks mark the oldest crust growth episodes of the Central Subprovince (Neves et al. 2015; Santos et al. 2015a, 2017b). The terrane is bounded by the adjoining Neoproterozoic Alto Pajeú and Rio Capibaribe terranes, and by the Serra de Jabitacá and Congo-Cruzeiro do Nordeste shear zones respectively (Santos and Medeiros 1999). Terrane assembly processes are still under discussion and Neves (2015) proposes an alternative division of the Central Borborema Province and contests the usage of the term “terrane”. However, the crustal origin of the region is not the focus of this paper.

The studied area is located near the southern boundary of the Alto Moxotó Terrane (Fig. 2a), dominated by garnet-biotite ± sillimanite paragneisses/schists of the Sertânia Complex that are intruded by orthogneisses and migmatitic orthogneisses, whose the main protolith composition varies from granodioritic to syenogranitic. Calc-silicate rocks are present outcropping as minor blocks, but do not have regional significance at the working scale. This whole set is characterized by strong aligned and folded magnetic anomalies that represent the regional structural framework of the area, which represents the starting point of the ductile structural investigation of the area. The deep-seated structures, including major shear zones, already mapped by Lima et al. (2018), were also defined based on the magnetic images, i.e. first vertical and tilt derivatives (Figs. 1c and 1d).

3. Mesoscopic Structural Observations

The studied area is located in the heart of a strongly folded region. The imposed fold pattern on the studied rocks, especially in the orthogneisses, is typical of crust submitted to several stages of deformation/folding, which in the studied area is mostly controlled by the regional shear zones (Fig. 2). Based on geological mapping and detailed outcrop-scale investigation, we hierarchized the structural markers of the area in three deformation events: D_1, D_2, and D_3 (Table 1). Such description does not necessarily correspond to distinct tectonic phases but is merely used for didactic purposes. A later phase corresponds to a brittle regime and, despite the widespread related structures, is not described in this contribution, which is focused on deep-seated markers.

D_1 stage represents an ancient and complex migmatitic fabric that is poorly preserved in some para-derived migmatitic paragneisses of the Sertânia Complex and in minor occurrences of ortho-derived metatexites. The latter are interpreted as local gneissic-migmatitic basement occurrences in the region. Their chronological significance is still unknown, inferred as Paleoproterozoic in age based on inherited metamorphic zircon crystals as discussed in previous studies (Santos et al. 2015a). Part of the fabric is partially or completely obliterated by later tectonics, especially the transcurrent regime. However, highly folded members (F_1 generation) can be locally observed and dominate in well exposed anatexites (Fig. 3a), whereas local vein-like structures are interpreted as evidence of advanced stages of anatexis. Ptygmatic folds with axial planes developed parallel or nearly parallel to a strongly folded foliation are widespread, marking segregation episodes between a dominant gabbro/diorite mesosome and tonalite/aplite leucosome layers. In ortho-derived migmatites, neosome is mostly isotropic to weakly foliated and might exhibit breccia structures with remnants of mafic paleosome angular xenoliths of variable composition.

Observed D_2 deformation markers are described in several portions of the Central Subprovince and are present in all gneissic sequences of the Alto Moxotó Terrane. In spite of moderate to strong folding imposed by D_3 tectonics, D_2 markers are seen mainly in the core of the intrusive orthogneisses. S-L tectonites are the most prominent outcrop-scale structural members of these rocks, including gneissic to protomylonitic sheets that are interpreted in similar areas of the Alto Moxotó Terrane as syn-tectonic intrusions (Santos et al. 2017a). S2-related schistosity and foliation planes gently dips (~4-12º) to S-SE, always associated with high pitch and down-dip mineral stretching lineation (L_2), composed of aligned amphibole and tourmaline tiny crystals. On observed X-Z mylonitic planes, kinematic criteria include S-C and shear bands C and C´, as

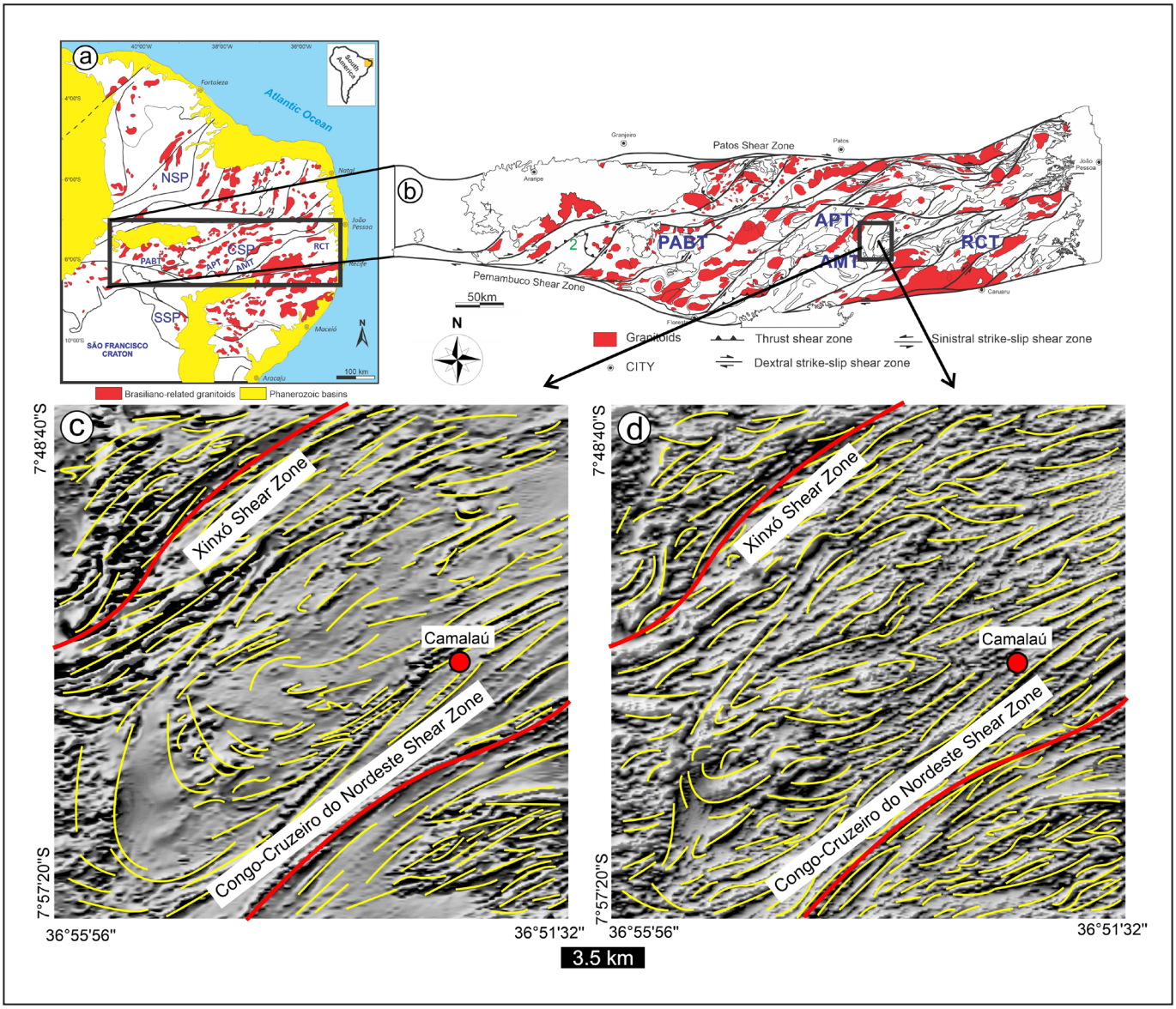

FIGURE 1 - Localization of the Central Subprovince in the context of the Neoproterozoic Borborema Province; b) The studied area within the Central Subprovince terrane map; c) The first derivative magnetic map of the studied area; d) Tilt derivative map of the studied area. Yellow lines mark the interpreted magnetic lineaments, whereas red lines mark the strike-slip shear zones, the main structures.

well as asymmetrically deformed porphyroclasts, suggesting top-to-the north mass transport, i.e. tectonic vergence to N-NW (Fig. 3b). F_2 folds when preserved are mostly NW-SE trending, but later refold imposes variable trend directions. They are mostly rootless, overturned and recumbent, presenting tight to isoclinal geometries.

Lastly, D_3 phase deformation markers are the most remarkable structures in the area. The main structures are the NE-SW oriented Xinxó and Congo-Cruzeiro do Nordeste shear zones producing banded to mylonitic fabrics associated to sinistral-strike kinematics, which is largely known for most of the shear zones of the Transversal Subprovince (Santos and Medeiros 1999). Such structures represent major magnetic lineaments, even at regional scale, especially the Congo-Cruzeiro do Nordeste Shear Zone. Also, based on integrated geophysical and microstructural data, a dominant dextral vorticity has been recently observed in other portions of the Alto Moxotó Terrane for the latter structure (Neves et al. 2017). The lack of local evidence of partial melting related to ortho-derived mylonites developed in these shear zones as well as rotated and well-preserved early garnet porphyroclasts remnant might reflect low-temperature strain development (at least in the study area). S_3 foliation is mostly NE-SW, mainly subvertical to vertical, especially close to the mapped shear zones, dipping to NW and SE. L_3 mineral stretching lineation present variable orientations, but sub-horizontal alignments predominate (Fig. 3c). The associated D_3 kinematic criteria include σ- and δ-type feldspar porphyroclasts that are always surrounded by a well-preserved banded to anastomosing foliation matrix. In spite of widespread S-C structures (Fig. 3d), C- and C´ type shear bands are present but not common. Strong mylonitization is well-marked on protomylonitic to ultramylonitic members that exhibit abundant syntectonic rotated and asymmetrically deformed garnet porphyroclasts on para-derived members (Fig. 3e).

Lastly, F_3 folding delineates the major regional structural framework of the Camalaú region, developing inclined axial surfaces that are mainly oriented in the NE-SW direction (Fig.

3f). At least part of it is interpreted as refolding of the NW-SE F_2 thrust-related folds. In outcrop scale, they are mostly intrafolial and range between close to isoclinal members and, in spite of progressive refolding, generally follow the regional trend. Sheath folds are abundant and interpreted as syn-kinematic structures cropping out on mylonites close to the Congo-Cruzeiro do Nordeste shear zone. Refolding of F_2 is also reinforced by the presence of inclined mineral stretching lineation, which might be related to interference geometry between L_2 and L_3 structures, i.e., a possible evidence of progressive deformation.

4. Discussion

The Camalaú region presents a complex structural framework, in which for didactical purposes, we simply defined three deformation stages that can be expanded in future detailed reserach (Fig. 4). The earlier deformation phase is only preserved on strongly folded migmatites that present variable degrees of partial melting, including para- and ortho-derived members. It has been suggested that this stage is Paleoproterozoic in age, constrained by the presence of Rhyacian-Orosirian (2.15-2.0 Ga) metamorphic zircon grains on the Sumé region (N of the studied area), that precede an interval of the oldest metamorphic peak in the region (Santos et al. 2015a). Such statement is in accordance with recent magmatic and metamorphic ages obtained on early gneissic and migmatitic sequences in the Alto Moxotó Terrane (Neves et al. 2015; Santos et al. 2017b) that point out to a major crustal accretion episode during this period. Furthermore, such structural pattern is similar to other Paleoproterozoic basement inliers within the Borborema Province, including a number of examples from the Central Subprovince (Santos et al. 2004, 2017a; Neves et al. 2017), as well as in the rest of South America (Brito Neves 2011).

However, further north (Patos town, Paraíba region), Paleoproterozoic ages identified on anatexites are interpreted as inherited crust of a major migmatization event that is dated at ca. 566 ± 6 Ma (Viegas et al. 2014), thus, considered as part of the Brasiliano Orogeny. Considering that a younger episode has not been clearly described yet for neosomes and even gneissic domains of the Alto Moxotó Terrane, up to now, such correlation is unlikely and merely speculative. The D_2 deformation markers identified in this study correspond to thrust/tangential tectonics, described as similar to Alpine/Himalayan nappes (Santos et al. 2017a), and are better preserved in other areas of the Alto Moxotó Terrane, such as the Sumé Region (Santos and Santos 2019). In the studied

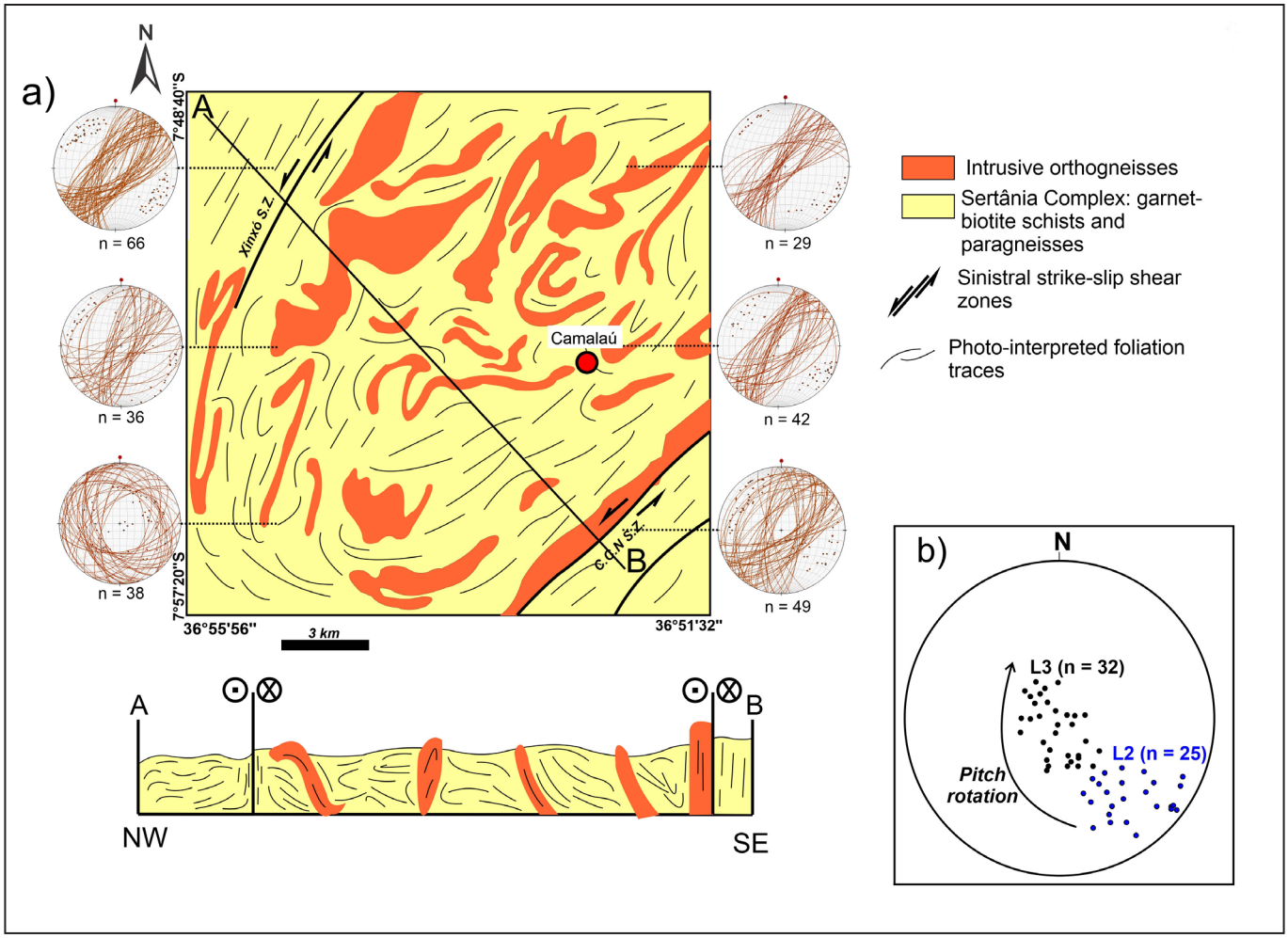

FIGURE 2 - Simplified geological map of the studied area showing the foliation traces and structural and plotted foliation planes on distinct sectors of the studied area; b) Stereogram showing the variation of the mineral stretching lineations (L_2 and L_3), suggestive of transition between thrust and strike-slip regimes. Stereograms are equal area (lower hemisphere), Schmidt-Lambert..

TABLE 1 - General description of the deformational evolution of the studied area.

Deformation episode	Associated structures	Characteristics
D_1	S_1, F_1	Intense migmatization, including strongly folded members and development of vein-like structures. The fabric is partially to completely overprinted by the late deformation, especially the transcurrent phase.
D_2	S_2, L_2, F_2	Thrust tectonics marked on S-L tectonites and sheets of orthogneisses that present gentle dipping foliation. It is associated with high pitch mineral stretching lineation and sin-tectonic overturned to recumbent folds. Associated kinematic criteria and additional structural markers show top-to the-NW tectonic vergence. S_2 foliation is also later folded by D_3 tectonics.
D_3	S_3, L_3, F_3	Recorded mainly on the rocks related to the Xinxó and Congo-Cruzeiro do Nordeste shear zones, the major structures of the area. It is characterized by NE-SW mylonitic corridors and refolding of previous formed structures, which are variable in terms of interlimb angle. High-angle foliation and sub-horizontal linear structures as well as the orientation of the kinematic criteria are suggestive of transcurrent sinistral orientation of the mostly deformed rocks. Inclined L_3 lineation is also observed and might be interpreted as an intermediate record between tangential and vertical deformation stages.

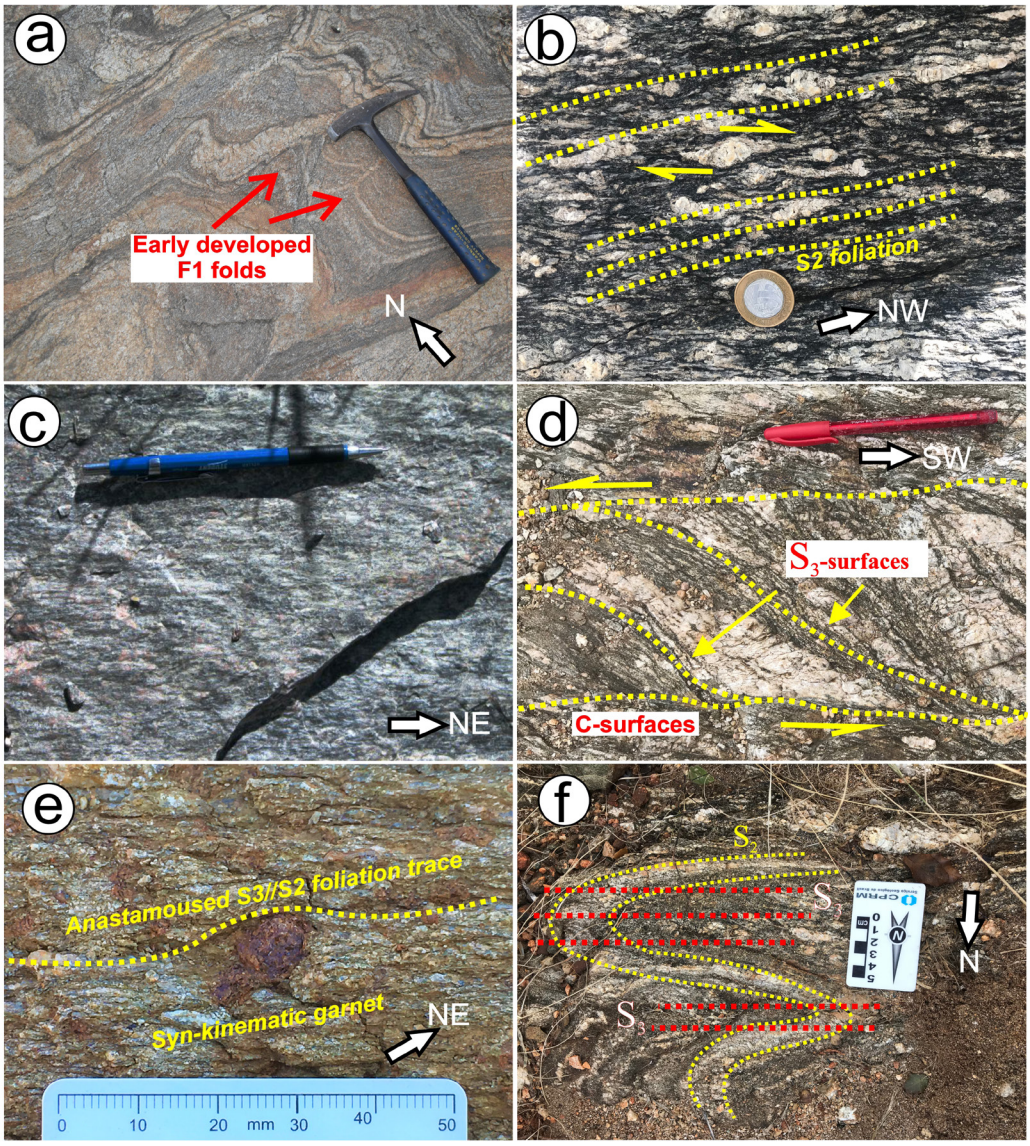

FIGURE 3 - Mesoscopic aspects of the studied area: a) Folded migmatite showing evidence of early deformation in the studied area; b) deformed porphyroclast along the S_2 foliation, suggesting top-to-the-NW tectonic vergence during thrusting event; c) horizontal to sub-horizontal mineral stretching lineation recorded in intrusive mylonitic orthogneiss (L_3); d) S-C structures as well as a deformed quartz-feldspar aggregate suggesting sinistral movement related to the Congo-Cruzeiro do Nordeste Shear Zone, cropping out in metasedimentary rocks of the Sertânia Complex; e) syn-kinematic garnets deformed along vertical foliation planes related to strike-slip tectonics in garnet-biotite schist from the Sertânia Complex; f) folded S_2-related foliation by the later transcurrent D_3 deformation resulting in the development of close to isoclinal syn-kinematic folds.

area, we assume that crustal shortening produced inclined to recumbent and close to isoclinal folds in the core of the orthogneiss sheets, also producing local migmatization. Such structural pattern suggests that crustal accretion affected the region during a plate convergent stage, considered to be late-Neoproterozoic in age (Rodrigues and Archanjo 2011). Such event can also be responsible for the tectonic inversion of the early structures, producing a series of nappes with top-to-the north/northwest mass tectonic transport, known in the region as part of the the Riachão do Bacamarte Thrust System (Rodrigues and Archanjo 2011; Santos et al. 2012).

Nevertheless, the most remarkable structural markers of the area post-date horizontal convergent episodes and are clearly materialized in a pair of NE-SW sinistral strike-slip shear zones, i.e. Xinxó and Congo-Cruzeiro do Nordeste. Besides the development of mylonites and protomylonites on both ortho- and para-derived rocks, these structures are coeval to the curved foliation trace lines that are evident on the geological map, related to the folded shape of the studied rocks. Despite variable orientations of hinge lines and axial planes of the new developed folded structures (F_3), major folds trend to SW in map and outcrop scale, which can be constrained by the rotated of foliation strike due to the shearing activity.

In the intrusive orthogneisses, refolding (F_2 to F_3) is evident, confirmed by the development of later foliation that coincides with axial planes of previously folded rocks. In addition, the delineation of structures in map is suggestive of the development of Type-3 interference fold pattern, in which, only axial planes of F_2 are folded (Ramsay and Huber 1987). Such behavior might be explained by progressive deformation, which is coherent with the structural evolution described by Rodrigues and Archanjo (2011) in the Campina Grande region (further north). The development of oblique mineral stretching lineation, i.e. intermediate pitch orientation, also reinforces rotation from L_2 to L_3 and might reflect strain portioning between basement and metasedimentary rocks in other areas of the Central Subprovince of the Borborema Province as suggested by Neves et al. (2005).

Similar interference fold pattern within the Alto Moxotó Terrane has already been described in near areas, and interpreted as the result of nucleation and growth of shear zones with contrasting kinematics (Neves et al. 2018). Authors have shown that dextral kinematics predominate in the Congo-Cruzeiro do Nordeste Shear Zone, producing the Caroalina fold-interference pattern. In our case, both shear zones seem to have similar geometry and kinematics, producing a regional drag fold coeval to the shear zones nucleation. In addition, based on the strong refolding of thrust-related early folds (i.e. F_2 to F_3), strongly related to the kinematic progression between contractional to strike-slip tectonics, we suggest that the Camalaú region corresponds to a strongly folded area in which major structures were developed during Neoproterozoic progressive deformation, throughout one single tectonic event, i.e. the Brasiliano Orogeny.

5. Conclusions

The Camalaú region is structurally complex, being affected by three ductile deformation stages. D_1 is restricted to punctual basement occurrences and migmatites developed in the Sertânia Complex, producing variable facies of folded anatexites. D_2 stage is represented by the core of strongly low-dipping sheets of orthogneisses, whose major kinematic markers suggest top-to-the NW tectonic vergence, coinciding with a number of thrust-related structures within the Alto Moxotó Terrane described as the Riachão do Bacamarte Thrust System. In addition, the most prominent structural markers in the area are related to NE-SW strike-slip Xinxó and Congo-Cruzeiro do Nordeste shear zones that produced mylonitic rocks in both ortho- and para-derived rocks as well as later generation of folds trending to SW. The regional folded aspects of the studied rocks as well as the map distribution of foliation is compatible with Type 3 interference fold pattern, however additional data is still needed. Lastly, we conclude that late Neoproterozoic progressive deformation (thrust to strike-slip regime) during the Brasiliano orogeny strongly affected the region, overprinting early structural markers, which might be Paleoproterozoic in age.

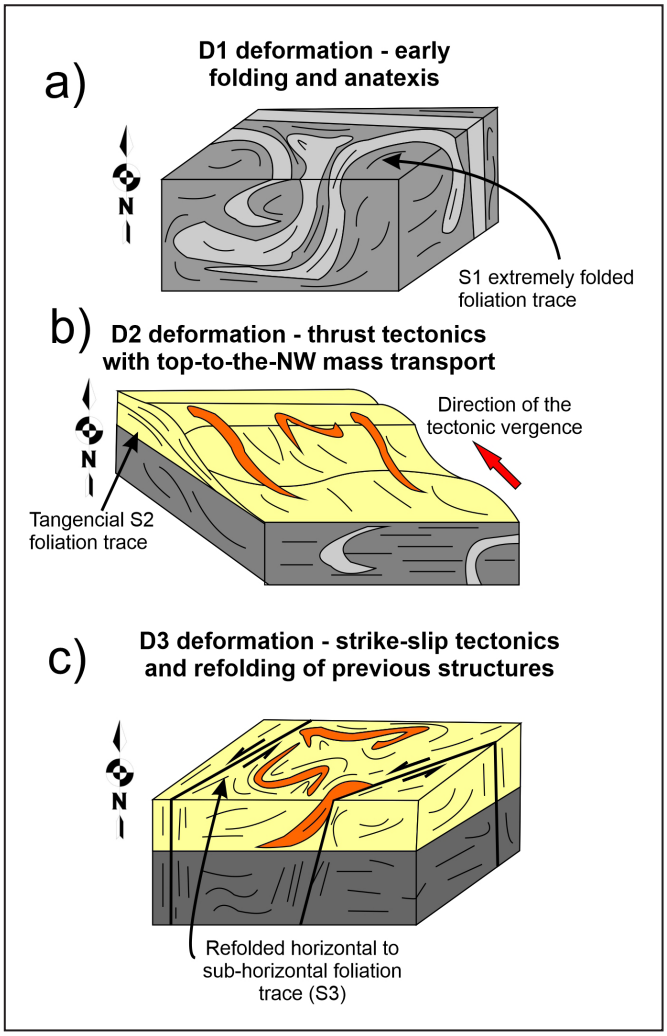

FIGURE 4 Proposed schematic evolution of the studied area: (a) Anatexis and the development of early folding and neosome of the basement rocks; (b) Nappe-like development structure with top-to-the-NW tectonic mass transport; (c) folding and refolding of previous structural markers, mostly due to nucleation of the Sinistral Xinxó and Congo-Cruzeiro do Nordeste shear zones.

Acknowledgements

This paper is an integrative effort of the undergraduate students and the advisor professor of the *Applied Mineralogy*

and Crustal Evolution Lab of the Federal University of Pernambuco, Brazil. The authors thank the support given by the National Institute for Tectonic Studies – INCT. Dr. Evandro Klein is kindly acknowledged for the invitation and we are honored to contribute to the early years of the JGSB. Sergio Wilians de Oliveira Rodrigues and an anonymous reviewer are thanked for their commentaries and suggestions.

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