Journal of Structural Geology 103 (2017) 167–184

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Two-stage terrane assembly in Western Gondwana: Insights from structural geology and geophysical data of central Borborema Province, NE Brazil

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A R T I C L E I N F O

Article history:
Received 31 March 2017
Received in revised form
3 September 2017
Accepted 17 September 2017
Available online 19 September 2017

Keywords:
Polycyclic deformation
Western Gondwana
Borborema Province
Accretion tectonics

A B S T R A C T

Combined geophysical and structural data from the Transversal Subprovince of the Borborema Province (NE Brazil) highlight the internal structure of, and interrelationships between, the constituent terranes. Radiometric and magnetic maps show distinctive signatures for the Archean-Paleoproterozoic Alto Moxotó and Meso-to Neoproterozoic Alto Pajeú and Pernambuco-Alagoas terranes. Mapped radiometric and first and second order magnetic lineaments, associated with Euler deconvolution, enable correlation between geophysical data and major structures. In addition to early related deformation of the Alto Moxotó Terrane, combined analysis of late transposition foliations, lineations and kinematic criteria reveal a complex structural evolution marked by two distinct assembly stages. The first phase is characterized by thrust tectonics with top-to-the-south vergence, resulting in the juxtaposition of the allochtonous Alto Pajeú Terrane with the structurally underlying Alto Moxotó Terrane. The terrane boundary is delineated by the Serra de Jabitacá Shear Zone, which is associated with low dipping collisional granitic sheets and ca. 1.0 Ga mafic-ultramafic rocks interpreted as obtudcted ophiolite remnants. Later strike-slip movements strongly folded and obliterated thrust-related markers, and the continental scale E-W Pernambuco Lineament is interpreted as the result of lateral assembly between the composite Alto Pajeú-Alto Moxotó terranes and the Pernambuco-Alagoas Terrane during the metamorphic peak of the Brasiliano orogeny. Evolution of the Borborema Province reflects accretionary processes during the assembly of Western Gondwana.

1. Introduction

Orogenic belts develop through convergent and collisional episodes of plate interaction, resulting in areas of strong regional deformation. Despite the unique internal architecture of each orogen, they can be classified into three major end members, which are often temporally connected: accretionary, collisional and intracratonic (Cawood et al., 2009 and references therein). Crustal accretion in orogens occurs through frontal, lateral or oblique plate motions (Colpron and Nelson, 2006; Cawood et al., 2011a; Tetreault and Builter, 2012). The final result is a complex mosaic of folds, thrust faults, and strike-slip shear zones formed in response to a strong component of crustal shortening. Examples include the Appalachian-Caledonian and the Himalayan chains that resulted in the closure of the Iapetus and Tethys oceans respectively, followed by a final stage of continent-continent collision. In addition, frontal subduction may be subsequently followed by major lateral displacements via strike-slip shear zones, obliterating or overprinting

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https://doi.org/10.1016/j.jsg.2017.09.012
0191-8141/

early deformation stages, such as in the North America Cordillera and Terra Australis orogens (Dickinson, 2004; Cawood et al., 2011b).

Tectono-stratigraphic terranes are an important component of the orogenic architecture and represent fault-bounded crustal blocks with geological histories distinct from adjoining blocks (Coney et al., 1980). In Western Gondwana, it is assumed that convergent plate motions resulted in systematic terrane accretion events, which in the South American and West African mobile belts are mostly related to the Neoproterozoic Brasiliano-Pan African orogeny (Caby, 2003; de Wit et al., 2008; Brito Neves et al., 2014). Among major Western Gondwana orogens, the Borborema Province (NE Brazil) is characterized by a complex array of deformation, magmatic and metamorphic events spanning almost all the Precambrian. The province is connected to Africa by major lineaments and suture zones, constituting a key region to investigate major geodynamic processes of Western Gondwana assembly. For instance, accretionary episodes within the Borborema Province are constrained by geochronological and geophysical data as shown by Brito Neves et al., 2000; Van Schmus et al., 2008; Santos et al., 2010; Lages and Dantas, 2016 and Padilha et al., 2016. However, the nature and kinematics of terrane assembly are poorly understood. In addition, as in other provinces of Gondwana, recent studies has given major emphasis on the role of intracontinental deformation, challenging the Neoproterozoic terrane accretion model (e.g. Neves et al., 2017).

In this paper, we combine airborne geophysical data (radiometry and magnetometry) and structural analysis of part of the Alto Pajeú, Alto Moxotó and Pernambuco-Alagoas terranes of the central portion of the Borborema Province. Our goal is to unravel the structural architecture of these domains, including the role of the major shear zones that bound and internally disrupt the terranes, as well as resolving the sequence of tectonic events that they have experienced. We aim to demonstrate the significance of integrating geophysics and field geology to understand episodes of terrane development and assembly in the region and to provide a model for unravelling the development of other Precambrian polydeformed orogens.

2. Geological setting

2.1. Borborema Province

The Borborema Province constitutes the northeastern portion of the Precambrian platform of South American (Almeida et al., 1981). It can be traced into West Africa through Benin, Nigeria and Cameroon and is located in the central part of Western Gondwana (Fig. 1; Trompette, 1994; Van Schmus et al., 2008). The province is bounded to the south by the São Francisco Craton, to the west by the Parnaíba Basin, and to the north and east by marginal basins, comprising highly deformed and frequently migmatised Paleoproterozoic terranes, locally including Archean fragments (Brito Neves et al., 2000; Fetter et al., 2000; Dantas et al., 2013). Such terranes are interleaved with early to late Neoproterozoic terranes, forming mobile belts with widespread metamorphosed volcano-sedimentary (mostly metapelitic) sequences (Van Schmus et al., 2003; Hollanda et al., 2015) and remnants of Ediacaran continental magmatic arcs (Fetter et al., 2003; Araujo et al., 2014; Brito Neves et al., 2014). Several major shear zones transect the Bordorema Province (e.g., Transbrasiliano-Kandhi lineament) and separate major domains, with the E-W trending Patos and Pernambuco dextral shear zones, dividing the Northern, Central and Southern Subprovinces. Available Ar-Ar thermo-chronological determinations and U-Pb data indicate that deformation occurred between 590 and 500 Ma (Monié et al., 1997; Corsini et al., 1998; Neves et al., 2008, among others). The province is thought to have undergone a polycyclic Neoproterozoic history of accretion and collision-related events (Van Schmus et al., 1995, 2011; Brito Neves et al., 2000; 2014; Santos et al., 2000). This is similar to the history inferred for the provinces African counterpart, along the Trans-Saharan belt between the Hoggar Shield and Benin-Nigerian Province (Black et al., 1994; Dawaï et al., 2017). An alternative model, argues that the province corresponds to an intracontinental orogen consolidated in response to Neoproterozoic far-field stresses (Neves, 2015).

The Northern Subprovince is divided into composite terranes surrounded by supracrustal rocks as well as magmatic arcs containing Archean to Neoproterozoic lithotectonic successions. The Transversal Subprovince is divided into five terranes: São José do Caiano, Piancó-Alto Brígida, Alto Pajeú, Alto Moxotó and Rio Capibaribe. The Southern Subprovince contains the Meso-Neoproterozoic Pernambuco-Alagoas Terrane, as well as Neoproterozoic mobile belts that surround the São Francisco Craton (Santos and Medeiros, 1999; Brito Neves et al., 2000).

The studied terranes are bounded by the Serra de Jabitacá Thrust system in the north and Pernambuco Lineament in the south. The former separates the Tonian Alto Pajeú Terrane (also referred to as the Cariris Velhos orogen) and the Archean-Paleoproterozoic Alto Moxotó Terrane. The Pernambuco Lineament can be traced for almost 700 km and is correlated with the Adamoua Lineament in NW Africa. It displays dextral shear criteria and HT- and LT-mylonitic fabrics associated with Ediacaran granitic plutons (Davison et al., 1995; Neves and Mariano, 1999). The contrasting geological evolution on either side of this structure, the association with calc-alkaline arc-related magmas and the high strain conditions has led some authors, including Santos (1995); Brito Neves et al. (2000) to consider it as a major crustal boundary. This interpretation is also supported by different geophysical potential methods (Oliveira, 2008; Lima et al., 2015; Santos et al., 2014).

2.1.1. Alto Pajeú Terrane

The overall northeast-southwest trending Alto Pajeú Terrane is separated from the Piancó-Alto Brígida Terrane to the northwest by the NE-SW strike-slip Serra do Caboclo sinistral shear zone, and from the Alto Moxotó Terrane to the southeast by the poorly-defined Serra de Jabitacá thrust system (Santos and Medeiros, 1999, Fig. 2). The terrane is characterized by calc-alkaline and peraluminous Tonian granites with arc-related to syn-collisional geochemical signatures, metamafic rocks and metaultramafic rocks, including remnants of ophiolites and deep-arc roots (Serrote das Pedras Pretas Suite). It also includes pelitic metasedimentary and meta-volcanoclastic rocks of the São Caetano Complex that are interpreted to have formed in a back arc basin environment (Brito Neves et al., 1995; Santos, 1995; Lages and Dantas, 2016). The terrane is the type area for the Cariris Velhos orogeny (ca. 1.0–0.96 Ga, Kozuch, 2003; Santos et al., 2010). Paleoproterozoic crust is largely absent from the Alto Pajeú Terrane, which is abundant in the adjoining Alto Moxotó Terrane. Similar assemblages also occur in other parts of the province (Carvalho, 2005; Oliveira et al., 2010; Caxito et al., 2014a). Furthermore, Ediacaran granites are widespread and cross-cut the main supracrustal associations of the Cariris Velhos orogen, including the Serra do Arapuá, Riacho do Icó, and Quixaba plutons (Santos, 1995; Santos and Medeiros, 1999).

2.1.2. Alto Moxotó terrane

The Alto Moxotó Terrane corresponds to a high-grade metamorphic crustal block composed of orthogneisses, migmatites and metagranites (Floresta Suite), mafic-ultramafic rocks (Malhada Vermelha or Carmo Suites) and supracrustal sequences (Sertânia Complex) that experienced accretion and collision events between ca. 2.4 to 2.0 Ga (Fig. 2; Santos et al., 2004, 2015a). It records a major

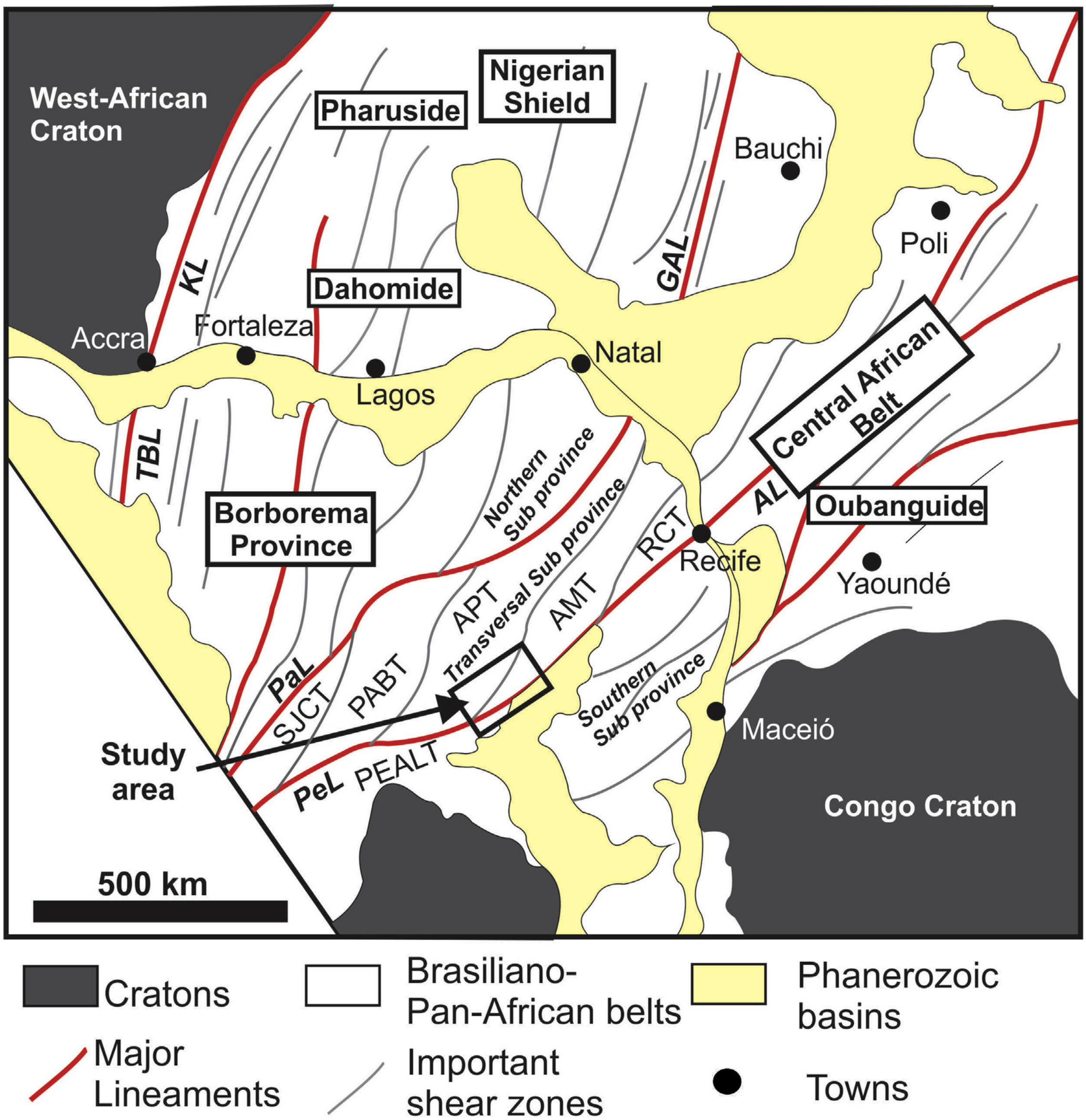

Fig. 1. a) Pre-drift reconstruction of Northeast South America and West Africa in Western Gondwana context with the main structural provinces and lineaments on its current position. SJCT = São José do Caianho Terrane, PABT = Piancó Alto-Brigída Terrane, APT = Alto Pajeú Terrane, AMT = Alto Moxotó Terrane, RCT = Rio Capibaribe Terrane, TBL = Transbrasiliano Lineament, KL - Khandi Lineament, PaL = Patos Lineament, GAL = Garoua Lineament, PeL = Pernambuco Lineament, AL = Adamoua Lineament.

eclogite to granulite facies metamorphic peak at ca. 1.9 Ga (Neves et al., 2015). Its boundary with the Southern Subprovince is the E-W continental scale dextral strike-slip Pernambuco Lineament (Fig. 2).

Santos et al. (2015b) have recently documented Neoarchean TTG rocks (Riacho das Lajes Suite) in the inner portion of the terrane, which are unique within the Transversal Subprovince. Furthermore, the terrane lacks evidence for the Cariris Velhos and Brasiliano orogenic events, but does contain minor occurrences of Cambrian A-type granites along its margins (Guimarães et al., 2005). Such features led several authors, including Brito Neves et al. (2000) and Santos et al. (2004) to consider this domain as an exotic Paleoproterozoic fragment within the Neoproterozoic Transversal Subprovince.

2.1.3. Pernambuco-Alagoas Terrane

The Pernambuco-Alagoas Terrane occupies the northern portion of the Southern Subprovince. The southern limit of this terrane is defined by the Belo Monte Jeremoabo Shear Zone (Brito Neves et al., 2000). The main geological units of the terrane range in age from ca. 1.13 to 0.96 Ga and are represented by the Cabrobó supracrustal sequence, which includes paragneisses, metagraywackes and calc-silicate rocks, and the Belém do São Francisco Complex, composed of granitic to granodioritic banded orthogneisses and migmatites (Fig. 2; Silva Filho et al., 2010 and references therein).

The structural framework of the terrane is interpreted as the result of intense Brasiliano-related deformation overprinting a Tonian fabric. One of the most important characteristics is the widespread occurrence of Ediacaran to Cambrian granitic intrusions, which are completely absent in the adjacent Alto Moxotó Terrane. These include mainly high-K calc-alkaline to shoshonitic batholiths, which has been recently grouped as Buíque-Paulo Afonso, Águas Belas-Canindé, Maribondo-Correntes and Ipojuca-Atalaia (Silva Filho et al., 2010), as well as minor bodies like the

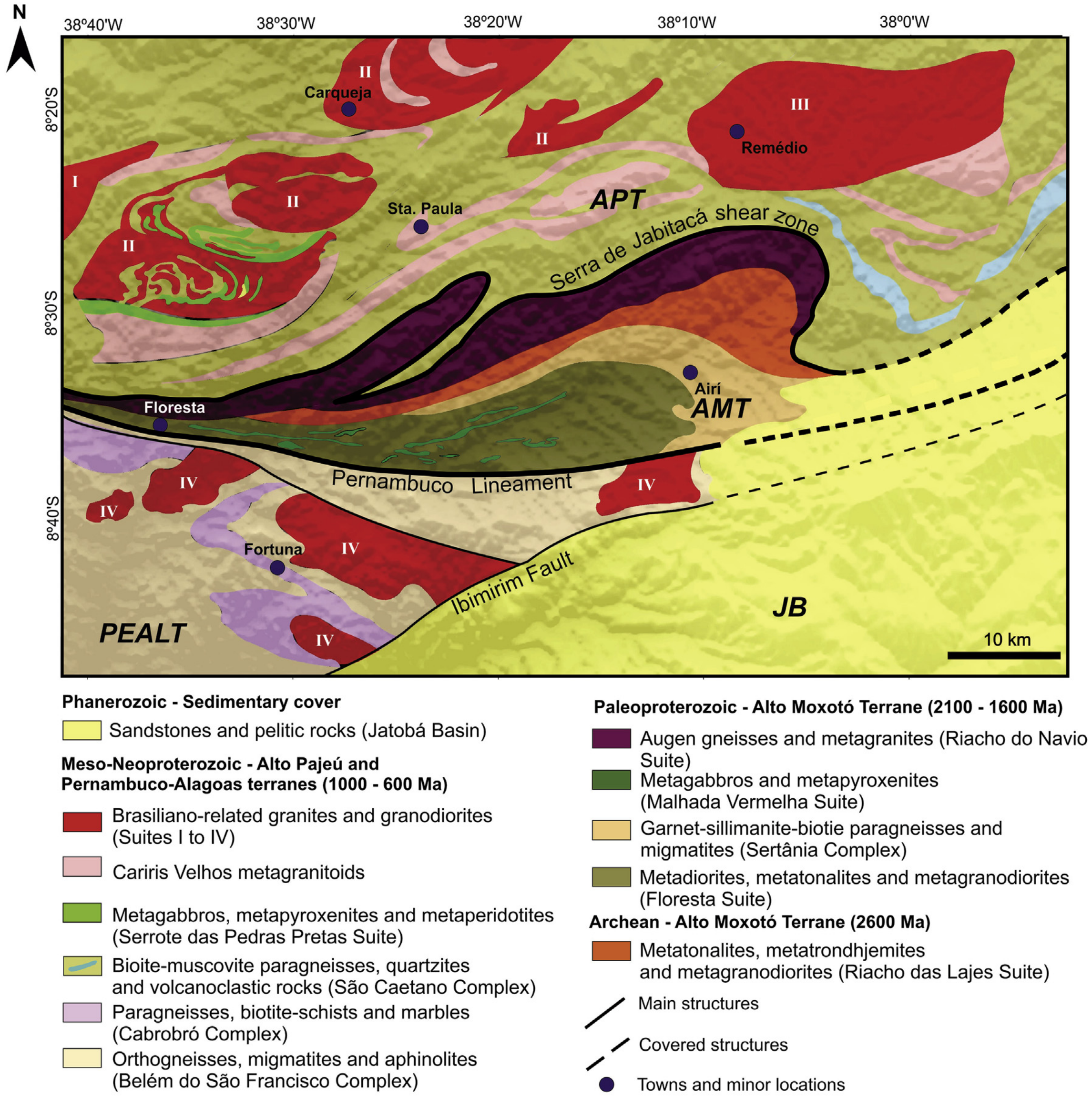

Fig. 2. Geological map of the study area. Ediacaran granitic suites: I = Serra do Arapuá, II = Riacho do Icó, III - Quixaba, IV = Fortuna. Terranes: APT = Alto Pajeú, AMT = Alto Moxotó, PEALT = Pernambuco Alagoas. JB = Jatobá Basin. The thicker black lines corresponds to the proposed geological Terrane boundaries.

Fortuna intrusion, which are interleaved with Paleoproterozoic supracrustal sequences (Silva Filho et al., 2014). Such granitic rocks mark the development and evolution of a continental arc during the Brasiliano orogeny. Recently, local occurrences of Archean rocks has also been described in the westernmost portion of this terrane (Cruz et al., 2015).

3. Geophysical dataset

Airborne radiometric and magnetic data for the study area were obtained from the Pernambuco-Paraíba and Paraíba-Rio Grande do Norte projects undertaken by the Geological Survey of Brazil (CPRM) in 2010 that cover an area of 134.644,89 km^2. These data were used to identify anomalies, delimit areas of contrasting geophysical character, and define lineaments within and between terranes (Fig. 3).

The N-S-trending flight lines were spaced at 0.5 km, whereas E-W tie lines were spaced at 10 km. The nominal flight height and speed were 100 m and 270 km/h, respectively (Lasa and Prospectors, 2010), and sampling intervals were 1 s for the gamma spectrometer and 0.1 s for magnetometer. Geophysical data were processed with the GEOSOFT Oasis Montaj 8.0 at the University of Brasília.

Total count (TC), eTh/K ratio as well as RGB (RGB = red, green and blue) ternary composition maps were created using the gamma-ray spectrometric data to delimit compositional variations across the study area (Jaques et al., 1997). For analysis of magnetic data, we used the Magnetic anomaly (MA), First Vertical Derivative (DV), Total Gradient (TG) and Tilt Derivative (TDR). The total gradient is suitable for identification of the borders of magnetic bodies in regions of low latitude and in the presence of significant remanence when sources of interest are shallow or very regional (Li, 2006; Isles and Rankin, 2013). Tilt derivative (Miller and Singh, 1994) was applied to enhance the edges of magnetic sources related to geological contacts and structural fabric.

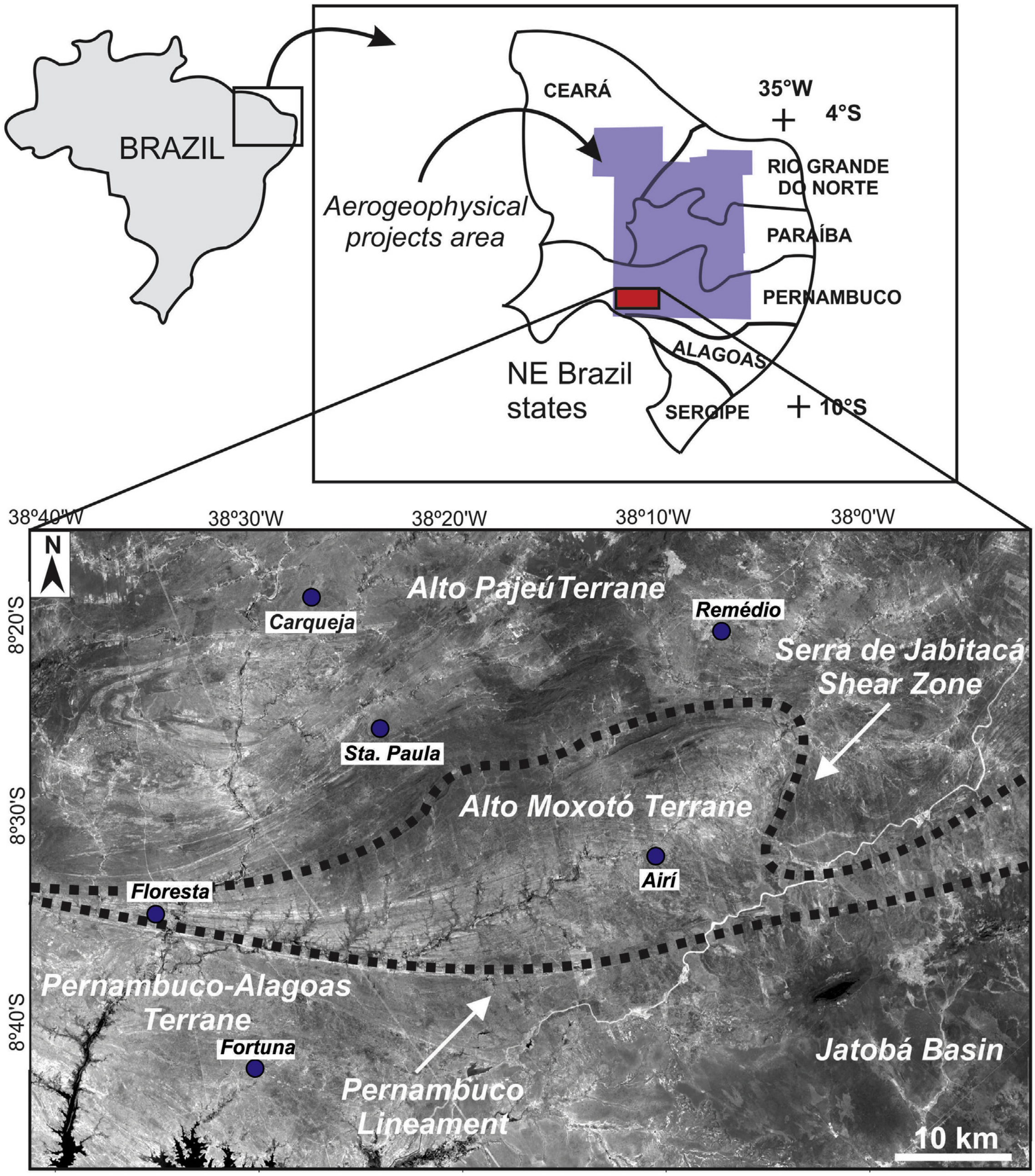

Fig. 3. Covered area by the Pernambuco-Paraíba and Paraíba-Rio Grande do Norte geophysical projects from Brazilian Geological Survey in NE Brazil, with a satellite image of the study area. The thick black dashed line represents the terrane boundaries.

4. Results

4.1. Gamma ray spectrometric data

Interpretation of radiometric data was based on the distribution of the radioelements in order to define major contrasts between the studied terranes. All channels (K, eTh and eU) were used to obtain general information about the study area (not shown), but with major emphasis given to the Total Count (TC), eTh/K ratio and composite RGB (Figs. 4 and 5). The TC map was used to define a total of 11 radiometric domains (A to K), which are closely associated to the major mapped geologic units (Fig. 2). The strong correlation between radiometric and field geological data reflects the low relief and scarce vegetation cover in the study area. Major and secondary lineaments, were identified on the basis of trends in the radiometric data.

The Alto Pajeú Terrane comprises the majority of identified radiometric domains. Domains A and B are characterized by moderate to strong K values, which correspond to the Brasiliano plutonic suites; the Riacho do Icó suite has granodioritic to granitic composition, whereas Quixaba and Serra do Arapuá suites correspond to monzo-to syenogranites. Domain C corresponds to a northeast elongated body with slight enrichment of K values, and correlates with the Cariris Velhos metagranites. Domain D is characterized by intermediate concentration of radionuclides (Fig. 4a and b). This signature can be attributed to supracrustal rocks, specifically muscovite-schists and intermediate metavolcanic rocks of the São Caetano Complex. In this terrane, Domain I

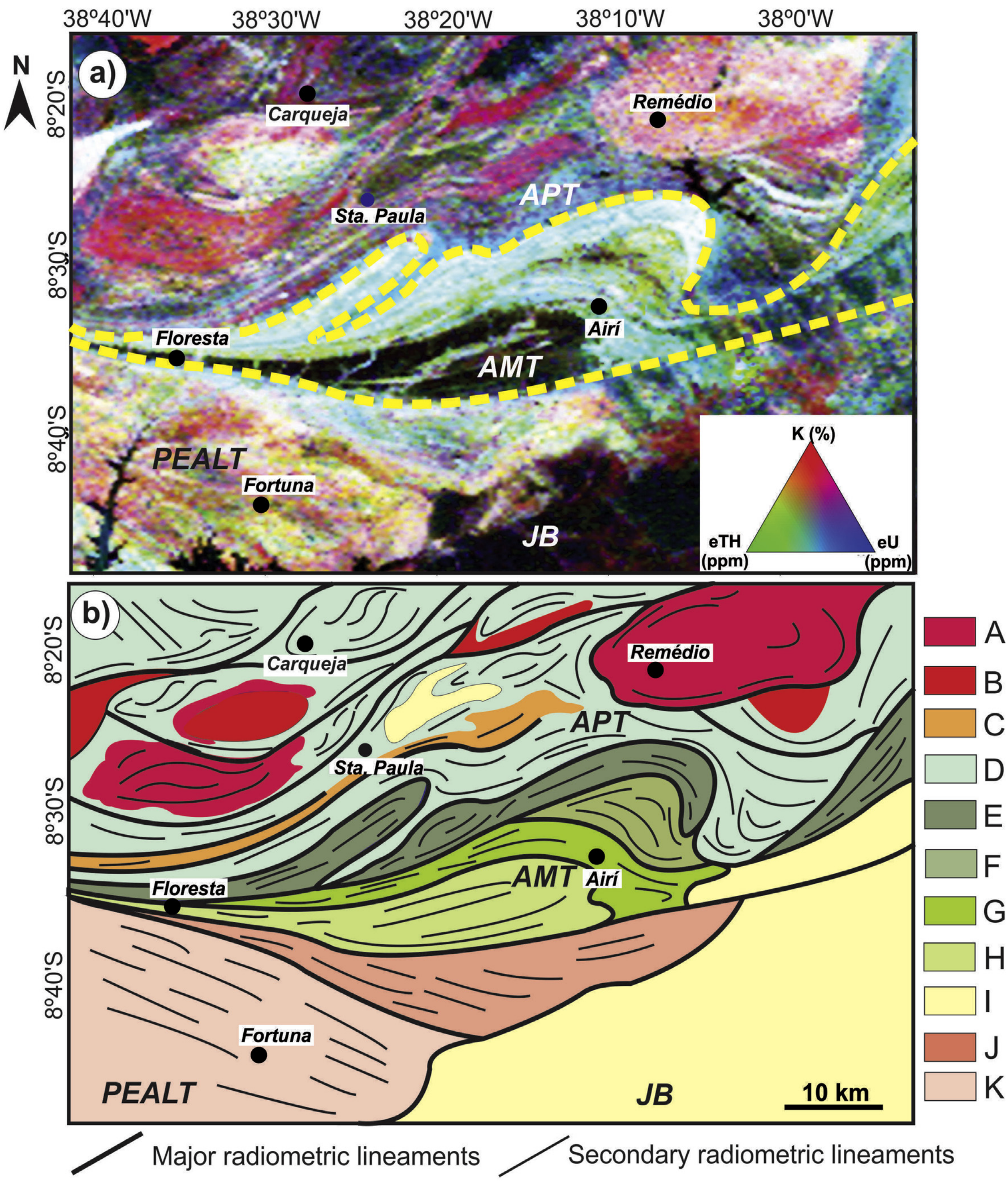

Fig. 4. Gamma-ray spectrometric products of the study area: a) Ternary RGB composition map; b) map of interpreted radiometric domains. Such domains are defined by contrasting signatures on the total count map. The thick yellow dashed line represents the geophysical terrane boundaries. The same is displayed in Fig. 5–7. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

corresponds to a local, discontinuous, poorly mapped Phanerozoic cover which has a very similar pattern to the Jatobá Basin in the SE portion of the study area. In addition, the gamma-ray spectrometric map of the Alto Pajeú Terrane is characterized by the alternation of low and high contents of radionuclides (Fig. 5a). The rock heterogeneity within the Alto Pajeú Terrane is reflected in values ranging from low to high on the TC map (6.9–28.5 μR/h). Low to moderate values are attributed to supracrustal rocks of the São Caetano Complex, whereas higher values record the signature of Brasiliano granitoids. This correlation is consistent with the distribution of eTh/K values (Fig. 5b). Radiometric-defined lineaments are mostly oriented in the NE-SW direction (Fig. 5c and d).

The Alto Moxotó Terrane presents a heterogeneous distribution of radionuclides, recorded by domains E, F, G and H (Fig. 4a and b). E domain is characterized by intermediate eU and eTh compositions, and corresponds to highly deformed monzogranitic gneisses, possibly enriched in monazite. F domain is represented by enrichment in eTh as compared to the other radionuclides, which is attributed to the Archean tonalitic, trondhjemitic and granodioritic rocks of the Riacho das Lages Suite. The G domain displays an intermediate distribution of K, eTh and eU, and is associated with metagraywackes, paragneisses and migmatites of the Sertânia Complex. Domain H has low values of radionuclides, where TC is around 6.9 μR/h (Fig. 5a), reflecting the dioritic to granodioritic

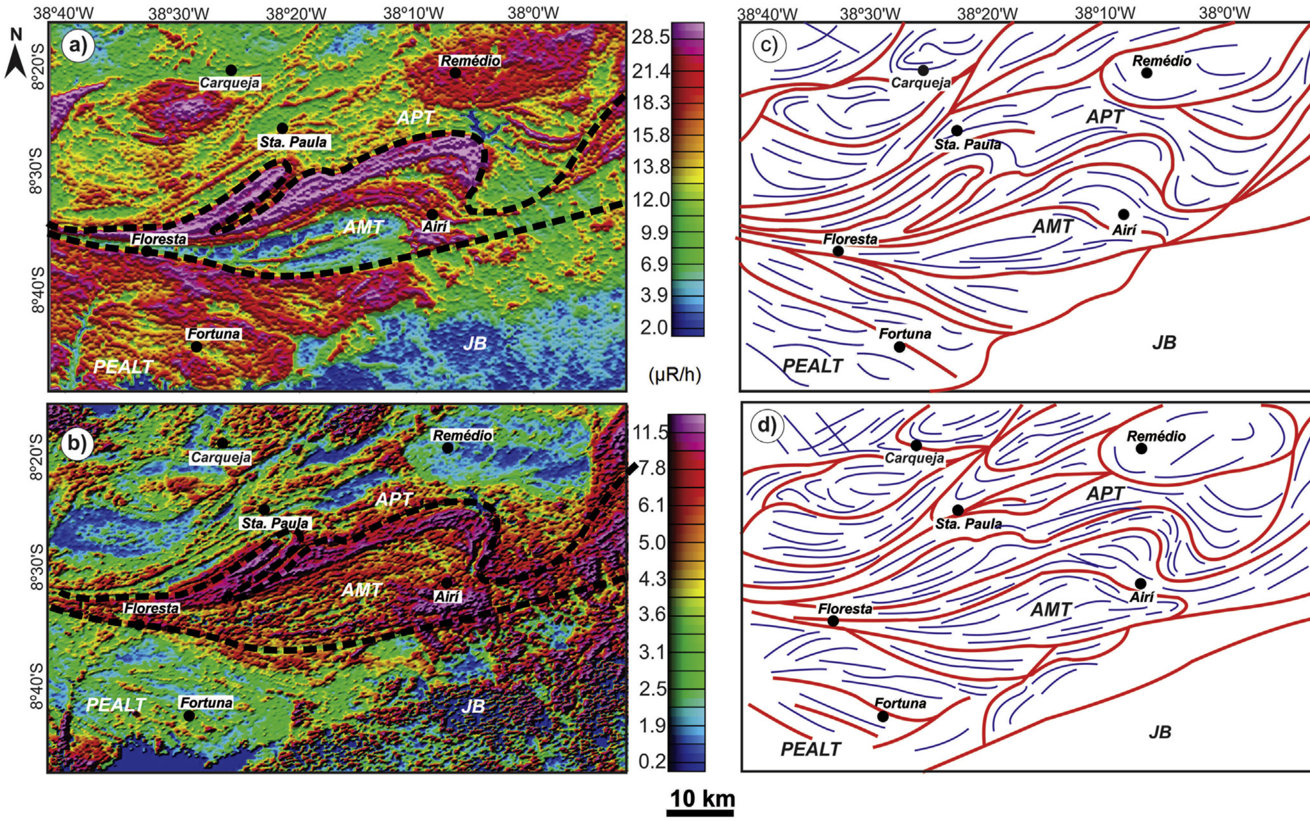

Fig. 5. Gamma-ray spectrometric maps as well as the main proposed terrane boundaries (thick black dashed lines): a) Total count (μR/h); b) eTh/K ratio. c) and d) corresponds to structural interpretations of a) and b) respectively. The thick red lines represent the major radiometric lineaments, whereas the blue lines correspond to secondary lineaments on c) and d). The same is displayed in Fig. 6–8. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

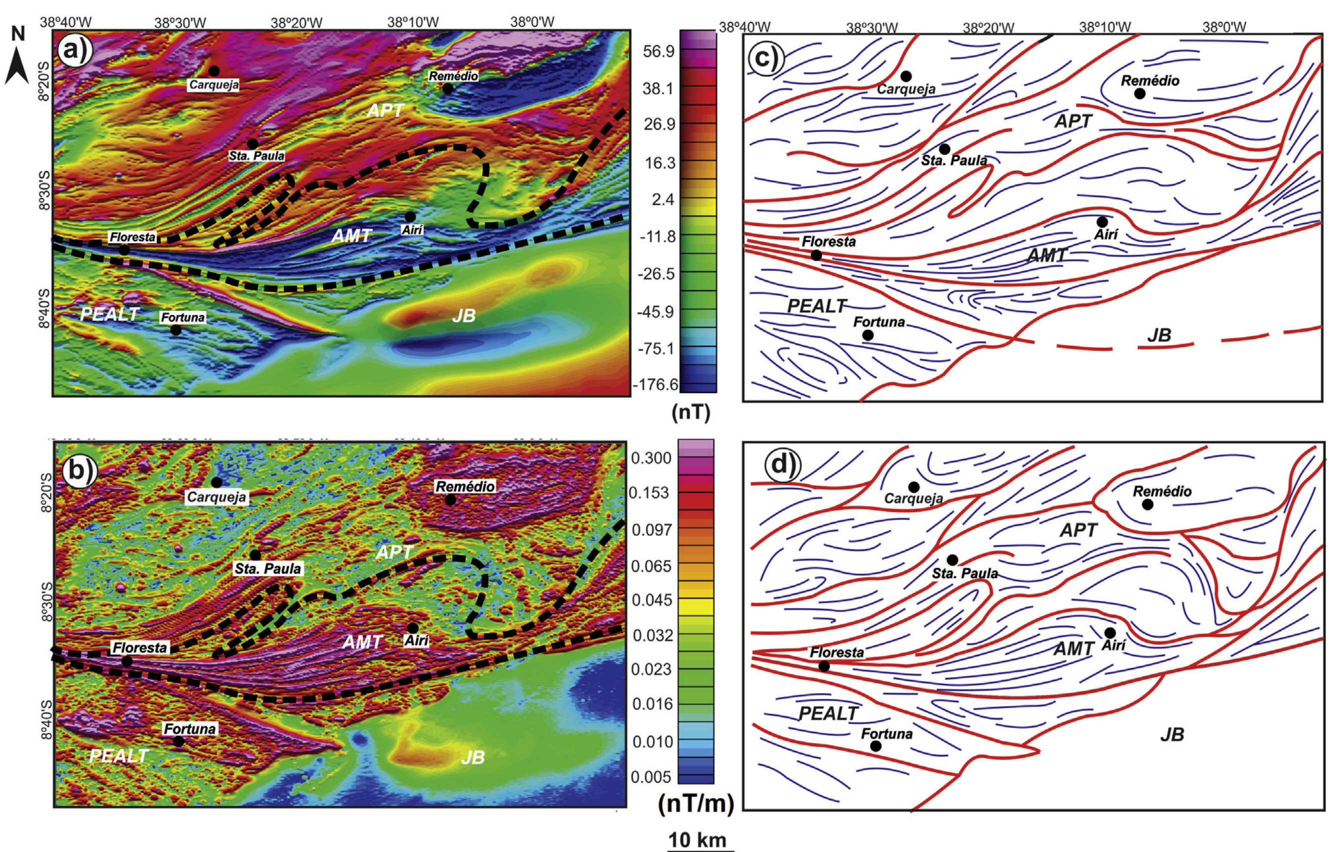

Fig. 6. Magnetic maps: a) Magnetic anomaly and b) Total Gradient. c) and d) corresponds to structural interpretations of a) and b) respectively.

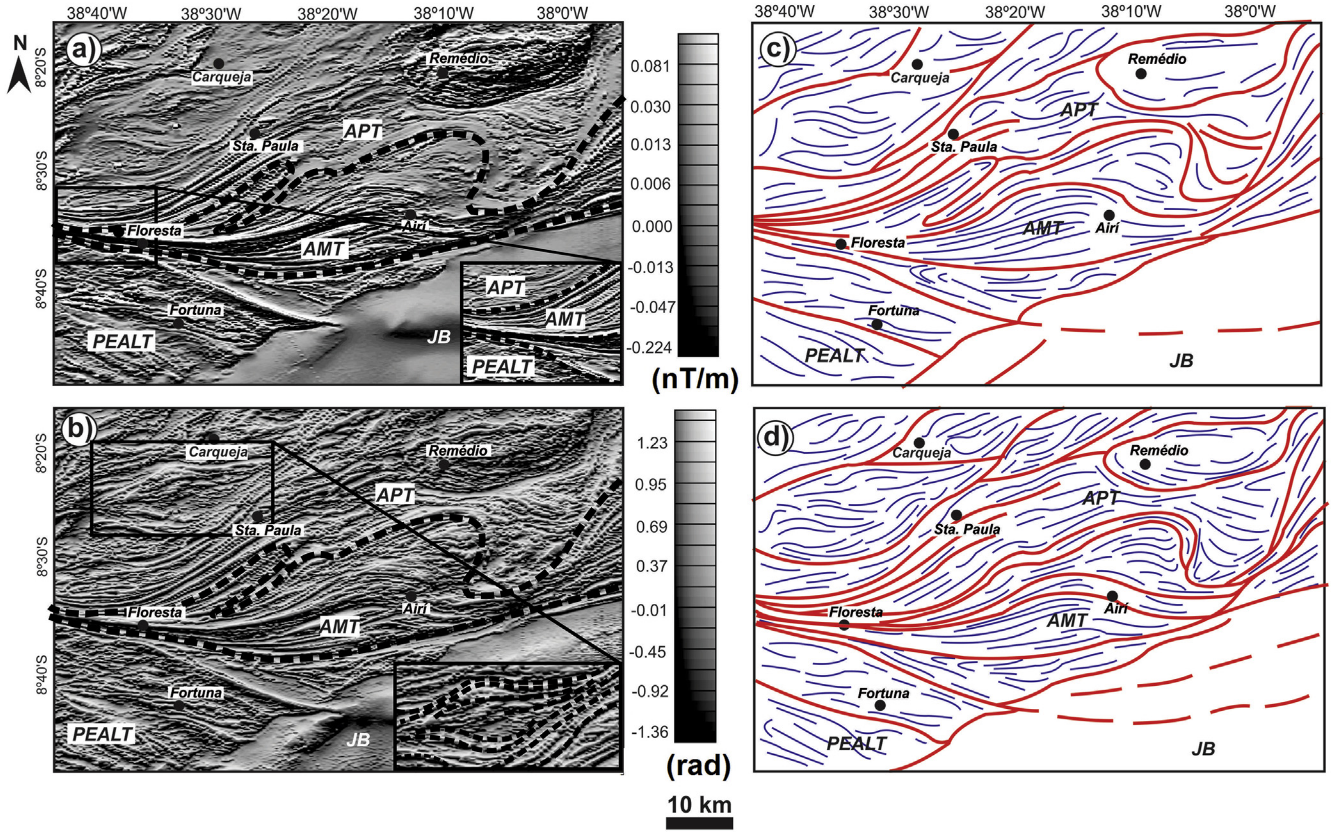

Fig. 7. Magnetic products: a) First vertical derivate and b) Tilt derivate maps. Note the splay termination of shear zones between the studied terranes as well as sigmoid shapes imposed by the intercalation of magnetic structures. c) and d) corresponds to structural interpretations of a) and b) respectively. The black boxes represent regional structures revealed by geophysics: on a) - The splay termination of terrane boundaries and b) major sigmoid formed in response to conjugated pairs of strike-slip shear zones.

Table 1
Major characteristics of the interpreted magnetic domains on the TG, First and Tilt derivative maps.

Interpreted magnetic domain	Terrane	Average directions of magnetic lineaments	Description
I	Alto Pajeú	N40°E and E-W	Irregular magnetic relief reflecting localized magnetic sources with associated gradients ranging from 0.013 to 0.0032 nT/m.
II	Alto Pajeú	N25°E	Slightly irregular magnetic relief and high magnetic anomalies values, ranging from 16.3 to 56.9 nT (Fig. 6a) with intermediate to high gradients (0.032–0.300 nT/m).
III	Alto Pajeú	N65°E and S80°E	Very low magnetic anomalies, ranging between 17.6 and −75.1 nT. Average magnetic gradients are 0.300 nT/m.
IV	Alto Pajeú	E-W and N75°E	Rugged magnetic pattern, considerably high magnetic intensity (>45.7 nT) and high gradients (0.200 nT/m).
V	Alto Moxotó	N42°E	Rugged magnetic pattern and a curvilinear shape with high magnetic intensities (16.3–38.1 nT).
VI	Alto Moxotó	N65°E	Elongated and folded shape, being characterized by high magnetic values (16.3–38.9 nT) and low gradients (0.016–0.032 nT/m).
VII	Alto Moxotó	N35°E, N75°E, E-W and N-S	Rugged magnetic relief with mostly negative magnetic anomalies (−26.5–11.8 nT). Gradients are mostly low (0.016–0.023 nT/m), excepted to localized higher values.
VIII	Alto Moxotó	E-W	Very low magnetic anomaly values (around −75.1 nT) and high gradients (>0.153 nT/m).
IX	Pernambuco-Alagoas	E-W and N45°W	Low magnetic expression (−45.9 nT), except for local magnetic peaks. High gradients ranging from (0.054 to 0.153 nT/m).
X	Pernambuco-Alagoas	N60°W	Very low magnetic intensity anomalies, ranging from −75.1 to −26.5 nT and gradients are intermediate to high (0.032–0.153 nT/m).
XI	Pernambuco-Alagoas	N75°W	Low to intermediate magnetic anomalies and gradients ranging from −11.8 to −16.3 nT and 0.027 −0.045 nT/m, respectively.

Floresta Suite as well as intercalated mafic bodies of the Malhada Vermelha Suite. The radiometric signature of domains E, F and G marks a progressive increase of eTh/K ratio from south to north (Fig. 5b). Radiometric lineaments of the Alto Moxotó Terrane are intensively folded, but in the southern portion they trend largely E-W (Fig. 5c and d).

The Pernambuco-Alagoas Terrane is subdivided into radiometric domains J and K. Both domains comprise metamorphic rocks of the Belém do São Francisco Complex, however the more potassic signature of K domain can be related to the presence of K-rich syenitic to alkali-feldspar granitoids of the Fortuna Suite (Fig. 4a and b). The radiometric signature observed on the TC map (Fig. 5a) shows an overall relatively homogeneous distribution of radionuclides, ranging from intermediate to slightly high (15.8–21.4 μR/h). However, anomalously high values (>21.4 μR/h) punctuate the area and correlate with Brasiliano K-rich granites (Fig. 5a). In addition,

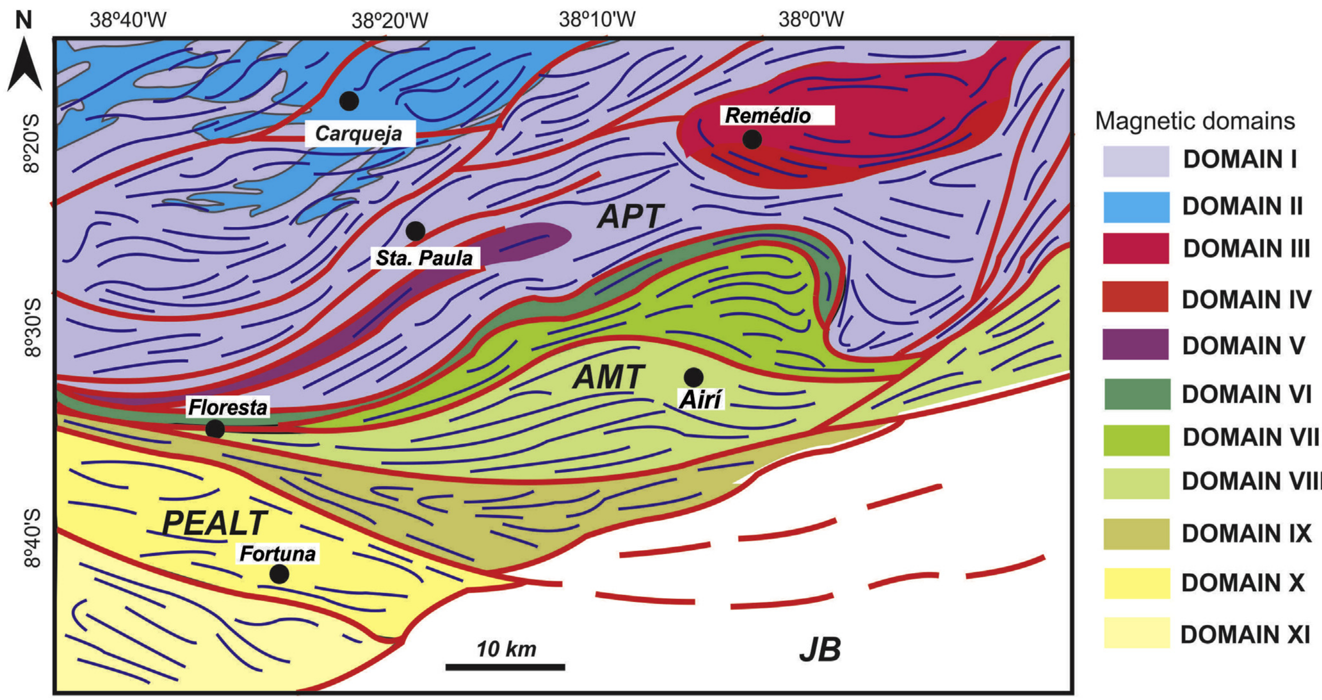

Fig. 8. Interpreted magnetic domains and main magnetic lineaments for the study area. The different magnetic domains were interpreted based on gradient, relief and orientation of first order and second order lineaments.

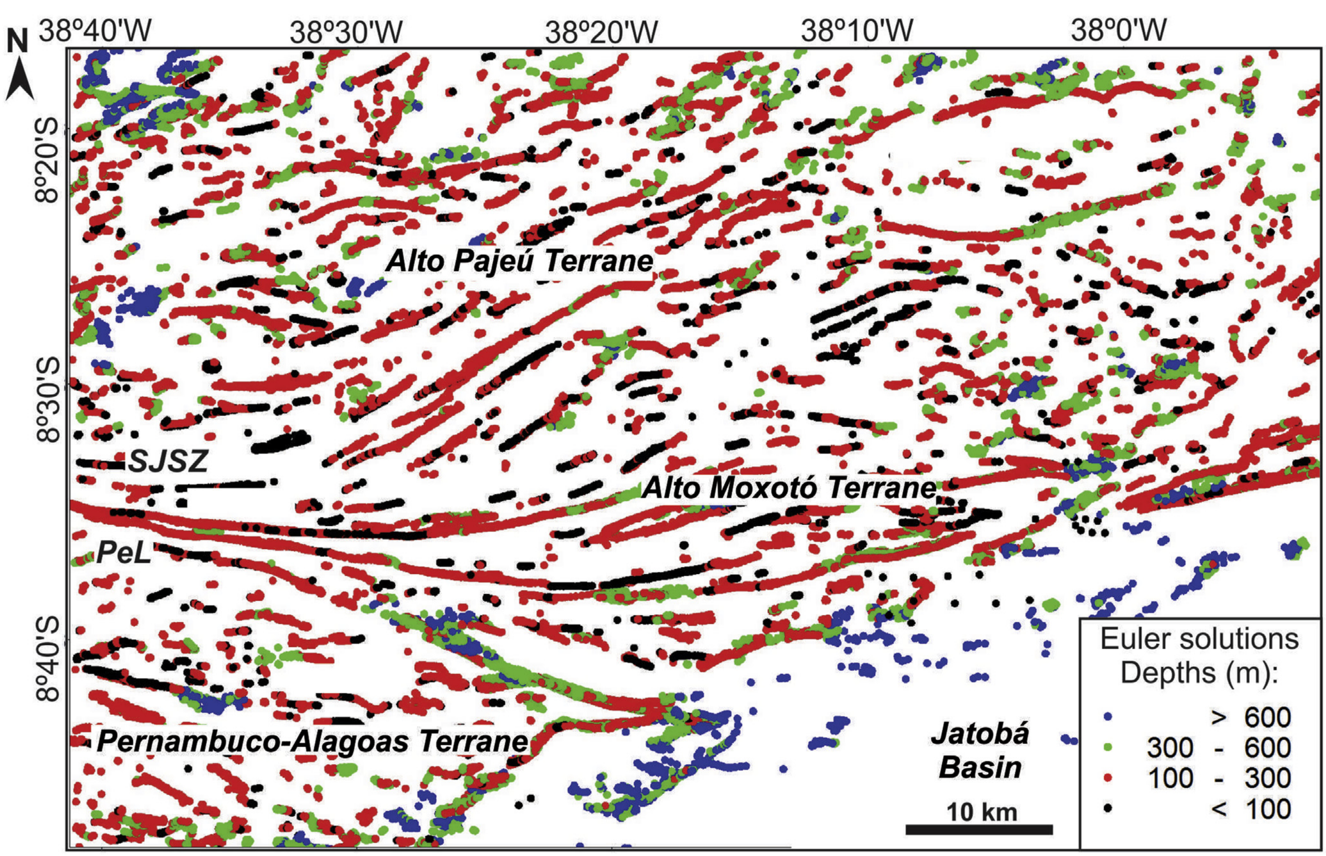

Fig. 9. 3D Euler deconvolution for the study area for structural index 1. PeL = Pernambuco Lineament, SJSZ = Serra de Jabitacá Shear zone.

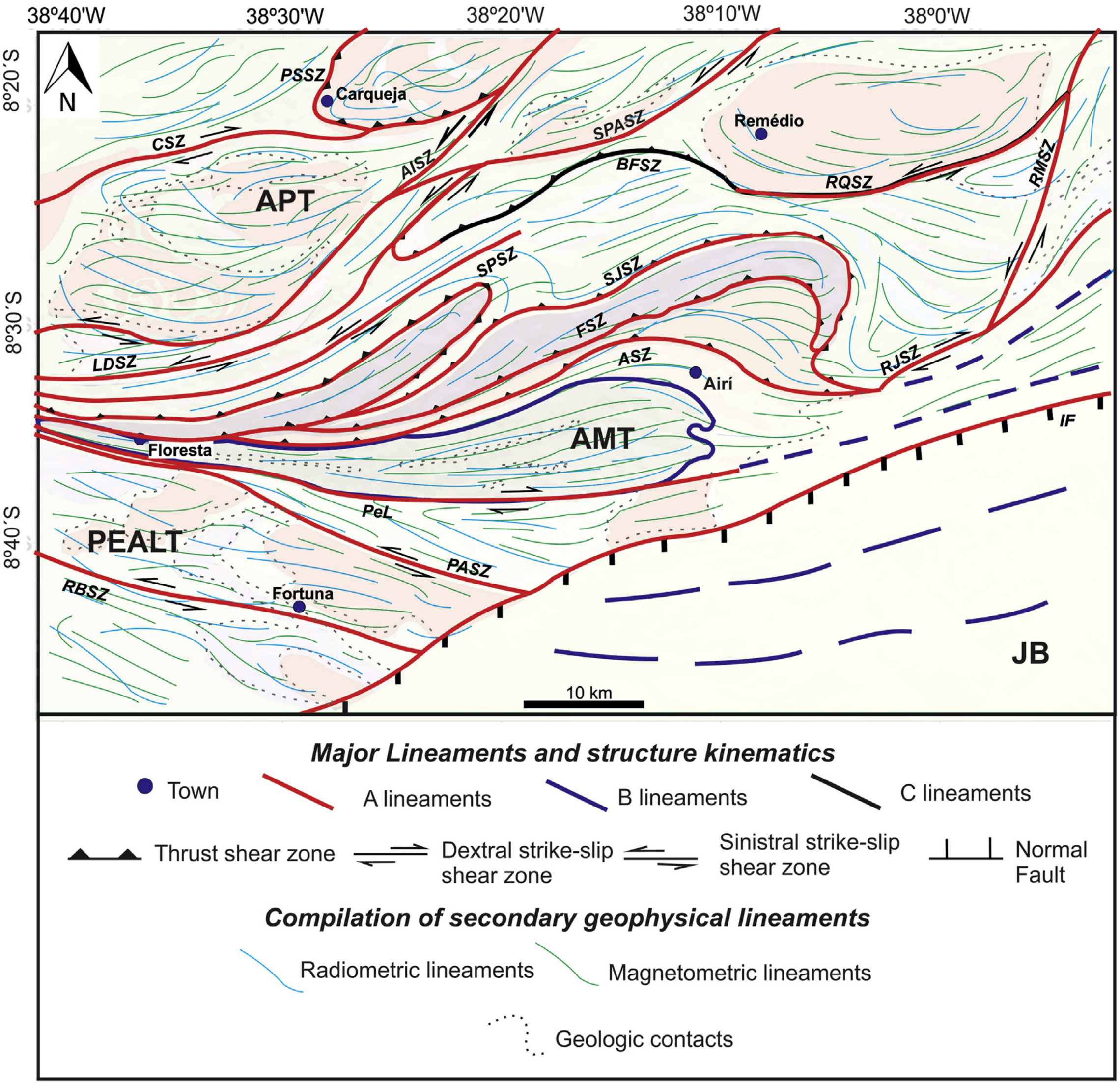

Fig. 10. Integrated geophysical and geological data for the main structures of the study area. PSSZ = Poço do Salgueiro shear zone; CSZ = Carqueja shear zone; AISZ = Afogados da Ingazeira Shear zone; SPAZ = Santa Paula Shear Zone; LDZ = Lagoa do Defunto Shear Zone; SPSZ = São Pedro Shear Zone; BFSZ = Barra da Forquilha Shear Zone; RQ = Riacho Quixaba Shear Zone; SJSZ = Serra de Jabitacá Shear Zone; FSZ = Floresta Shear Zone; AISZ = AiríShear Zone; RJSZ = Riacho Jacaré Shear Zone; PeL = Pernambuco Lineament; PASZ = Poço da Areia Shear Zone; RBSZ = Riacho do Buraco Shear Zone; RMSZ = Riacho da Maravilha Shear Zone; IF = Ibimirim Fault.

the eTh/K ratio map (Fig. 5b) is characterized by very low ratios (1.9–2.5). Within the Pernambuco-Alagoas Terrane, radiometric lineaments follow a NW-SE trend (Fig. 5c and d).

4.2. Magnetic data analysis

Integration of MA and TG maps (Fig. 6a and b) enable delineation of the main magnetic domains. Combining these data with First derivative and Tilt derivative maps allowed recognition of major structural trends (Fig. 7a and b): first order lineaments include boundaries of magnetic domains whereas second order lineaments correspond to alignments within domains (Fig. 6c, d, 7c and 7d). Based on major variations of magnetic gradient values, amplitudes, reliefs and pattern of structural lineaments, we identified eleven magnetic domains (Table 1 and Fig. 8).

4.2.1. Euler deconvolution

In order to obtain additional information on source position and depths to residual magnetic sources, we performed Euler deconvolution (Thompson, 1982; Reid et al., 1990). In our approach, we choose a structural index of 1 and an associated window of 1250 m. Overall, the position of Euler solutions is in agreement with the location of the magnetic lineaments (Fig. 6). Four main categories of depth intervals were recognized: less than 100 m, between 100 and 300 m, between 300 and 600 m and more than 600 m (Fig. 9). Depths varying from 0 to 100 m are mainly present in the Alto Pajeú Terrane, but are also present to a lesser extent in the other terranes. Linear features ranging from 100 to 300 m in depth are widespread in all terranes, including the proposed terrane boundaries. Sources ranging from 300 to 600 m are relatively scarce, and occur mostly along major lineaments in NWSE, ENE and NE-SW directions in the Pernambuco-Alagoas, Alto Moxotó and Alto Pajeú terranes. Deeper solutions (>600 m) in the studied terranes are concentrated in the NW region of the Alto Pajeú terrane and in the central portion of the Pernambuco-Alagoas terrane. In addition, deeper solutions are present along NW linear features of the Jatobá Basin.

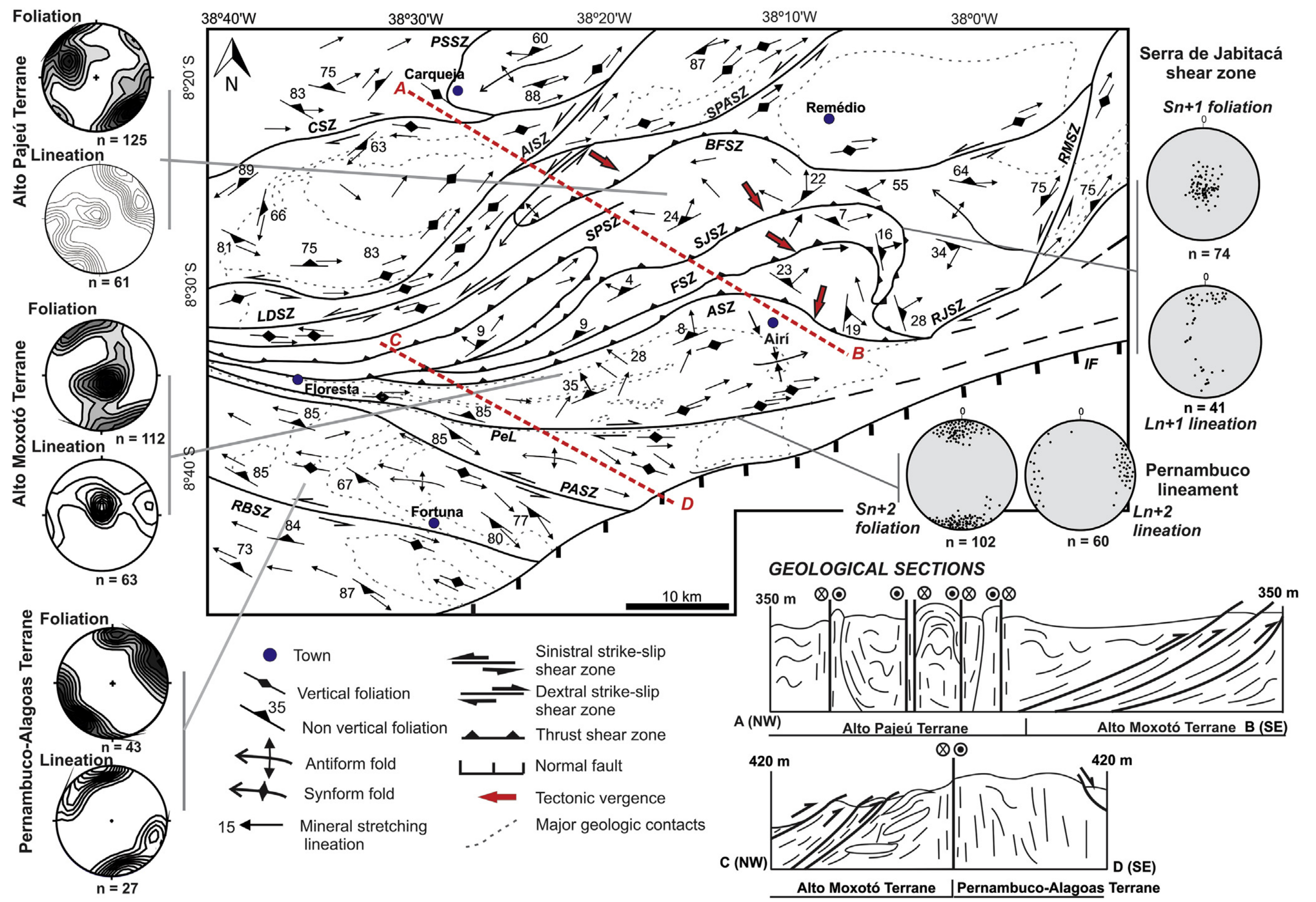

Fig. 11. Structural map of the study area with schematic geological sections and synthetic contour plots stereograms (lower hemisphere Schmidt projections). Structures label are as in Fig. 10.

4.3. Structural analysis

A detailed mesoscopic and microscopic structural analysis was conducted in the orthogneisses and supracrustal rocks of the study area. It was guided by lineament types delineated by geophysical interpretations. On this basis we defined three categories of lineaments (A-C). “A” lineaments are those that are well displayed on radiometric and magnetic maps, and are confirmed by field data. “B” lineaments were only identified on the magnetic products, mostly because of the Phanerozoic cover of the Jatobá Basin. “C” lineaments were not identified on the geophysical maps, but were observed in the field (Fig. 10). Structural markers and overprinting relationships allowed us to define three ductile deformation stages: D_n, D_{n+1} and D_{n+2}, and the brittle D_{n+3}. The distribution of field measurements of planar and linear fabrics as well as structural geological sections are presented in Fig. 11.

4.3.1. Ductile deformation stages

Ductile deformation is responsible for the strongly penetrative planar fabric in orthogneisses and supracrustal rocks. It is also responsible for the generation of different tectonites, which occur associated to the first and second order lineaments identified on the magnetic maps.

The D_n deformation corresponds to the random migmatitic fabric, and is restricted to the central portion of the Alto Moxotó Terrane. Recognition of its nature as well its associated kinematic markers are difficult to resolve in the field, as they are partially to totally overprinted and obliterated by later structures. D_n is characterized by the development of foliation planes (S_n) found in migmatitic portions of the Riacho das Lajes Suite and Sertânia Complex. The associated metatexitic facies are frequently folded and cross-cut by vein-like structures in zones of intense in situ anatexis. The main D_n structures appears as open to tight folds in stromatic veins probably formed during partial melting (Fig. 12a) with hinge lines plunging towards N-S, NE-SW and NW-SE directions. Schollen and raft structures are also observed (Fig. 12b).

D_{n+1} structures are abundant at the contact between the Alto Pajeú and Alto Moxotó terranes. They are characterized by a series of thrust surfaces that coincide with first order magnetic lineaments inside D_n. The main associated rocks are proto-mylonites and mylonites that develop planar and plano-linear fabrics, especially in rocks of the São Caetano Complex, and Tonian Cariris Velhos metagranites in the Alto Pajeú Terrane and in the Riacho do Navio, Riacho das Lajes and Floresta Suite in the Alto Moxotó Terrane. We analyzed four thrust-directed shear zones, which from north to the south are: Barra de Forquilha (BFSZ), Serra de Jabitacá (SJSZ), Floresta (FSZ) and Airí (ASZ, Fig. 11). These structures trend mainly NE-SW and E-W forming a major tectonic horse system. They are characterized by flat-lying to gently dipping S_{n+1} foliation (Fig. 11; Fig. 12c), which can locally form duplex structures at map scale. The foliations dip moderately to the N and NW and are associated with a stretching mineral lineation (L_{n+1}) with medium to high pitch values (Fig. 12d). S_{n+1} foliation planes can be truncated or folded by S_{n+2} fabrics, resulting in tight to isoclinal antiforms and

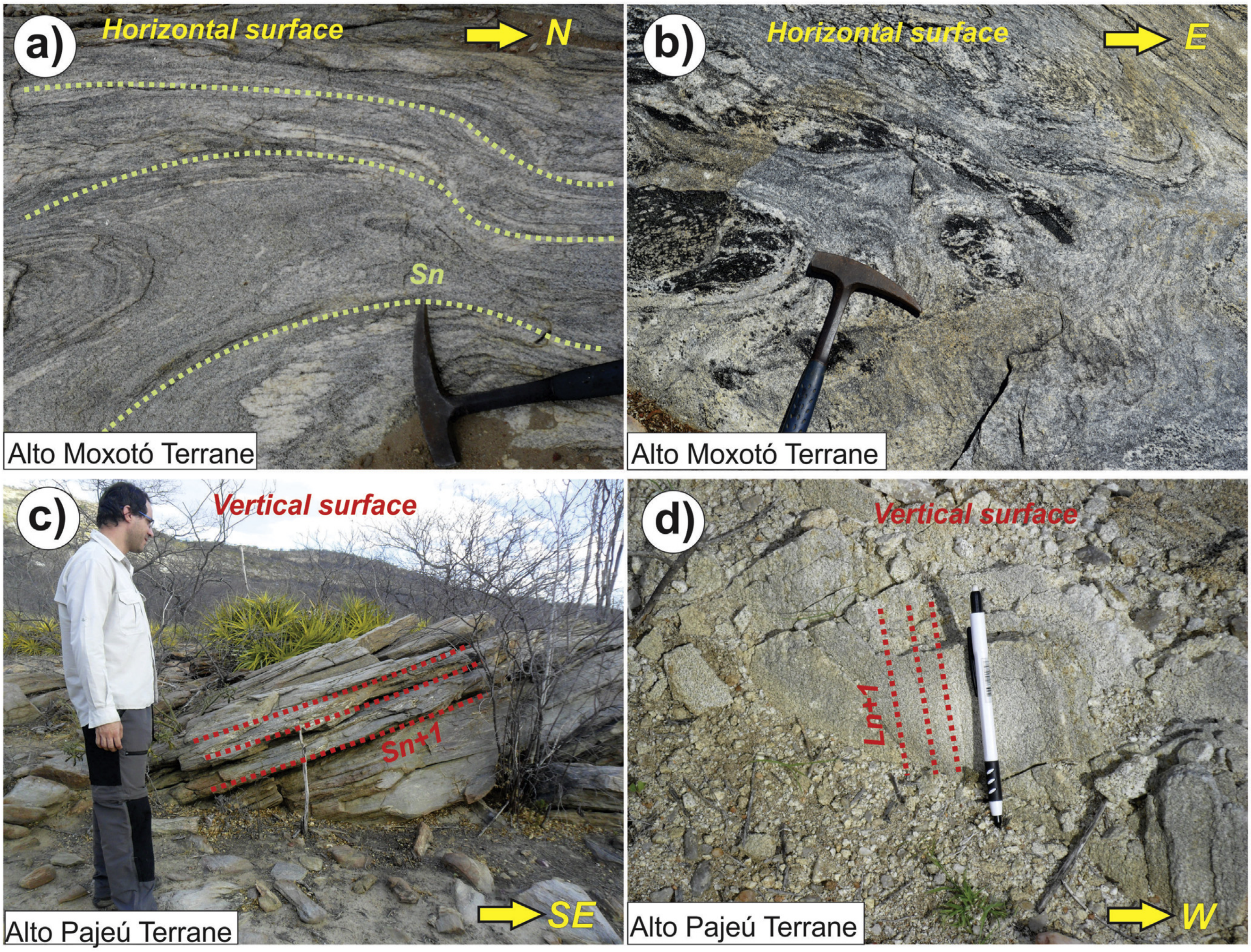

Fig. 12. Structural markers related to D_n and D_{n+1} phases. a) Stromatic to folded migmatite of the ca. 2.6 Ga Riacho das Lajes Suite exhibiting relict S_n foliation (intrafolial fold) in a metatexitic facies; b) strongly mobilized diatexite of the Riacho das Lajes Suite showing schollen structure associated with mafic facies; c) gently dipping S_{n+1} foliation in tabular sheet of Cariris Velhos metagranitoid of the Alto Pajeú Terrane; d) High pitch L_{n+1} mineral stretching lineation on fine-grained Tonian (ca. 0.92 Ga) metagranitoid.

synforms responsible to L_{n+1} rotation. In addition, the F_{n+1} structures have close to tight interlimb angles and include ptygmatic folds (Fig. 13a). The latter structures might also be formed by melt injections in the host rock. Kinematic criteria that include C and C' shear bands, highly deformed σ-type quartz and K-feldspar porphyroclasts, indicate a top-to-the-south tectonic vergence (Fig. 13b). The most deformed tectonites show an intense recrystallization of the rock matrix and quartz grains (with undulose extinction, Fig. 13c), which in the mylonites and proto-mylonites include mica fishes (Fig. 13d).

D_{n+2} form the dominant structures in the study area, corresponding to the majority of the first and second order magnetic lineaments. In the Alto Pajeú Terrane, this event is represented by a complex network of NE-SW and E-W trending strike-slip shear zones. This pattern of shear zones results in the tear drop shapes of supracrustal rocks of the São Caetano Complex on the NW portion of the study area. (Fig. 7c). The main related shear zones are Afogados da Ingazeira (AISZ), São Pedro (SPSZ) and Carqueja (CSZ) (Fig. 11). Mesoscopic fabrics, including directional, oblique and down-dip lineations indicate that the Barra da Foquilha Shear Zone (BFSZ) combines elements of transcurrent and thrust stages or may represent a transpressional fabric. The main regional structure of this stage is the strike-slip dextral Pernambuco Lineament (PeL), which separates the Alto Moxotó and Pernambuco-Alagoas terranes. Planar-linear tectonites predominate in the internal part of the Pernambuco-Alagoas Terrane. They consist of local protomylonites that deform banded orthogneisses of the Belém do São Francisco Complex. The main D_{n+2} fabrics of this terrane are recorded in the strike-slip NW-SE trending sinistral Poço da Areia and Riacho do Boi shear zones.

Unlike the flat-lying S_{n+1} foliation, the S_{n+2} planar fabric is characterized by sub-vertical to vertical mylonites and ultramylonites, as well as banded orthogneisses corresponding to lateral simple shearing (Fig, 11; Fig. 14a). These rocks are frequently associated with a well-developed sub-horizontal to horizontal L_{n+2} mineral stretching lineation (Fig. 14b) defined by quartz + K-feldspar ± biotite aggregates. Kinematic indicators of D_{n+2} include rotated asymmetric quartz-aggregates and σ-type porphyroclasts of quartz and K-feldspar, mantled quartz and feldspar σ-type sigmoids and C- and C'-types shear surfaces including mica fish (Fig. 14c). The SC' dextral fabric is particularly obvious in mylonites related to the Pernambuco Lineament, characterized by recrystallized quartz and feldspar porphyroclasts, locally embedded in an anastomosing S_{n+2} foliation. F_{n+2} folds are associated with the main shear zones, including open to tight and isoclinal synforms, antiforms and overturned folds with curved hinge lines. Oblique

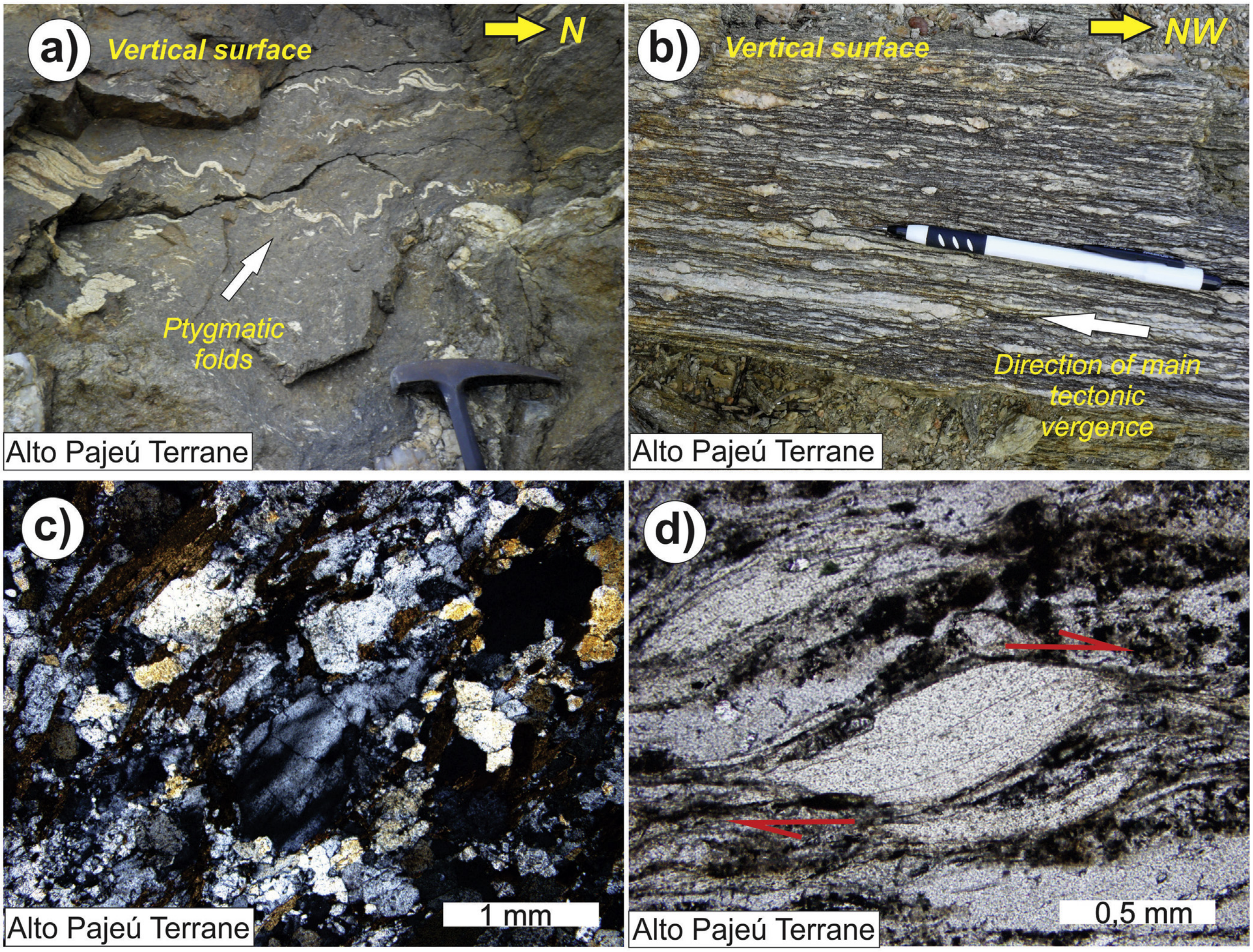

Fig. 13. Structural markers related to D_{n+2} phase D_{n+1} phases. a) F_{n+1} ptygmatic folds indicating distinct competency between leucocratic and mesocratic materials; b) 8°/360Az dipping S_{n+1} mylonitic fabrics in a linear tectonite of the ca. 0.97 Ga São Caetano Complex, with associated asymmetric porphyroclasts suggesting top-to-the-S thrust vergence; c) quartz ribbons with ondulose extinction in a recrystallized quartz matrix in protolylonitic rock; d) micafish developed in a mylonitic facies of the São Caetano Complex associated with the Serra de Jabitacá Shear Zone, exhibiting clockwise movement.

mineral stretching lineation (Fig. 14d) are also observed, suggesting D_{n+1} and D_{n+2} fabrics interference or an oblique movement of D_{n+2} due to a compressive component. The high strain corridors associated with major shear zones, such in the Pernambuco Lineament show local development of sheath folds.

4.3.2. Brittle deformation

Brittle structures were observed only at a mesoscopic scale and include faults and fractures that vary in dip from horizontal to vertical, and are usually discordant with respect to the regional foliation. However, some fractures are concordant with the main S_{n+2} shear zones, especially close to the Pernambuco Lineament. These structures are consist of quartz veins or quartz-feldspar segregations that cross-cut the main L_{n+2} mineral stretching lineation and hinge lines of S_{n+2} folds. Discordant structures are represented by local strike-slip faults, some of which form conjugate shear systems, and including domino patterns oriented in NE-SW and NW-SE (Fig. 15a). They are characterized by fault slickensides composed of recrystallized quartz, chlorite and sericite (Fig. 15b).

5. Discussion

Accretionary orogenic belts are major sites of crustal growth (Cawood et al., 2009, 2013) and are widely described in several parts of Western Gondwana, including examples of all ages. Most of them occupies its margins as those from the Tasman orogenic system in Australia (Coney et al., 1990; McElhinny et al., 2003; Cawood, 2005) and the Argentine Precordillera in west South America (Ramos, 1998; Thomas and Astini, 2003). However, the identification of terrane processes within a number of the provinces of Gondwana remains a difficult task, mainly due deformation-related reworking events.

Integration of geophysical and structural data for the Alto Pajeú, Alto Moxotó and Pernambuco-Alagoas terranes of the Borborema Province constrain the structural framework and evolution of this portion of Western Gondwana. Key geophysical features suggest that the lithotectonic associations in the area correlate with distinct fault bounded terranes that underwent subsequent amalgamation. These features include: (i) distinct content of radionuclides, including eTh enrichment and K-depletion in the Archean-Paleoproterozoic terrane, relative to the other terranes, which reflects the primitive nature of the principal rock units as well as the

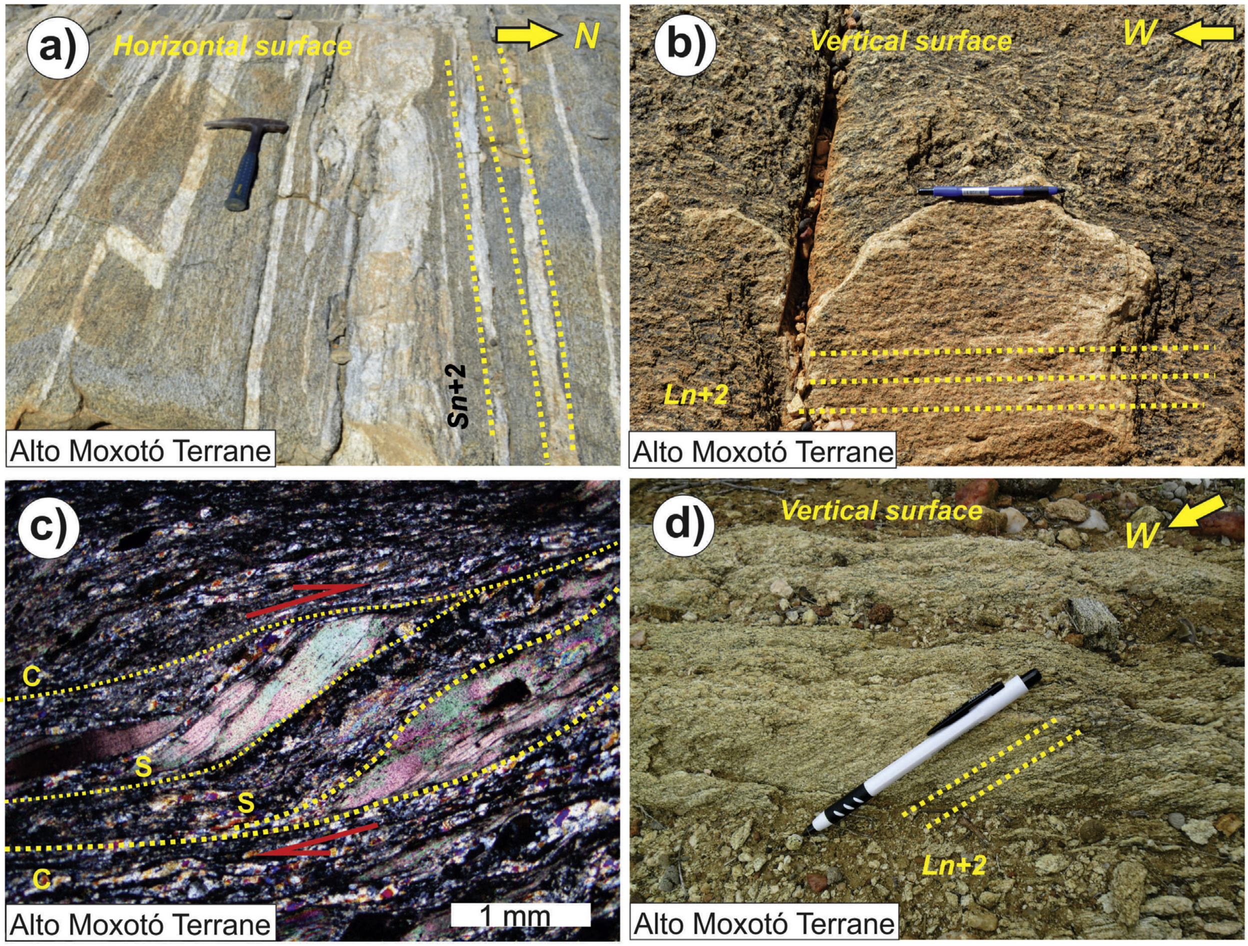

Fig. 14. Structural markers related to D_{n+2} phase. a) Banded orthogneiss of the ca. 2.1 Ga Floresta Suite displaying deformed leuco- and mesocratic E-W bends; b) horizontal L_{n+2} stretching mineral lineation associated to a vertical S_{n+2} foliation plane of the Pernambuco Lineament; c) photomicrograph of granodioritic mylonite with mica fish arranged between C-type shear bands associated with the Pernambuco Lineament; d) oblique L_{n+2} lineation in myloniticparagneiss of the ca. 2.01 Ga Sertânia Complex related to the Pernambuco Lineament.

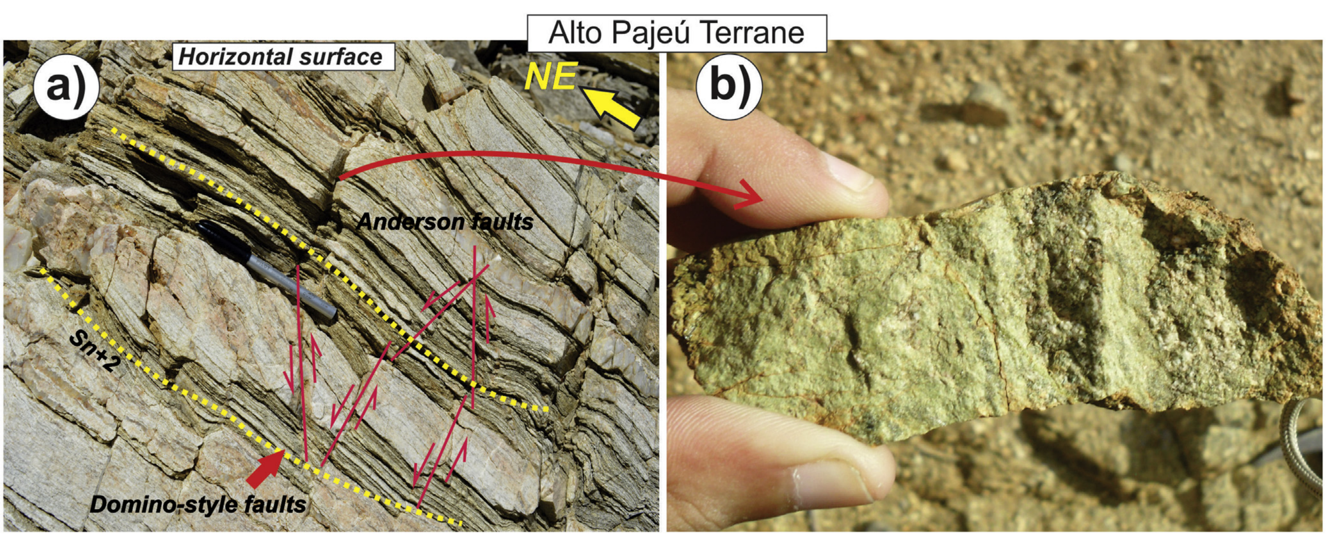

Fig. 15. Structural markers related to a) D_{n+3} Conjugated pair of fractures forming domino-like structures of deformation cross-cutting S_{n+2} foliation planes in paragneiss of the ca. 0.97 Ga São Caetano Complex; b) Detail of collected sample from fracture plane in a), showing neo-formed greenish mineral aggregates (probably quartz, chlorite and sericite).

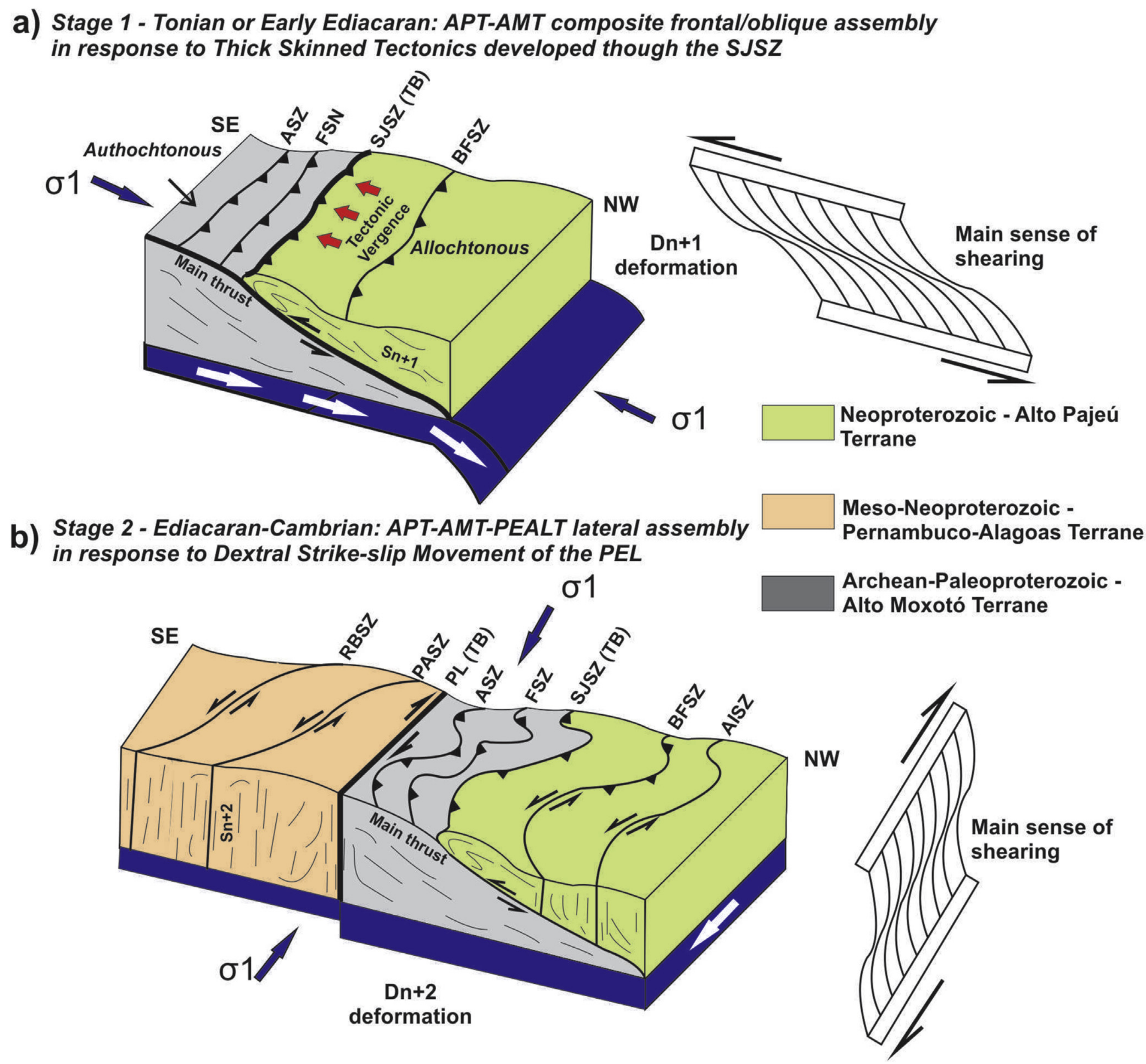

Fig. 16. Structural model for terrane collage between the studied terranes. Terranes - AMT - Alto Moxotó, APT = Alto Pajeú, RCT = Rio Capibaribe, PEALT = Pernambuco Alagoas. Shear zones - RBSZ = Riacho do Boi, PASZ = Poço da Areia, PL = Pernambuco Lineament, ASZ = Airí, FSZ = Floresta, SJSZ = Serra de Jabitacá, BFSZ = Barra da Forquilha, AISZ = Afogados da Ingazeira. TB = Terrane boundary.

absence of Brasiliano granites (K-rich); and (ii) contrasting magnetic signatures between the terranes, with more magnetic rocks present in the Alto Pajeú Terrane (Fig. 6a), whereas the Alto Moxotó Terrane is characterized by low magnetic anomalies. Such a signature can be interpreted as the presence of Tonian Fe-Ti ore occurrences, which are restricted to the former terrane. In addition, the polyphase deformation history is constrained by the integration of abundant interpreted radiometric and magnetic first and second order structures and mapped structural markers, whereas Euler deconvolution constrain the position and geometry of the top of the main magnetic anomalies.

In spite of the early folded foliations and migmatitic structures recognized in the internal portions of the Alto Moxotó Terrane, thrust and transcurrent tectonics are dominant. The Serra de Jabitacá Shear Zone is interpreted as a nappe-related terrane boundary, reflecting the transported allochthonous character of the Alto Pajeú Terrane with respect to the Alto Moxotó Terrane, which in the Borborema Province, corresponds to an older basement domain. Furthermore, we speculate that crustal shortening related to thrust deformation on both terranes, represent frontal/oblique accretion resulting in a major basement-core nappe structure consistent with thick-skinned tectonics similar to the accretion of island arcs and other continental fragments towards the Eurasian margin (Pfiffner, 2006; Hall et al., 2008; Pubellier and Meresse, 2013).

The origin of mapped thrust belts in the Borborema Province is usually related to terrane accretion during the early stages of the Brasiliano Orogeny (Brito Neves et al., 2000; Rodrigues and Archanjo, 2011). However, accretion could also occur during the 1000-920 Ma Cariris Velhos orogeny. Evidence for this latter interpretation includes: (i) mapped tectonic sheets of Tonian/Cariris Velhos low-angle dipping metagranites and mylonites with top-to-the-south tectonic vergence, which has a geochemical signature compatible with magmatic arc to collision-related settings (Santos, 1995; Santos et al., 2010); (ii) the existence of dioritic-granitic dykes in the northern portion of the Alto Pajeú Terrane that cross-cut similar thrust-related Tonian rocks, known as Minador Suite, being interpreted as pre-Brasiliano (Sales et al., 2011), thus, marking a pre-strike-slip and post-thrusting extensional stage; and (iii) the lack of thrust-related top-to-the-south structural markers in the oldest Ediacaran granites. In addition, ca 1.0 Ga rocks from the Serrote das Pedras Pretas Suite are associated with the Serra de Jabitacá Shear Zone, being interpreted as a relic of obducted Cariris Velhos oceanic crust (Santos, 1995; Lages and Dantas, 2016). Nevertheless, we recognize that there are no available geochronological data for tangential deformation, especially in the Transversal Subprovince (i.e. Ar-Ar plateau ages or U-Pb analysis on monazite), thus the exact timing of frontal/oblique terrane assembly is still an open question.

Evidence for strike-slip tectonics is widespread in the Borborema Province. In the study region, this is mainly represented by the Pernambuco Lineament that develop E-W high strain corridors and strongly folds previous structures such as the Serra de Jabitacá Shear Zone. Such structures consist mainly of mylonites up to several kilometers wide, which in along the eastern branch of the lineament is associated with several syn-tectonic granites (Vauchez et al., 1995; Weinberg et al., 2004). Nonetheless, the age of transcurrent boundaries is still not clearly constrained, but overall strike-slip movements in the Borborema Province are related to a metamorphic peak around ca. 590-560 Ma, during the Ediacaran-Cambrian Brasiliano Orogeny (Vauchez and Egydio-Silva, 1992; Archanjo et al., 2008; Brito Neves et al., 2014; Viegas et al., 2014).

The geometry of structures in the Airí area is consistent with those reported from classic accretionary orogens (e.g. Kusky and Bradley, 1999; Collins, 2002), and involve initial thrust structures associated with terrane assembly followed by transcurrent movements. The proposed polycyclic evolution in the Transversal Subprovince (Fig. 16) is also supported by recent magnetotelluric investigation of Padilha et al. (2016) which suggests that the Cariris Velhos orogeny represents an important accretion marker, followed by crustal remobilization during the Brasiliano event.

Most models of Gondwana assembly propose that its final configuration is the result of multi-stage subduction and collision of cratonic blocks, small continents and allochtonous terranes (Collins and Pisarevsky, 2005). Intense deformation during the orogenic cycle strongly overprints early crust, hindering the precise definition of assembly processes as well as paleogeographic correlations (e.g. de Wit et al., 2008). Alternatively, in some provinces of Western Gondwana, intracontinental or intracratonic deformation is invoked as a major process (Meira et al., 2014; Neves et al., 2017). A crucial point is to precisely define the location and kinematics of major boundaries, which can provide clues concerning that terranes were accreted via major thrust or oblique subduction zones and/or subsequently dispersed by strike-slip movements (Cawood et al., 2002). For instance, the Transbrasiliano-Kandi Lineament represents a large-scale suture zone that marks a long-lived Neoproterozoic deformational/accretionary history on the West Gondwana orogen (Araújo et al., 2016 and references therein).

Our results coupled with other geophysical investigations demonstrate the role of major regional structures on the amalgamation of Western Gondwana (e.g., Santos et al., 2014; Correa et al., 2016; Lima et al., 2015). Recently described Tonian to Ediacaran ophiolitic sequences, continental magmatic arc-related granites, and high-pressure to ultra-high-pressure rocks (Caxito et al., 2014b; Santos et al., 2015c; Brito Neves et al., 2016 and references therein) coupled with suture zones mapped in NE Brazil and counterparts in Africa (Black et al., 1994; Brito Neves et al., 2014) highlight the importance of accretion tectonics in the building of this portion of Western Gondwana.

6. Conclusions

Aeromagnetic and radiometric datasets combined with field-mapped structures suggest that the central portion of the Borborema Province, NE Brazil, formed via two distinct stages of terrane assembly. Evidence for polyphase deformation is constrained by meso- and microscopic observations, including foliation transposition, distinct orientation of lineations as well as several kinematic criteria associated with major shear zones. Geophysical data show contrasting signatures for the major units of the studied terranes.

The prominent mylonitic fabric associated with the Serra de Jabitacá Shear Zone is associated with a thrust-related sense of movement between the Neoproterozoic Alto Pajeú and Archean-Paleoproterozoic Alto Moxotó terranes. The age of this assembly is uncertain being either i) early stages of Brasiliano convergence or ii) during the development of the Cariris Velhos orogeny (ca. 1000-960 Ma) in the Early Neoproterozoic, resulting in obduction of the 1.0 ophiolitic fragment of the Serrote das Pedras Pretas Suite. Later strike-slip shear zones resulted in regional folding and oblique to horizontal linear fabrics, such as those associated with the Pernambuco Lineament, which is considered the main record of lateral to oblique assembly of the composite Alto Pajeú and Alto Moxotó terranes with the Pernambuco-Alagoas Terrane to the south. According to our model, this event took place during a metamorphic peak of the Brasiliano orogeny (ca. 590-560 Ma), developing high strain zones and local anatexites within major shear zones.

Lastly, taking into account our data and recent geophysical investigations in the Borborema Province, we suggest that distinct phases of terrane collage might be acted as building processes of Western Gondwana inner orogens during the Neoproterozoic. Despite the difficulty on recognizing the role and evolutionary aspects of most crustal boundaries, accretion tectonics provide a fair explanation for the juxtaposition of several heterogeneous domains that are limited by regional/continental scale structures.

Acknowledgements

The authors are grateful for the editor(s) Cees Passchier and João Hippertt of Journal of Structural Geology for their attention and care, during all stages of publication. Jean-Luc Bouchez, Marcos Egydio-Silva, and an anonymous reviewer are thanked for their criticism and suggestions that strongly improved the original manuscript. Carlos José Archanjo is also thanked for early discussion. ELD and RAF acknowledge National Council for Scientific and Technological Development (CNPq) financial support through INCT Estudos Tectônicos and research fellowships. PAC was supported by Australian Research Council grant FL160100168. We also thank CPRM — Serviço Geológico do Brasil for providing access to geophysical data for academic purposes.

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