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Tectonics of the Northeastern border of the Parana Basin (Southeastern Brazil) revealed by lineaments domain analysis

Marcos Roberto PINHEIRO[1], Paola CIANFARRA[2], Fernando Nadal Junqueira VILLELA[3], Francesco SALVINI[4]

[1] Laboratory of Pedology - Department of Geography of the University of São Paulo, m3279574@usp.br

[2] Laboratory of Quantitative Geodynamics and Remote Sensing – Roma Tre University, paola.cianfarra@uniroma3.it

[3] Laboratory of Pedology - Department of Geography of the University of São Paulo, geovillela@usp.br

[4] Laboratory of Quantitative Geodynamics and Remote Sensing – Roma Tre University, francesco.salvini@uniroma3.it

Abstract

According to the classical paradigm of plate tectonics the cratonic area of the inner part of South America is considered tectonically stable. Nevertheless, the role of neotectonics on the shape of the Brazilian landforms has been demonstrated by several authors. In this work we perform a lineament domain analysis to explore the regional meaning of the sparse and local evidences of neotectonics within Southeast Brazil and frame them in a regional tectonic evolutionary model. Results from lineament analysis allowed finding out two main domains, NW-SE and NE-SW trending. These structural directions frame within an E-W strike-slip corridor characterized by a poly-phased tectonic history. A pre-Neogene left-lateral shear was followed by a right lateral movement whose activity is presently ruling the landform evolution of the region. The two identified structural trends from lineament analysis may

represent the Cenozoic reactivation of ancient weakness zone and relate to the upper Cenozoic South Atlantic drifting and N to NW movement of the South America.

Keywords: Lineament domains; intraplate strike-slip deformation belt; Parana Basin border; Neotectonics

1. Introduction

A classical paradigm in structural geology is that plate boundaries are the only tectonically unstable areas, whereas the intraplate regions are stable, as evidenced by the concentration of the seismic zones along the border of plates (McKenzie and Parker, 1967; Le Pichon, 1968; Morgan, 1968). In this context, intraplate regions, including the continent passive margins, present relatively low seismic and tectonic activities, and their influence on landform development is expectedly low (e.g. Summerfield, 1988 and reference therein), such as in the intraplate Brazilian territory (central region of the South America Plate).

On the other hand, a strong influence of tectonics on the Brazilian landforms has been evidenced since the classical studies of Freitas (1951), Ruellan (1952) and Ab´Saber (1965), which also highlighted the role of the Cenozoic tectonics (Bezerra and Finzi, 2000) and presence of low seismicity (Bianchi et al., 2018). More recent studies proved that neotectonics, the tectonic regime acting since Neogene (Hasui, 1990; Saadi, 1993), plays an important influence on the landform development of various zones of Brazil, as in the ~~tertiary~~ Cenozoic sedimentary basins of the South region (Salamuni et al., 2004), in the large depressions and plateaus of the Southeastern region (Morales, 2005, Bricalli and Mello, 2014; Pinheiro & Queiroz Neto, 2015 and 2016), in the Amazonia region (Val et al., 2014)~~,~~ and in the Brazilian territory as a whole (Ross, 2016).

Despite these information on tectonics in the intraplate Brazilian territory, it has been difficult to understand its influence in some regions, as in the border of the Northeastern Parana Basin, the large Paleozoic sedimentary basin of the central-eastern region of the South America Plate. In these regions, outcropping faults ~~generally~~ are sometimes characterized by ~~have very~~ small displacements and the kinematics indicators (i.e. slickensides) may be ~~are~~ inconspicuous due to the unconsolidated rheology of the rocks surface (Bjornberg, 1969; Pinheiro, 2014), thus locally complicating the inference of the (paleo) stress-fields. In these cases, tectonic studies are efficiently supported by seismographic, geodetic, and remote sensing data, as well as on paleo-seismicity. Please note that the systematic works done by authors (e.g. Sousa 1998; 2002; Santos and Ladeira, 2006) contributed highlighting the evolutionary framework of the border of the Northeastern Parana Basin.

One efficient technique for tectonic studies of planetary surfaces is the lineament domain analysis that revealed particularly suited to unravel the tectonic framework of intraplate regions (Cianfarra and Salvini, 2014 and 2015). Lineaments are morphological and geological alignments of ridges and valleys in continental zones and scars associated with the seafloor spreading, drifting, and fracture zones in oceanic areas (Wise et al., 1985; Cianfarra and Salvini, 2015). They present length spanning from few tens to thousands of kilometers, and can be identified through enhancement of remote sensing images and aerial photographs. Sub-parallel lineament clusters form lineament domains (Wise 1967 and 1969; Cardamone et al., 1976; Bodechtel and Munzer 1978; Salvini, 1979; Wise et al. 1979; Wise et al., 1985; Norini et al. 2004; Morelli and Piana, 2006; Pal et al. 2006). Domains consist of tens to hundreds lineaments and persist on regions spanning over thousands of square kilometers giving rise to lineament swarms (Cianfarra and Salvini, 2015; Lucianetti et al., 2017).

Despite the unsuccessful attempts to frame lineaments into the classical structural geology features, based on the observation that they seldom correspond to know geologic elements

(e.g., Campbell, 1987; Koch and Mather 1997; Haeberlin et al. 2004; Gomez and Kavzoglu 2005; Solomon and Ghebreab 2006; Morelli and Piana, 2006; Pal et al. 2006; Pinheiro, 2014; Souza and Perez Filho, 2016), researches demonstrated that lineament domains and swarms reflect crustal geodynamic effects on planetary surfaces (e.g., Funiciello 1977; Salvini et al. 1979; Cianfarra and Salvini, 2014 and 2015, Mazzarini et al., 1994; Pischiutta et al., 2013; Lucianetti et al., 2017; Rossi et al., 2018). In fact the spatial arrangement and azimuthal clustering of regionally sized lineaments mimic the crustal stress trajectories. ~~In this way, lineament domains are an effective tool to highlight the crustal tectonics of the investigated region~~. In this way the comparison between the know regional geodynamic setting of the study area and the results from lineament domain analysis that point out the orientation of the crustal stress field ~~Their analysis~~ provides the basis for the preparation ~~of crustal stress models, considering the main lineament domain directions~~ tectonic evolutionary models of regions that suffered even poly-phased tectonic deformations. In fact, according to Wise et al. (1985) and Cianfarra and Salvini (2015), the main lineament domain in a region is perpendicular to the least horizontal compression that is, σ2 in compressional, and σ3 in extensional or strike-slip tectonics regimes, according to Anderson theory. Conversely the main lineament domain is parallel to the maximum horizontal compression that is, σ1 in compressional and strike-slip tectonics, or σ2 in extensional tectonics. Ambiguities in these correspondences between stress orientation and lineament domain direction can be solved by framing this analysis into the expected geodynamic regimes. One exception is constituted by the lineament domains in prevailing kinematic conditions (i.e. regional strike-slip faults) were we have the presence of a lineament domain parallel to the shear vector (Rossi et al., 2017). In this context, the aim of this research is the study of the lineament domains of a sector of the Northeastern border of the Parana Basin in order to determine the main lineament trends, the

related stress-fields and the relations between these last and the geological and tectonic evolution of the region.

2 Geological and tectonic setting

2.1 Paraná Basin: Geologic and Tectonic Framework

Paraná Basin is a large geotectonic province in the Central-East region of South America and span through four countries, namely Brazil, Argentina, Paraguay and Uruguay. Its origin is related to Paleozoic times, when South America and Africa continents were part of the Gondwana supercontinent (Fernandes and Amaral, 2002; Strugale et al., 2007; Pinto and Vidotti, 2019). The Paraná Basin is considered a typical intracratonic basin (Milani & Ramos, 1998) discontinuously covered by sedimentary successions ranging from Upper Ordovician to Upper Cretaceous times (Milani, 1997). Total sediment thickness exceeds 7000 m in the central depocenter (Milani and Zalán, 1999) and deposited in various environments. Basalt flows and intrusions of alkaline and basic rocks are also included in the succession (Figure 1).

The geological history of the Paraná Basin can be summarized into four main stages (Figures 1 and 2; Almeida, 1980; Milani, 1997). (1) Initial subsidence of the basin and marine transgression until the mid-Devonian, followed by regression in the Frasnian (Upper Devonian). (2) Initially intense tectonic activity from the Carboniferous to the Middle Permian with the deposition of sediments (Tubarão Super group – Gondwana I Supersequence) under prevailing glacial conditions. Successively, a weak tectonic activity lasted until the Upper Permian and led to the slow subsidence of the central Paraná Basin. This, associated to the end of the glacial period, led to a renewed marine transgression with the deposition of the Passa Dois Group (Gondwana I Supersequence) of sediments deposited in deep-to-shallow marine and fluvial/lacustrine/tidal environments. (3) Weak tectonic activity associated to local slow subsidence with deposition of the aeolian and fluvial

sediments of the Botucatu and Pirambóia Formations (São Bento Group - Gondwana II and III Supersequences) under desert conditions from Triassic to Eo-Cretaceous times. (4) Reactivation of old tectonic structures related to the opening of the South Atlantic with massive volcanic eruptions (Serra Geral Formation - Gondwana III Supersequence) in Eo-Cretaceous time, deposition of the Bauru Group (Gondwana III Supersequence) of sediments under continental conditions (aeolian, fluvial, and alluvial environments), with reduction of the intensity of the tectonic activity in Upper Cretaceous and Early Palaeogene times.

Soares et al. (1982) identified five main lineament trends around N-S to ENE-WSW in the Parana Basin from Landsat satellite images; Zalán et al. (1990) consider that the basement of the basin is constituted by NW-SE, NE-SW and E-W structures. According to Milani et al. (1990), the NW-SE and NE-SW trends would be older than the E-W direction, at least in the eastern region of the basin. Fulfaro et al. (1982) consider that the NW-SE trend is the oldest and developed in Upper Pre Cambrian times during the build-up of the basement of the Parana Basin . According to these ~~A~~authors this direction and structural zones are related to old aulacogens.

This tectonic is responsible for diversified movements along the main structural lineaments, including normal, reverse, and strike-slip displacements, horst, and fault-related folding. On the other hand, the concentration of tectonic movements left weaker effects in the intermediated regions, limited to gentle and large dome structures (IPT, 1985). This structural scenario created topographic contrasts, which have been erased in Upper Cretaceous or Paleocene times by the peneplanation processes which affected the eastern-central Brazil (King, 1956). These planed landforms were disturbed during the Paleogene, when the old tectonic structures were reactivated in extensional/compressional tectonic environments related to the South Atlantic drifting (Almeida, 1980). The rotation of the South America plate has changed the tectonic framework since the Neogene, causing strike-slip reactivation

of old structures (Hasui, 1990; Saadi, 1993) that in turn gave locally rise to normal (transtension) and reverse (transpression) faults in the Parana Basin (Hasui et al. 1995; Riccomini, 1995; Santos and Ladeira, 2006; Pinheiro & Queiroz Neto, 2015; 2016).

2.2 Geologic and geomorphologic setting of the study area

The study area is the São Pedro and Botucatu ridge region, a sector close to the Northeastern border of the Paraná Basin, in the State of São Paulo – Southeastern Brazil (figure 2). The region is at the transition between two large morpho-sculptural units, the Western Plateau and the Paulista Peripheral Depression (Ross and Moroz, 1997). The plateau is formed by Eo-Cretaceous basalt flows of the Serra Geral Formation and fine aeolian sandstones of the Botucatu Formation. Locally, these units are topped by sandy to rudaceous deposits cemented by silica and iron oxides (Itaqueri and Marilia Formations). The depression developed on the Triassic fine to conglomeratic aeolian/fluvial sandstones of the Pirambóia Formation (Caetano-Chang and Wu, 2006), which are capped by an Upper Pleistocene colluvial sandy cover (Pinheiro and Queiroz Neto, 2015 and 2016). The origin of the large depression and its adjacent plateau is related to the ~~Tertiary~~ Cenozoic circumdenudation process of the Parana Basin margins, caused by large rivers entrenched in the old structures (Ab'Saber, 1965 and 1969; Pinheiro, 2014; Pinheiro and Queiroz Neto, 2014).

According to Soares et al. (1982), Ferreira (1982), Fulfaro et al. (1982), IPT (1989), Milani et al. (1990), Quintas (1995), Saad (1997), large NE-SW and NW-SE structural alignments (mega-structural features) cross the Paulista Peripheral Depression and the Western Plateau. Hasui et al. (1993) considered that the NW-SE features are younger and their movement displaced and rotated the NE-SW structures. On the other hand, Riccomini (1995), which mapped the main alignments of the São Paulo State, considered that the main alignments have NW-SE, NNW-SSE and WNW-ESE directions. According to Riccomini (1995 and 1997)

sinistral and dextral strike-slip movements have been inferred along NNW-SSE and WNW-ESE faults. These movements frame within a E-W trending right-lateral shear zone. The São Pedro and Botucatu ridge regions are characterized by the same main structural alignment, namely NW-SE and NNW-SSE.

Despite the reported evidence of tectonics in the study area, previous studies considered that Cenozoic tectonics would have been weak in the region (i.e., Bjornberg, 1969; Bjornberg et al., 1971). However, more recent studies demonstrated that tectonics played an important role in the evolution of the region, especially its neotectonics. Ladeira and Santos (1996), Riccomini (1995; 1997) and Santos & Ladeira (2006) identified normal, reverse and strike-slip neotectonic faults in the backslope of the São Pedro Ridge. Riccomini (1995) identified normal and reverse faults (NE-SW and NW-SE) offsetting Quaternary deposits at the Pitanga Structural High region and Siqueira (2011) correlated the origin of this structural high to the neotectonics. Sousa (2002) and Morales (2005) identified strike-slip reactivation of normal faults in the Pau D´Alho Structural High. Pinheiro (2014) and Pinheiro and Queiroz Neto (2015) identified neotectonic traces of sinistral strike-slip reactivation of the Santa Maria-Cabreúva Lineament (NW-SE), extensional joints and normal faults (NW-SE and NE-SW) in fluvial Quaternary deposits, and uplifting and downlifting of tectonic blocks in the pediment surface of the São Pedro region. Eventually, Guedes (2014) and Guedes et al. (2015) identified neotectonic deformations in the backslope of the Botucatu ridge and in the Western Plateau. All these evidences suggest that neotectonic activity in the region played an important role in the landform development. Here we provide further evidence that support the active role of neotectonics in the region by a multiscalar approach that includes the comparison of results from lineament domain analyses and structural field data. The found results allow framing the available sparse indications supporting neotectonic activity in the region within a geodynamic evolutionary model.

3 Methodology

This research was performed at both regional and local scales. The regional analysis involves the Botucatu and São Pedro regions, whereas the local one is focused in the São Pedro area (Fig.2). In the regional scale, the lineaments longer than 9000 m and wider than 180 m were analyzed, since they relate to the crustal stress-field (Wise et al., 1985). At the local scale, lineaments with a length between 1260 and 5000 m and wider than 90 m were analyzed, considering that they relate to local stress-fields at upper crustal levels.

The lineaments were identified on the DEM (Digital Elevation Model) of the SRTM (Shuttle Radar Topography Mission, 2000) data, whose spatial resolution is approximately 30 m at this latitude (1 arc-second). Shadow images from rendering with sun elevation of 20° and 4 different lighting conditions (namely 0°, 45°, 90° and 135°), following the proposal of Wise (1969), were generated. This multiple image analysis allowed identifying lineaments not visible in some illumination conditions. These images were processed with the Envi™4.7 software, by means of a low-pass filter to neglect small morphological variations, and successively a high-pass filter (Laplacian) to highlight the tonal variations. Finally, the images were exported to bmp format for automated lineament analysis.

The lineaments were detected by the SID3 software (SALVINI, 2016). Parameters for lineament detection were inserted in the software, such as minimal and maximum length, width, the minimal length of each lineament segments, their maximum length to belong to the same lineament, and the pixel density along lineaments. These parameters are necessary because they define the main geometric characteristics of the lineaments to be detected. The mapped lineaments were cumulated into a database and statistically analyzed by the Daisy3 software (SALVINI et al. 1999). Azimuthal frequency analysis by polymodal Gaussian fit (Wise & Mccrory, 1982; Cianfarra and Salvini, 2016) of the data was performed to identify

the main azimuthal trends which correspond to the lineament domains (Wise et al., 1985; Cianfarra and Salvini 2014, 2015; Lucianetti et al., 2017; Rossi et al., 2018).

Field campaigns were realized in the São Pedro region (local scale area). A total of ~~671~~ 321 structural data were collected and included mainly extensional joints, large fractures and normal faults. Attitudes of structural data were projected and analyzed on a Schmidt Net (lower hemisphere) by Daisy3 software (Fig. 3). ~~All data were compared by considering their respective geological meaning, despite the differences in scales between lineaments recognized in images and fractures measured in outcrops.~~ The attitude of the measured structural dataset was compared to the results from the lineament domain analysis in order to identify possible azimuthal correlation between the two dataset, although characterized by dimensions of different orders of magnitude. All the collected brittle deformations were analyzed without considering their origin or type, even if this information was recognized in the field and recorded. This grouping was intentionally followed due to the purpose of the present work, aimed to relate surface expressions as the lineament domains to crustal stresses. All open brittle deformations contribute to weakened rock rheology, and therefore enhance the modeling capability of erosional processes.

4 Results and Discussions

4.1 Lineament Domain and Structural Data Analysis

The result of the lineament detection of the Botucatu and São Pedro Ridge region (regional analysis, Fig 2A) shows that there are 387 regional lineaments (minimal length: 8921 m; maximum length: 21.273 m; average length: 12.352 m) with several orientations, yet they are concentrated in two main trends, NW-SE and NE-SW (figure 4), with sub-ordered group in the E-W direction. These orientations correspond to those identified by Zalán et al. (1990) in

the lineaments of the whole Parana Basin, confirming the consistency of our results in being related to the regional stress-field.

These main lineament directions correspond to the lineament domain following the proposal of Wise (1967; 1969), Cianfarra and Salvini (2015 and 2014), among other authors. These trends are dominant in most part of the region, and deviations can be ascribed to local factors, such as lithological variations, anisotropy of rocks and fault intersections. The NW-SE direction is the most important, considering that it corresponds to the main lineament domain characterized by the highest frequency associated to a relatively low standard deviation. The NE-SW direction is also important, and corresponds to a more scattered lineament domain.

When analyzed by lithologies, lineaments present the same azimuthal trends detected in the entire study region, namely NW-SE and NE-SW (fig. 5). Although NE-SW trend is a little more defined than NW-SE in the Pirambóia Fm (Triassic), Botucatu and Serra Geral (Eo-Cretaceous), Marilla (Upper Cretaceous) and Itaqueri Formations (Paleocene/Eocene), it is not clear whether minor oscillations reflect a replace of the main trend, since the lineaments of the other formations clearly present the NW-SE as the principal.

The results of the regional lineament domain analysis, and of the analysis by lithologies show the presence of two nearly perpendicular trends (Fig 4B). Their presence may be differently interpreted, depending on their relative age. In the case of their contemporary formation, we may relate them to an equivalent of the development of systematic and non-systematic fracture systems (Price and Cosgrow, 1990). In this case the NW-SE system with its smaller standard deviation (sd=6.47°) would represent the main system normal to minimum horizontal stress, and the NE-SW (sd=7.64°) correspond to the system produced by the residual stress after the formation of the former domain. This scenario may relate either to a crustal NW-SE maximum horizontal stress (pure shear setting) or as being the effect of a

regional E-W, right-lateral shear (simple shear setting). The alternative hypothesis, relating to N-S left-lateral shear, seems less in agreement with the expected global-scale tectonics of the region. A different geodynamic model should be ascribed if we assume a different age for the two main lineament domains. In this case, the younger lineament domain would be the NW-SE (smaller sd, e.g. Cianfarra and Salvini, 2015) and the shifting from NE to NW was produced by a horizontal stress inversion, i.e. the NW component relatively increasing and becoming stronger than the NE. This exchange may relate to changes in the regional geodynamic setting of the region, that is contrasted by E-W shear and the development of the Atlantic passive margin. Due to the evidence of both domains it would be expected that this tectonic setting developed in Neotectonic times. The latter hypothesis is in accordance with the proposal of Hasui et al. (1993) and Etchebehere (2008), which considered that the NW-SE structures are newer.

In the local analysis of the São Pedro region (figure 6), where shorter, upper crustal lineaments were identified (minimum length: 1200 m; maximum length: 4371 m; average length: 1744 m), the results are very similar to the regional analysis. The NW-SE and NE-SW trends are again the most important and correlate to the regional lineament domain directions. The spatial analysis shows that, as in the regional scale, some minor deviations in the main directions are locally present and could be related to local factors. Local scale lineaments are slightly more frequent in the NE-SW direction than in the NW-SE. Despite this difference, the scattering of NE-SW lineament system is relatively higher (sd=25.74°) than the NW-SE (sd=19.32°) as in the regional analysis. In this way, in the case of a non- contemporary formation, the more recent trend is again the NW-SE for the São Pedro region. Such result is quite similar to those obtained in the lineament analysis by lithology (fig. 7): NW-SE and NE-SW directions are the most important in all scenarios and present small deviations, including in the younger lithologies (Neocenozoic deposits), whose lineaments are more clearly related

to the recent tectonics (Neotectonic). Thus, the hypotheses of origin and chronology of these lineaments are the same mentioned previously for the regional analysis.

The structural data measured in outcrops of the São Pedro region (fig. 3 and 8) show two main, nearly orthogonal, azimuthal families trending ~~N46W~~ N51°W and ~~N31E~~ N25°E. The first one in characterized by a ~~higher~~ smaller scattering (sd=~~10.95~~ 14.2) than the second one (sd=~~27.83~~ 20.7). The third, minor peak is nearly E-W orientated. The main azimuthal families mainly consists of extensional fractures (see fig.8d), the second azimuthal set is mainly made up of faults. The azimuthal analysis by polymodal Gaussian fit of the measured brittle deformations (faults and fractures) in Quaternary deposits (Fig.8c) again shows the main azimuthal trends, namely NW-SE, NE-SW, E-W and N-S.

~~These directions~~ The measured brittle deformation elements clustering into two nearly orthogonal azimuthal family set are nearly parallel to the main lineament domains found at the regional scale, despite the difference of over three order of magnitude in dimension between these features. It should be noted that some of the measured brittle deformation was detected in Quaternary deposits outcropping in the Botucatu - Sao Pedro region. This finding adds to the growing body of the recorded brittle deformations reported in literature (e.g. Riccomini, 1995 and 1997; Siqueira, 2011; Pinheiro, 2014; Pinheiro and Queiroz, 2015). Again please remember that only azimuthal correlations where analysed between the two sets of data. In fact we consider that all open brittle deformations contribute to weakened rock rheology, and therefore enhance the modeling capability of erosional processes.

These results drag some considerations: (a) the NW-SE and NE-SW are the most important azimuthal trends considering the three different scales of analysis with the NE-SW systematically more scattered than the NW-SE. This is true also for the analysis by lithologies; (b) the crustal stress has influenced the development of the regional lineaments

(related to lower crustal levels), the local scale lineaments (narrow and short structures, associated to upper crustal levels), and the fracturing at the outcrop scale; (c) considering the NW-SE direction as the main orientation of lineament domains and of extensional structures from field data (joints and normal faults), the main neotectonic stress tensor, or the youngest tectonic event, in the studied region will have the main horizontal compressional principal axis (σ1 or σ2) oriented NW-SE and the main horizontal extensional axis (σ2 or σ3) along the NE-SW direction, in accordance with the previous studies performed by Riccomini (1997), Facincani (2000), Sousa (2002), Morales (2005), Pinheiro (2014), Pinheiro and Queiroz Neto (2015). This is also in agreement with Santos and Ladeira (2006) that showed many NE-SW normal faults at the Itaqueri Range and associated them to an older tectonic event (always in Neotectonic times) that was followed by a switching of the horizontal component of the stress tensor and thus responsible for the younger NW-SE normal faults.

4.2 Discussions and Proposition of Tectonic Models

The observed two peaks in the azimuthal frequency of both the regional and local analyses can be related to five possible geodynamic frameworks that are illustrated in Figures 9 and 10. The different scattering value between the two lineament domains can be either interpreted as belonging to a systematic/non-systematic crustal deformation (Fig. 9) or to the occurrence of two separate geodynamic settings either in succession (Fig. 10A) or, alternatively coeval (Fig. 10B). In the first case the maximum horizontal stress would lie parallel to the more concentrated lineament domain, namely the NW-SE domain, and the NE-SW would represent the equivalent of a non-systematic fracture set (Price & Cosgrow, 1990) in extensional environments, i.e. with negative modules for both the minimum and maximum horizontal stress components. In an active extensional tectonic environment we assume that the stress decreases (extension) in the horizontal plane with time until the minimum

horizontal component (σ3) overrides the traction strength of the upper crust. This leads to the development of the first main lineament domain, the NW-SE in this research. The development of the resulting oriented anisotropic weakness prevents the application of significant extensional stress along the former minimum horizontal component. In this way, we observe an inversion of the horizontal components of the stress tensor and the formerly maximum horizontal stress component, which has a negative module, becomes the minimum horizontal component and the reduced component would represent the new maximum horizontal one. As the extensional conditions progress and the new minimum component reaches the traction strength of the upper crust, a new set of lineaments develop nearly perpendicular to the former one. Since it develops in an anisotropic environment, resulting from the presence of the former lineament domain, the azimuth of the newly generated lineaments will be influenced and result in a more scattered distribution. In this way the relatively younger lineament domain shows a slightly larger scattering.

The systematic/non-systematic lineament domain may relate to three geodynamic setting: (1) An overall extensional environment. (2) A regional arching resulting from crustal tectonic compression ("pure shear conditions") with NW-SE maximum horizontal stress component. Specifically, the onset of this stress condition produces both the NW-SE lineament domain and the regional arching of the region. In turn, this arching is responsible for the development in the upper crust of an inverted horizontal stress field due to the extension above the neutral surface of the arch with minimum horizontal stress perpendicular to its axis, that is along a NW-SE strike. This is responsible for the development of the younger and more scattered NE-SW lineament domain. (3) A regional E-W trending strike-slip corridor ("simple shear condition") whose right-lateral sense of shear creates the NW-SE compression (figure 9C). This latter model is similar to the Riccomini (1995; 1997) proposal, whose model considered that a NW-SE σ1 would reactive strike-slip faults related to long

lineaments of the São Paulo state (Southeastern of Brazil) in the neotectonic period. These three models are characterized by the higher scatter value of the younger, non-systematic, lineament domain (namely the NE domain)

The alternative models (Fig. 10) relate the development of two lineament domains to two different geodynamic events, which are successive with time (Fig. 10A) or alternatively coeval (Fig. 10B). In both cases the lineament domain with the smaller scatter relates to the younger event/episode (e.g. Cianfarra and Salvini, 2015; Rossi et al., 2018). In the studied area the lineament domain analysis indicate that the younger NW-SE regional compression superimposed to the pre-existing NE-SW compressive event. In this latter case two geodynamic scenarios are possible. The first one (Fig. 10A) is characterized by the tectonic activity along an E-W trending shear zone that inverted from an older left-lateral movement to the more recent right-lateral one, in this way producing the horizontal stress inversion. The other scenario (Fig. 10B) implies the existence of a regional stress with NE-SW main horizontal compression that combines with the discontinuous or successive activity of an E-W right-lateral shear zone, responsible for the younger NW-SE main compression.

To sum up, the tectonic evolution of the São Pedro and Botucatu region can be explained through different models. Nevertheless, the comparison of our results with the tectonic interpretations advanced by several authors (Hasui et al., 1993; Riccomini, 1995 and 1997; Saad 1997; Facincani, 2000; Fernandes and Amaral, 2002; Sousa, 2002; Morales, 2005; Santos and Ladeira, 2006; Pinheiro and Queiroz Neto, 2015) suggests that the scenario presented in Fig. 10B is the most reliable. This scenario describes the activity of a regional E-W strike-slip corridor with left-lateral sense of shear. This kinematics is responsible for a NE-SW main horizontal compression, and the formation of the oldest lineament domain along the same direction. This is in agreement also with the proposed tectonic evolution of the Cenozoic basins in Southeastern Brazil (e.g. Riccomini et al., 2004; Zalan and Oliverira,

2005) that suffered an E-W sinistral deformation in Paleocene-Eocene times, followed by dextral movements along E-W corridor with associated NW-SE normal faulting. Following the geodynamic evolution of the region, related to the drifting of the South Atlantic with the associated W and NW movement of the South America plate since Neogene times (Hasui, 1990; Saadi, 1993; Torsvik et al., 2009), the strike-slip corridor was affected by an inversion of the sense of shear. The new right-lateral movement produced the exchange of the previous Shmax and Shmin being the new Shmax NW-SE oriented and responsible for the formation of the younger, NW-SE lineament domain. The smaller scattering of the NW-SE lineament domain (both from the regional and the local scale analysis) and of the main fracture azimuthal family, confirms the relatively younger age of this domain (e.g. Cianfarra & Salvini, 2015).

This model is compatible either with Hasui et al. (1993) proposal, who advanced the hypothesis that the activity of the older NE-SW structures was followed by newer NW strike-slip faults, and with Saad (1997) synthesis map of the main structural features of the Paraná Basin in São Paulo state that is characterized by the presence of older NE-SW trending structural lineaments that were cut and rotated by newer NW-SE structures. Facincani (2000), Sousa (2002) and Morales (2005) computed a NW-SE main horizontal compression in the current (since Neogene) tectonic environment. Moreover, Fernandes and Amaral (2002), based on the brittle deformation and photo-lineament analyses, identified tectonic deformation events during the Cenozoic in the Eastern border of the Parana Basin. Among these, two events were the most important at the regional scale. The oldest one, assigned to the Paleogene-Neogene transition, is characterized by NE-SW main horizontal compression. The youngest Quaternary event has a NW-SE main horizontal compression.

The detected NW-SE and NE-SW lineament domains may easily represent the Cenozoic reactivation (Zalán et al., 1987; Cordani, 1984; Hasui, 1990; Saadi, 1993;

Vasconcelos et al., 2018) of structural trends and weakness zones that played an important role during the Neoproterozoic craton accretion (e.g. Tankard et al., 1995; Almeida et al., 2000; Tello et al., 2003) and Mesozoic fragmentation (Franzese and Spalletti, 2001; Vaughan et al., 2008; Torsvik et al., 2009) of the Gondwana supercontinent. Such inherited crustal, weakness corridor was/is compatibly oriented with the Neotectonic stresses to be reactivated.

The above considerations allow to constrain the activity of the E-W corridor, or the youngest part it, in Cenozoic times. Specifically the pre-Neogene, left-lateral shear was followed by a right-lateral sense of movement. Evidences of Quaternary faulting (Riccomini, 1995; Riccomini and Assumpção 1999; Siqueira, 2011; Pinheiro, 2014; Pinheiro and Queiroz Neto, 2015; Morales, 2005) corroborates the prosecution of the tectonic activity of the shear corridor till Quaternary.

The proposed strike-slip corridor in intraplate setting, characterized by a poly-phased tectonic history may represent the on-land propagation of oceanic fracture zone (Figure 10). A similar setting for the study region was previously hypothesized by Zalán (1987) and Saadi (1993) based on the near parallelism between the inferred continental strike-slip corridor and the offshore tectonic alignment. The same geodynamic scenario has been identified in the Southern Ocean where the Tasman and Balleny Fracture Zones show evidence of continental prosecution within the Northern Victoria Land, East Antarctica (Salvini et al., 1997; Storti et al. 2003; Zanutta et al. 2017 and 2018).

5 Conclusions

Results from the present work allow addressing a series of issues regarding the Cenozoic tectonic evolution of the Northeastern boarder of the Paraná Basin in the framework of the regional geodynamics.

The two main lineament domains identified in the study area, NW–SE and NE-SW trending, allow to infer the crustal stress fields associated to the two successive tectonic events that ruled the Cenozoic evolution of the region.

Specifically, the found lineament frame within a regional strike-slip deformation belt that develops in the intraplate environment of South America with E-W direction.

The poly-phased tectonic history of this corridor is characterized by a ~~pre-Neogene~~ Paleogene left-lateral shear followed by (Neogene) right-lateral movement.

This last is also responsible for the brittle deformation documented by various Authors in Quaternary deposits. In this way the younger, right-lateral regime is currently affecting the landform evolution of the region, classically interpreted as related to old tectonics, lithological variations, and climatic oscillations.

Following hypotheses advanced in the past decades from other authors, we infer that the described intraplate strike-slip deformation belt is an inherited weakness shear zone that played a major role in the Neoproterozoic craton accretionand Mesozoic fragmentation of the Gondwana supercontinent and prensently represents the continental prosecution of the off-shore fracture zones.

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Figure captions

Figure 1: Simplified geological map of the Paraná Basin, modified after Milani, 2004.

Figure 2: Location and hypsometry map of the Sao Pedro and Botucatu Ridges and simplified geological scheme of the São Paulo State.

Figure 3: Attitudes of the measured field structural dataset projected on a Schmidt Net (lower hemisphere) by Daisy3 software

Figure 4: Results of the regional scale lineament analysis in the Botucatu and São Pedro region. Polymodal Gaussian fit of the detected lineaments represented as rose diagrams. a. Results of the analysis by areas to study the spatial variation of the found domanins. b. Cumulative analysis showing the existence in the study area of two main lineament domains, nearly perpendicular and oriented NW-SE and NE-SW. The NW domain is systematically characterized by a smaller standard deviation (sd) and in represented with the red color. The NE, more scattered (higher sd) lineament domain is represented in blue color.

Figure 5: Polymodal Gaussian fit of the detected lineaments by lithologies in the the Botucatu and São Pedro region. The total number of lineaments related to the Tubarão Group and Marilia Formation is not statistically significant (<10) and were not considered in this analysis. The NW-SE and NE-SW lineament domains are represented respectively with red and blue colors.

Figure 6: Results of the local scale lineament analysis in the São Pedro region. Polymodal Gaussian fit of the detected lineaments represented as rose diagrams. a. Results of the analysis by areas to study the spatial variation of the found domains. b. Cumulative analysis showing the existence in the São Pedro region of two main lineament domains, nearly perpendicular and oriented NW-SE and NE-SW. The NW domain is systematically characterized by a

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Figure 7: Polymodal Gaussian fit of the detected lineaments by lithologies in local scale analysis of the São Pedro region. The total number of lineaments related to the Fluvial Deposits (Quaternary) is not statistically significant (<10) and were not considered in this analysis. The NW-SE and NE-SW lineament domains are represented respectively with red and blue colors.

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Figure 9: Possible tectonic models to frame the found lineament domain, considering that they are divided into systematic and non-systematic system. a. Systematic lineament domain (NW-SE) and non-systematic lineament domain (NE-SW) related to an extensional tectonics. b**.** Systematic lineament domain (NW-SE) and non-systematic lineament domain (NE-SW) related to a regional NW-SE compression (Shmax) responsible for an arching. c: Systematic lineament domain (NW-SE) and non-systematic lineament domain (NE-SW) related to a NW-SE compression (kinematic stress, Shmax) due to the right-lateral movement of a regional E-W strike-slip corridor.

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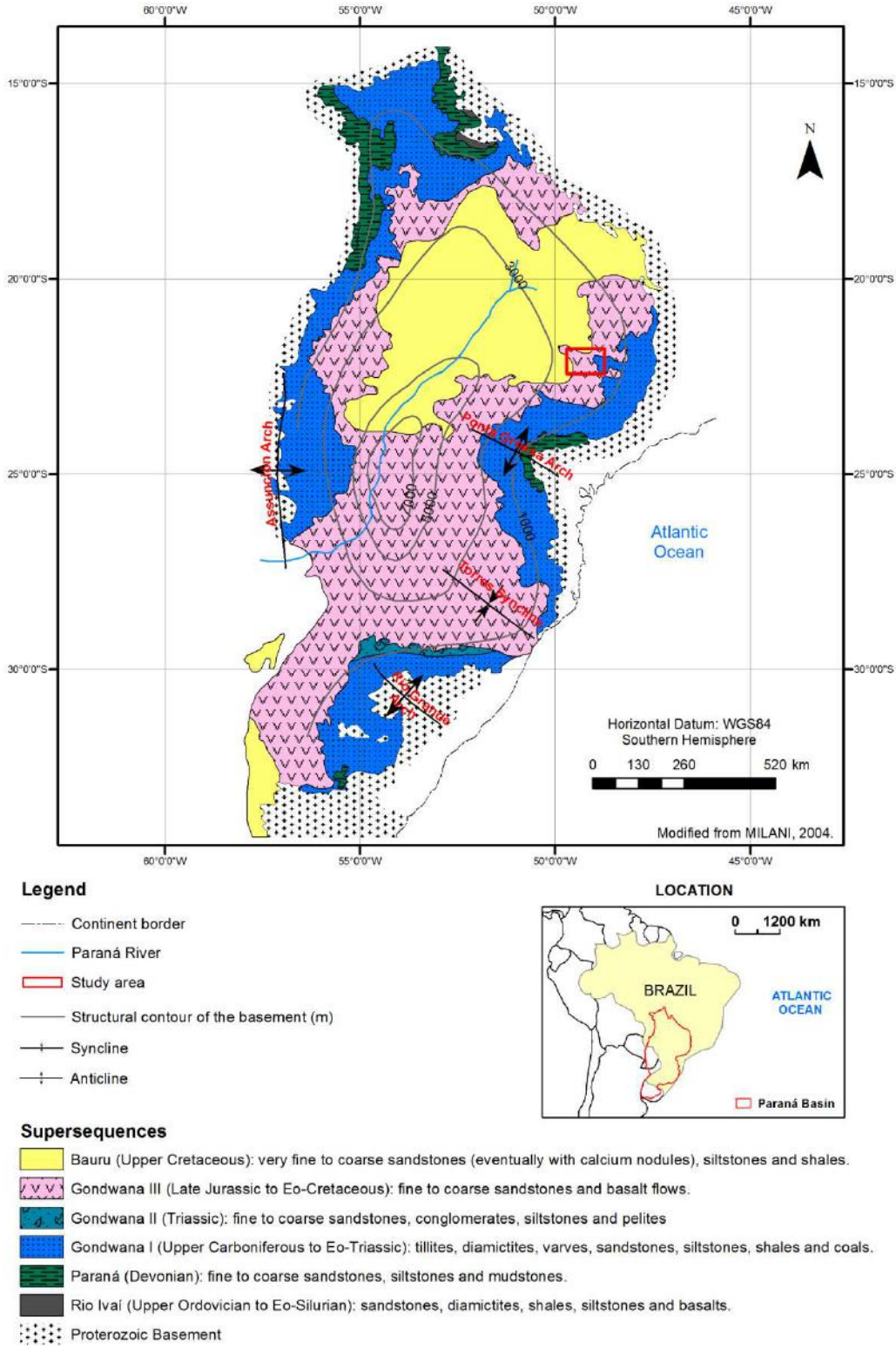
Figure 11 Proposed model of intraplate, strike-slip deformation belt within Southeastern Brazil.

Figures

Figure 1



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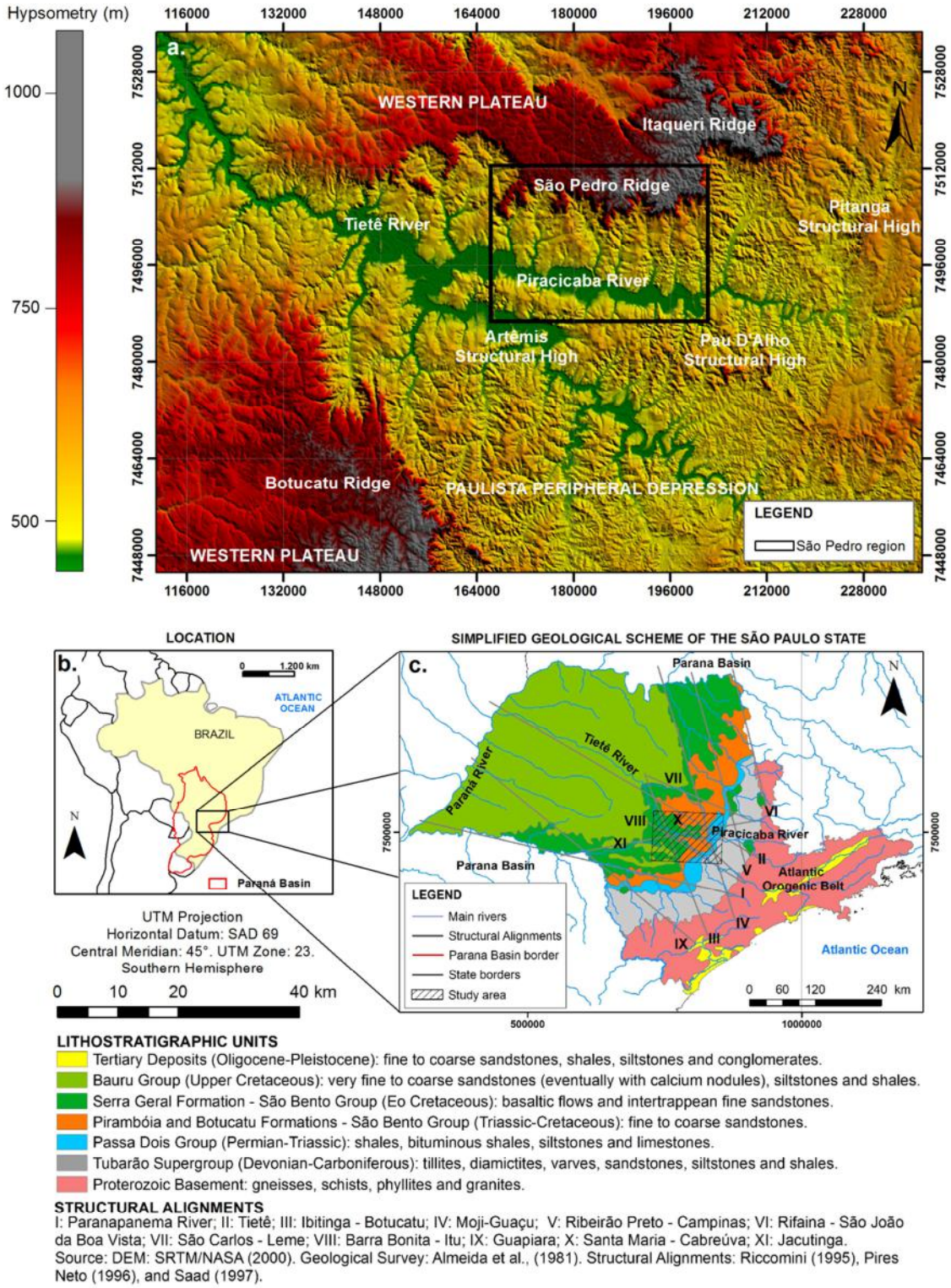

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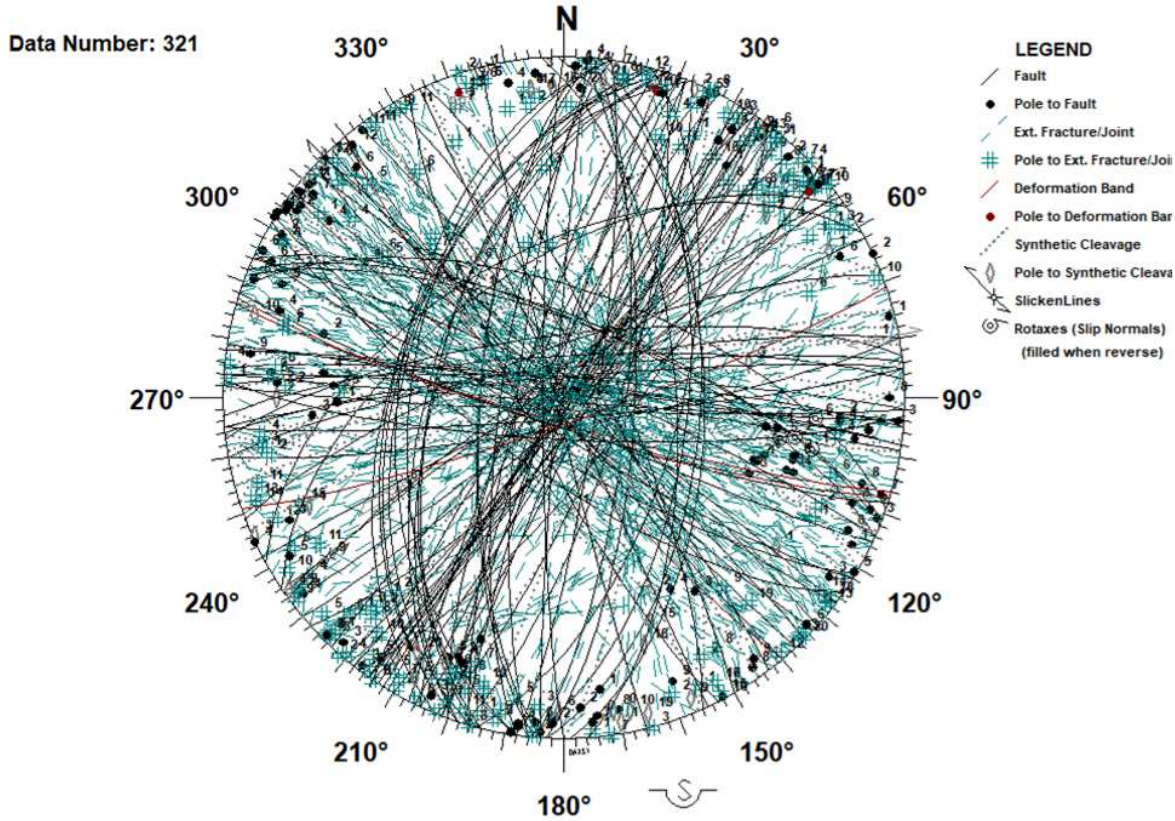

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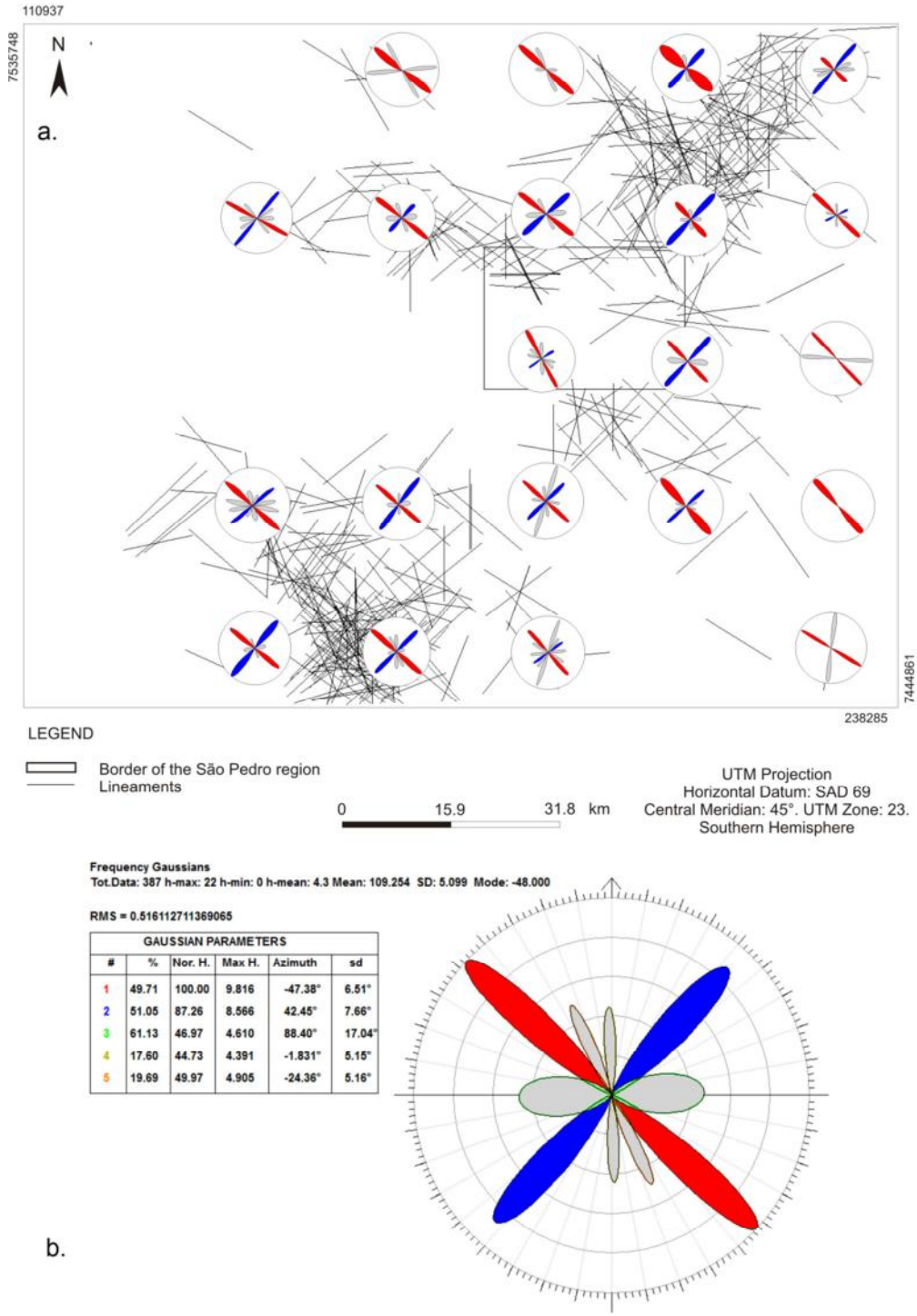

GAUSSIAN PARAMETERS					
#	%	Nor. H.	Max H.	Azimuth	sd
1	49.71	100.00	9.816	-47.38°	6.51°
2	51.05	87.26	8.566	42.45°	7.66°
3	61.13	46.97	4.610	88.40°	17.04°
4	17.60	44.73	4.391	-1.831°	5.15°
5	19.69	49.97	4.905	-24.36°	5.16°

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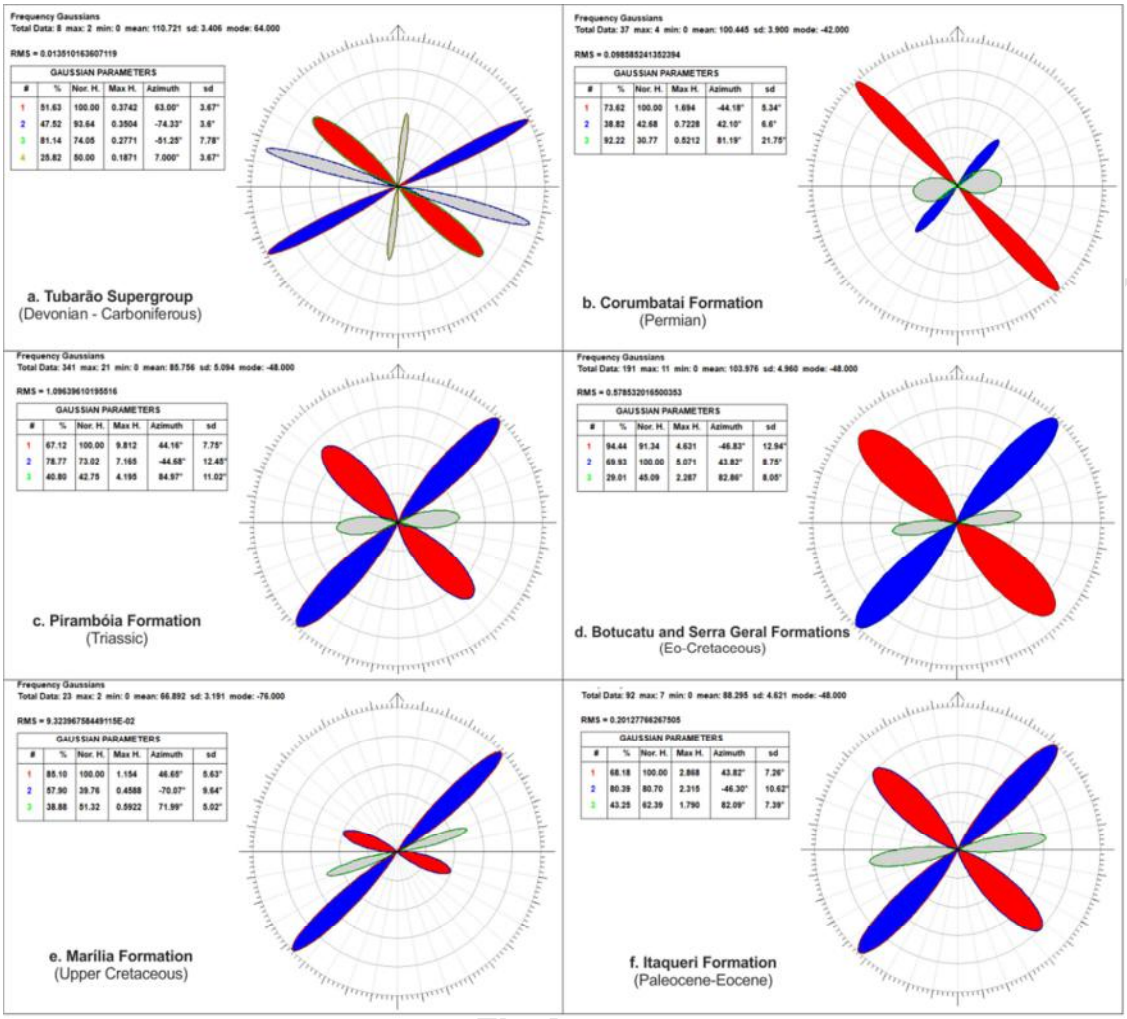

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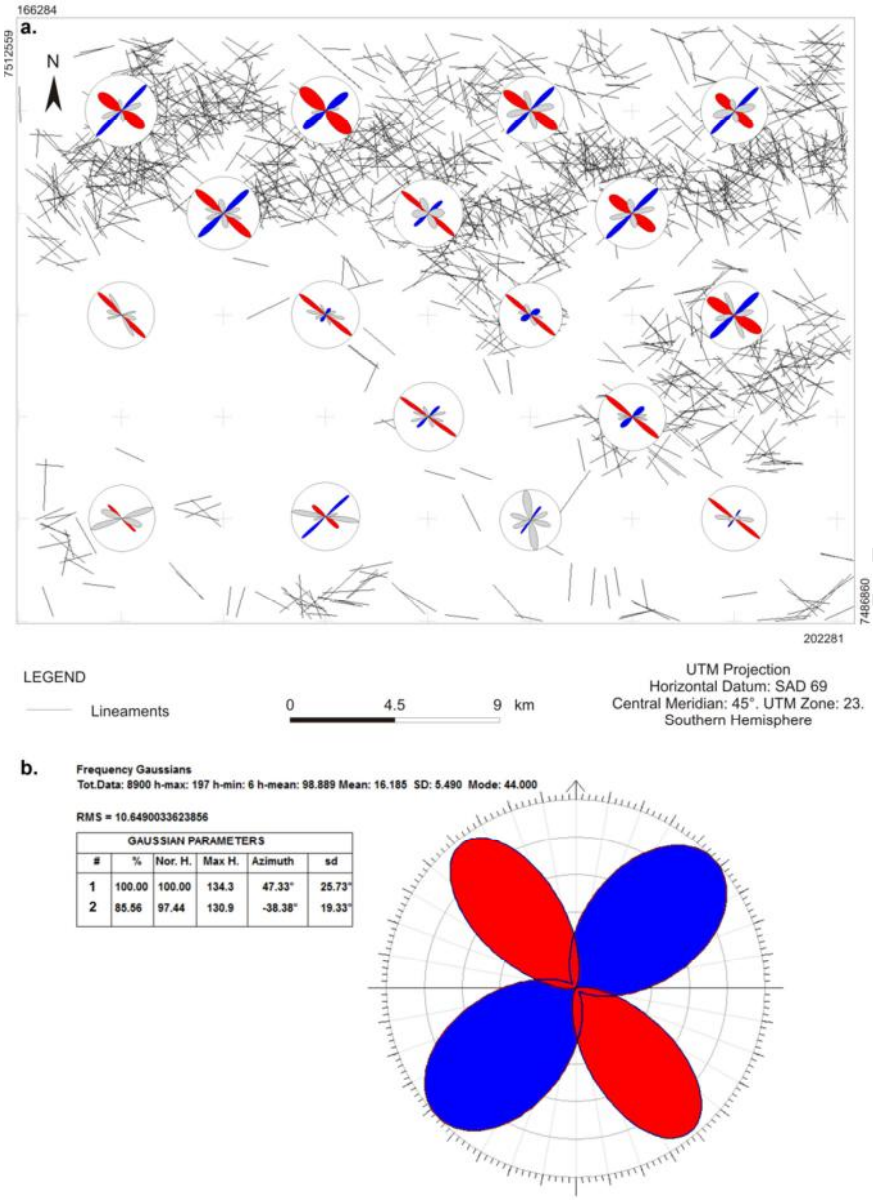

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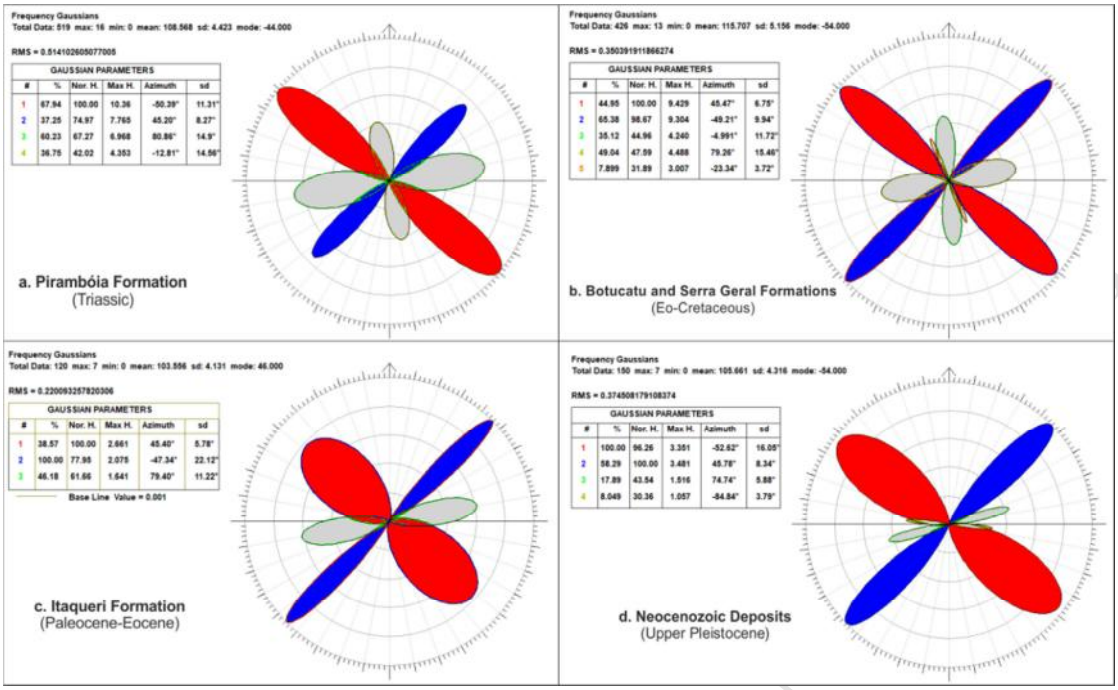

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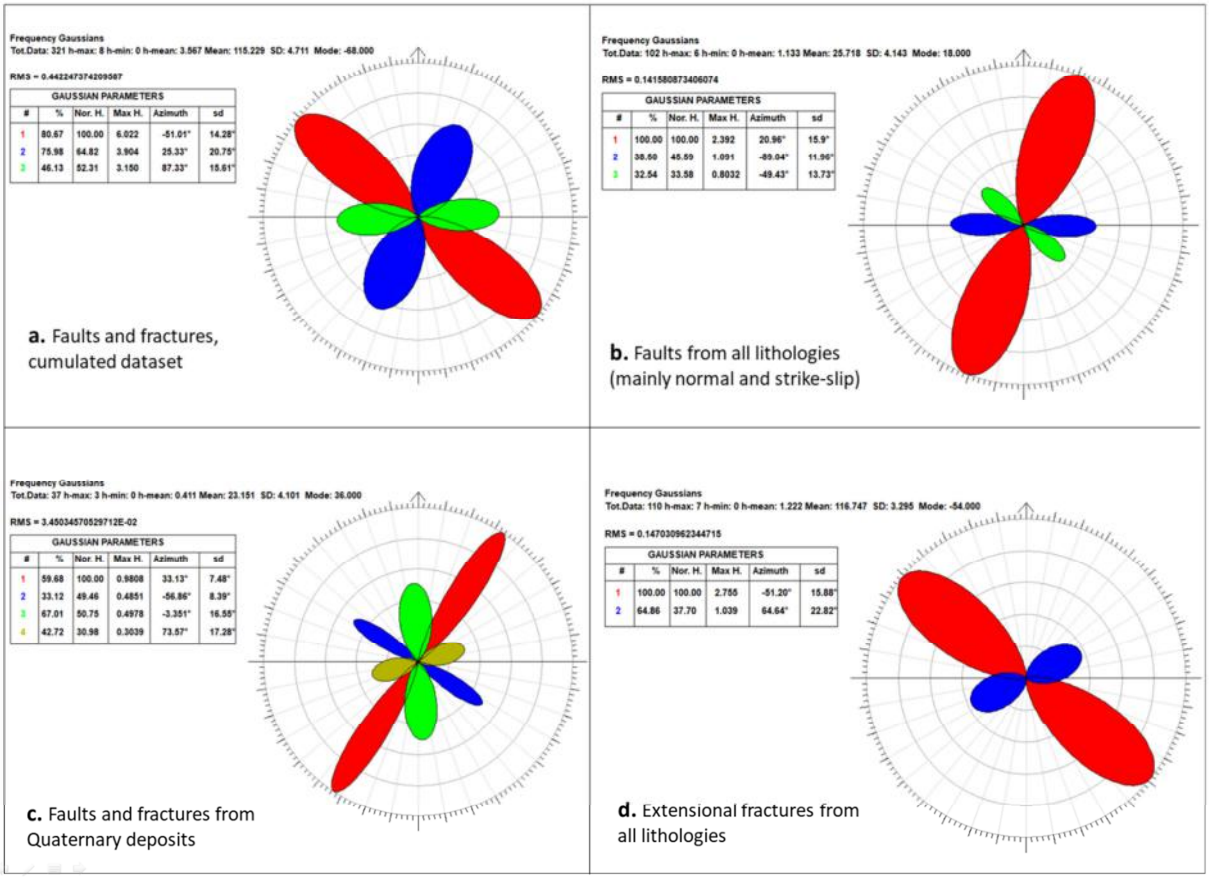

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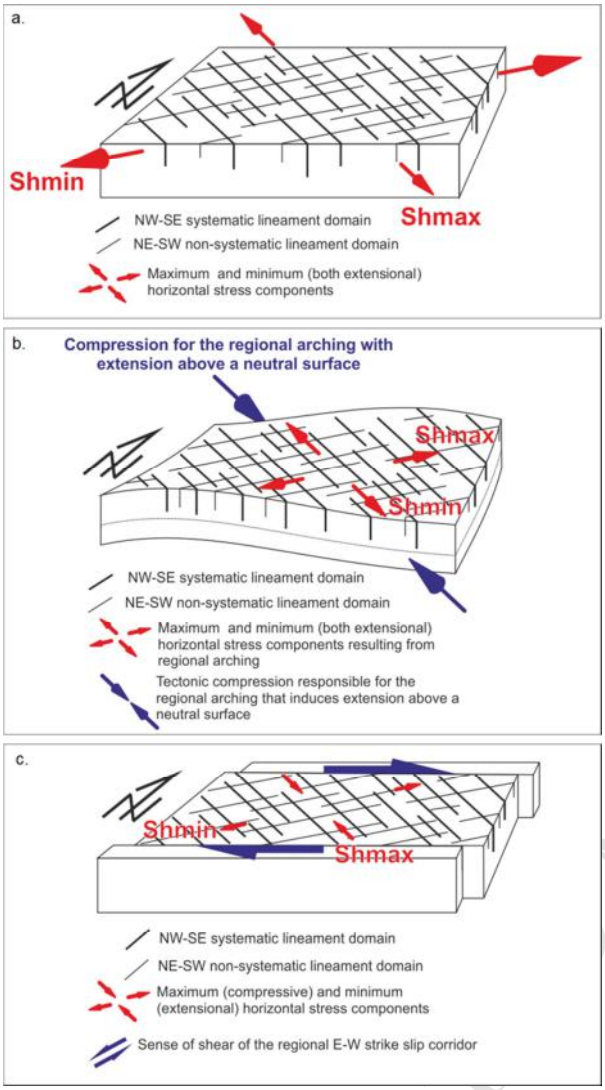

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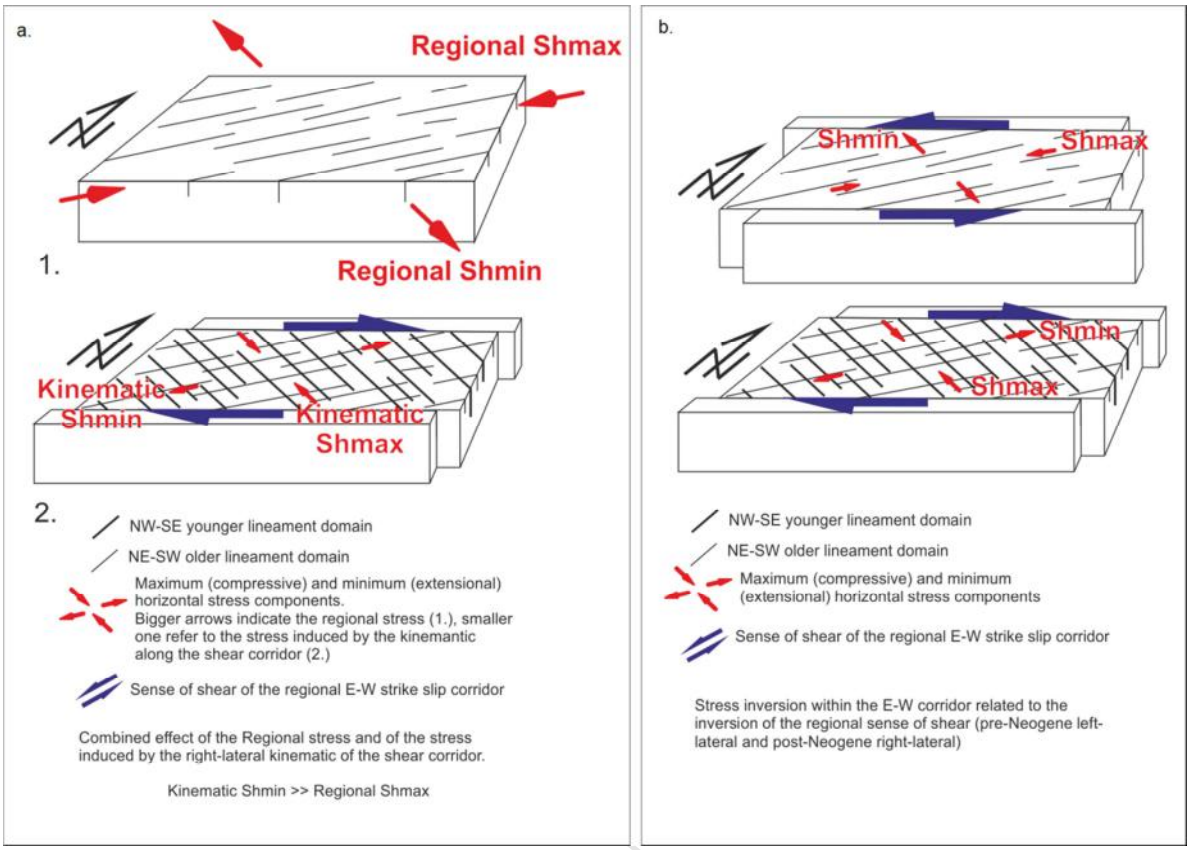

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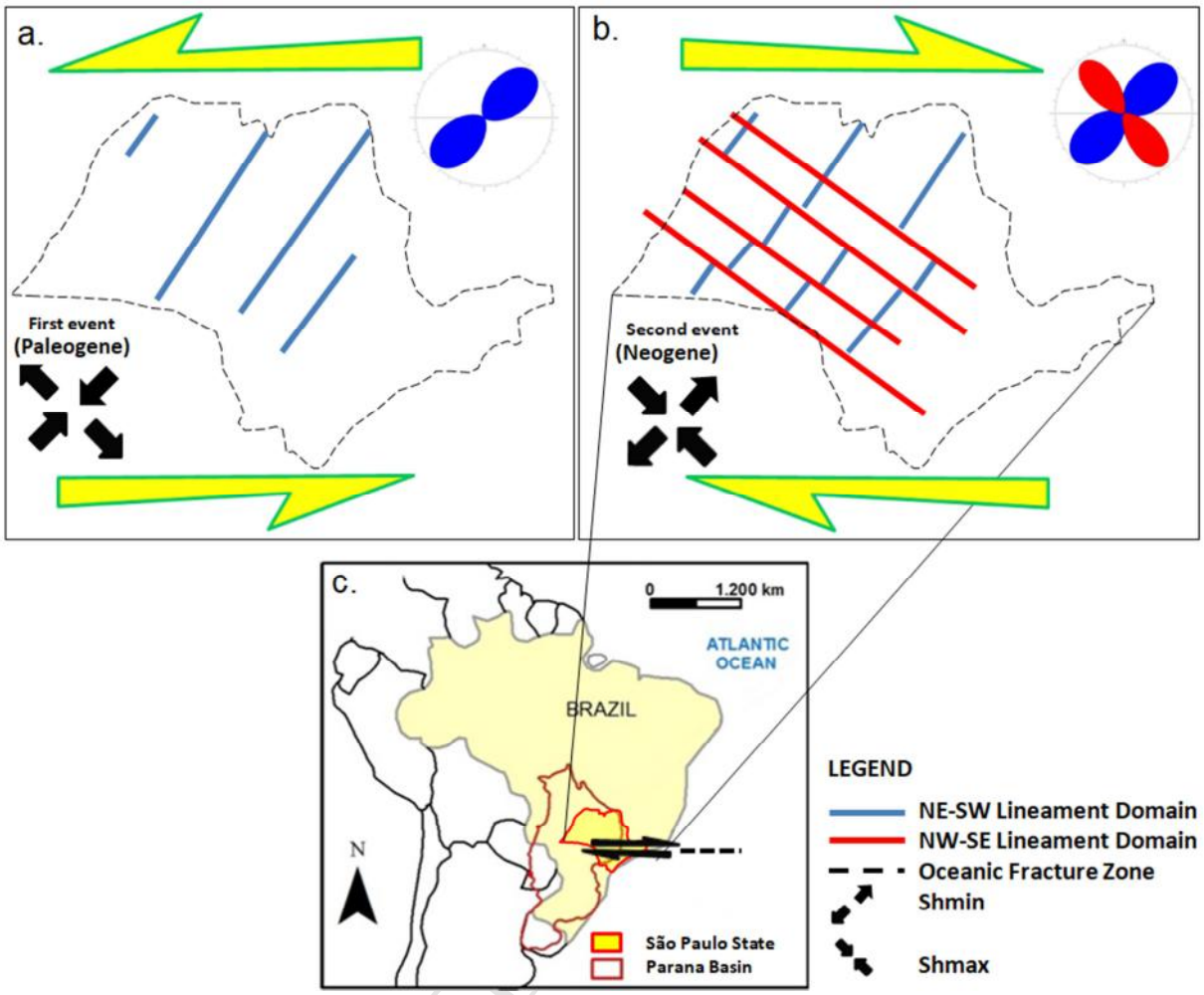

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Intraplate strike slip deformation belt within Southeastern Brazil

Pre-Neogene left lateral shear along E-W intraplate corridor

Post Neogene to Quaternary right lateral shear

Continental prosecution of oceanic fracture zones within South America