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Influence of preexisting structures on the variation of neotectonic paleostress orientation in an area of the Southeastern Brazilian Margin

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Abstract
The Southeastern Brazilian Margin presents a NE-SW-striking structural framework, which is characteristic of the Neoproterozoic Ribeira Belt. Other important structural trends along the area are associated with E-W and NW-SE-striking structures, being most related to the Mesozoic-Cenozoic tectonic evolution. A succession of Cenozoic tectonic events has been described by many authors in the Southeastern Brazilian. Among those Cenozoic tectonic events, a Neogene to Quaternary E-W dextral strike-slip regime (EW-DT) shows a wide distribution, presenting some variations in the stress field orientation. This research investigates the influence of the preexisting structural framework on the variation of the paleostress field orientation associated with the EW-DT tectonic event in a selected area in the onshore continental margin of the Southeastern Brazil. The study was carried out in three main stages: lineament analysis, paleostress field analysis, and numerical mechanical modeling. The paleostress field related to the EW-DT tectonic event in the studied area presents: NNW-SSE-striking maximum horizontal stress, and counterclockwise rotation influenced by the structural framework. Regarding this, the regional variation of the paleostress field is influenced by a preferential reactivation of NE-SW-striking structures while sets of approximately E-W-striking structures are the main local control of counterclockwise rotation of the stress field.

KEYWORDS: neotectonics; Southeastern Brazilian Margin; numerical modeling.

INTRODUCTION

The Cenozoic tectonic stress along the Southeastern Brazilian Margin has been studied since the 1970's in the context of a remarkable tectonic feature, with extension of hundreds of kilometers described as the "Serra do Mar Rift System" (Almeida 1976) or Continental Rift of Southeastern Brazil (Riccomini 1989) or Cenozoic Rifts System of Southeastern Brazil (Zalán and Oliveira 2005), composed by a complex of elongated tectonic valleys, flanked by mountainous areas and partly occupied by Paleogene sedimentary basins (Fig. 1). Riccomini *et al.* (2004) proposed a succession of Cenozoic tectonic events for the evolution of the Continental Rift of Southeastern Brazil, which has been recognized by other authors in several adjacent geologic compartments (Fig. 2).

Among the Cenozoic tectonic events recognized by Riccomini *et al.* (2004), the Neogene to Quaternary E-W dextral transcurrent event (EW-DT), characterized by NE-SW extension and NW-SE compression, presents an outstanding record within the different studied areas (Fig. 2). The stress field associated with the EW-DT tectonic event shows some variations in its orientation along the investigated areas, leading to two main questions: how these variations are spatially distributed and what factors control such variations.

Reactivation of preexisting discontinuities is an important mechanism of tectonic stress field accommodation. Generally, this process involves tectonic structures presenting geometries which are compatibles with the orientation of the new stress field, causing its local variations.

The Southeastern Brazilian Margin shows a NE-SW-striking structural framework, related to the Neoproterozoic tectonic evolution (Ribeira Belt). Also, E-W and NW-SE/NNW-SSE-striking structural trends are present in the study area, most associated with the Mesozoic-Cenozoic tectonic evolution of the continental margin.

The analysis of lineament swarms has been applied to characterize the structural framework of the Southeastern Brazilian Continental Margin (e.g. Liu 1987, Ribeiro 2010, Bricalli and Mello 2013, Brêda *et al.* 2018). Brêda *et al.* (2018) have recognized two main sets of lineaments based on length. These sets present a strong correlation to the main geologic domains. The longest lineaments (greater than 10 km long) exhibited an expressive correlation to the main structural framework of the Domain of Basement (NE-SW-striking trend of the Ribeira Belt) and also includes E-W and NW-SE-striking features attributed to the Mesozoic-Cenozoic tectonic evolution.

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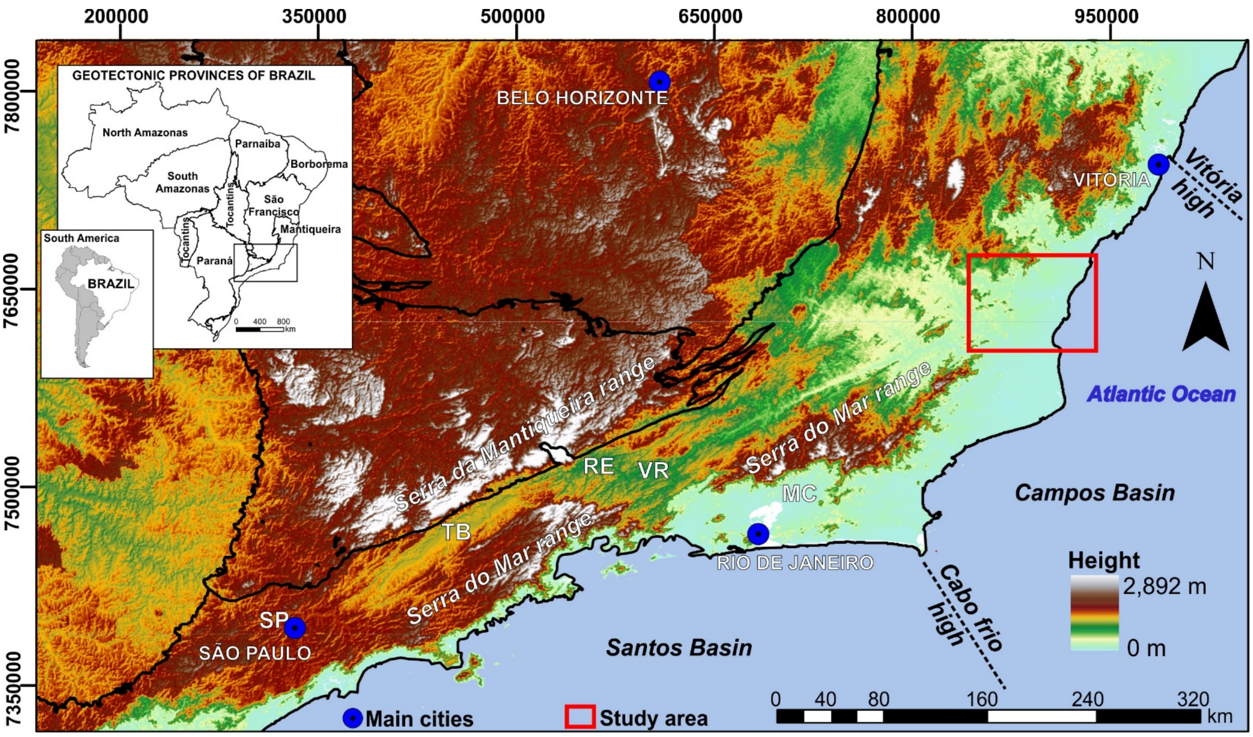
The minor lineaments (lesser than 10 km long) present a wide distribution and represent almost all the lineaments in Domain of Cenozoic Deposits. Thus, the authors related these minor lineaments to neotectonic features, as reactivated and/or neoformed structures, and the longest lineaments to older structures than those formed in the EW-DT neotectonic event.

This study aims to investigate the influence of the preexisting structural framework on the variations of the paleostress field orientation associated with the Neogene to Quaternary EW-DT tectonic event in a selected area in the onshore continental margin of the Southeastern Brazil. The study integrates paleostress field analysis, based on fault-slip data available in



SP: São Paulo Basin; TB: Taubaté Basin; RE: Resende Basin; VR: Volta Redonda Basin; MC: Macacu Basin.

Figure 1. Location of the study area in a hypsometric map of the Southeastern Margin of Brazil, highlighting the Serra do Mar and Serra da Mantiqueira ranges, which limit NE-SW elongated topographic depressions (parallel to the coastline), where the main sedimentary basins of the Continental Rift of Southeastern Brazil are located (according to Riccomini *et al.* 2004). The boundaries of the Brazilian geotectonic provinces are also indicated (identified in the upper left side of the figure, according to Bizzi *et al.* 2003)

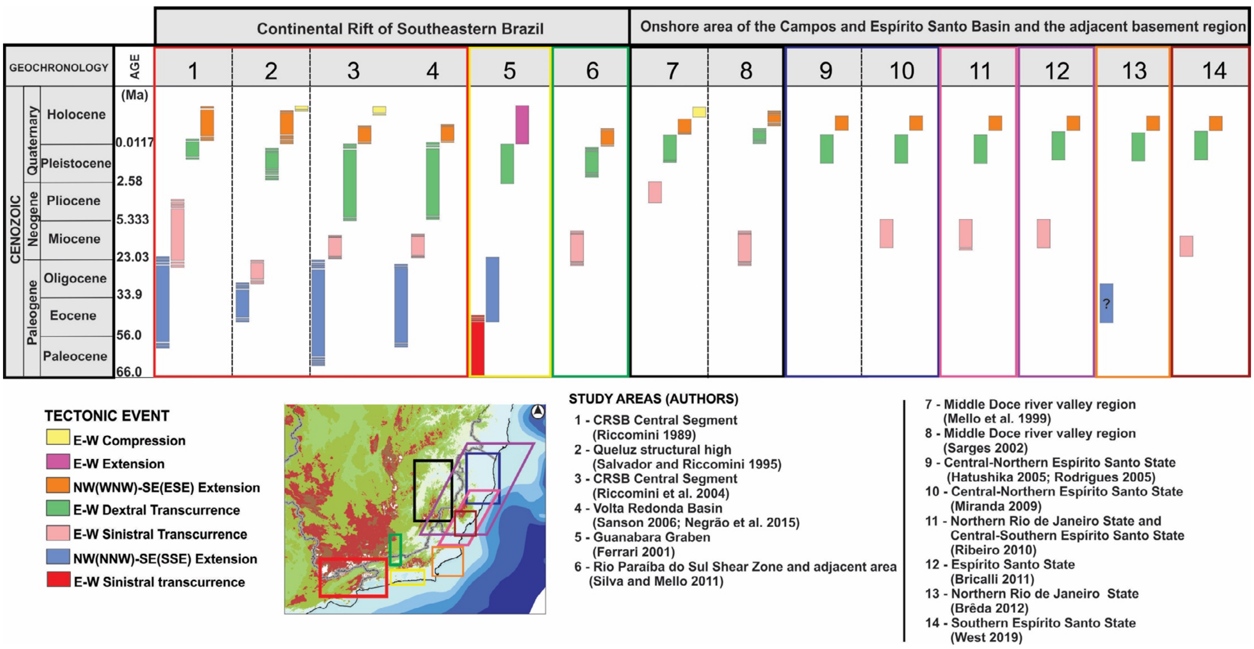


Figure 2. Cenozoic tectonic events recognized in previous studies in the Southeastern Margin of Brazil (Riccomini 1989, Salvador and Riccomini 1995, Mello *et al.* 1999, Ferrari 2001, Silva and Mello 2001, Sarges 2002, Riccomini *et al.* 2004, Hatushika 2005, Rodrigues 2005, Sanson 2006, Miranda 2009, Ribeiro 2010, Bricalli 2011, Brêda 2012, Negrão *et al.* 2015, West 2019). The colored polygons on the map correspond to the several areas investigated in the region. These areas are numbered on the side and in the table above (in which the different areas are colored with the same colors).

the literature, and the application of numerical mechanical modeling to simulate paleostress field variation and structural reactivation. Numerical modeling is a methodological approach which is still underexplored in the context of the studies developed in the region.

GEOLOGICAL SETTING

The study area encompasses the onshore region adjacent to the northern portion of the Campos Basin (Figs. 1 and 3).

The area presents two main geologic domains: Neoproterozoic to Eopaleozoic basement rocks; and Cenozoic sedimentary terrains. In the adjacent oceanic region there are Mesozoic to Cenozoic sedimentary and volcanic rocks, which fill the Campos Basin.

The basement rocks are associated with the tectonic evolution of the Ribeira Belt (included in the Mantiqueira Geotectonic Province — Almeida *et al.* 1977, Heilbron *et al.* 2004). This orogenic system resulted on the amalgamation of Western Gondwana Paleocontinent during the Neoproterozoic Brazilian-Pan African Orogeny. The Ribeira Belt has developed from two main collision periods (605 to 560 Ma and 535 to 510 Ma) and presents a NE-SW-striking structural trend (Heilbron *et al.* 2004), best marked in the southern sector of the study area.

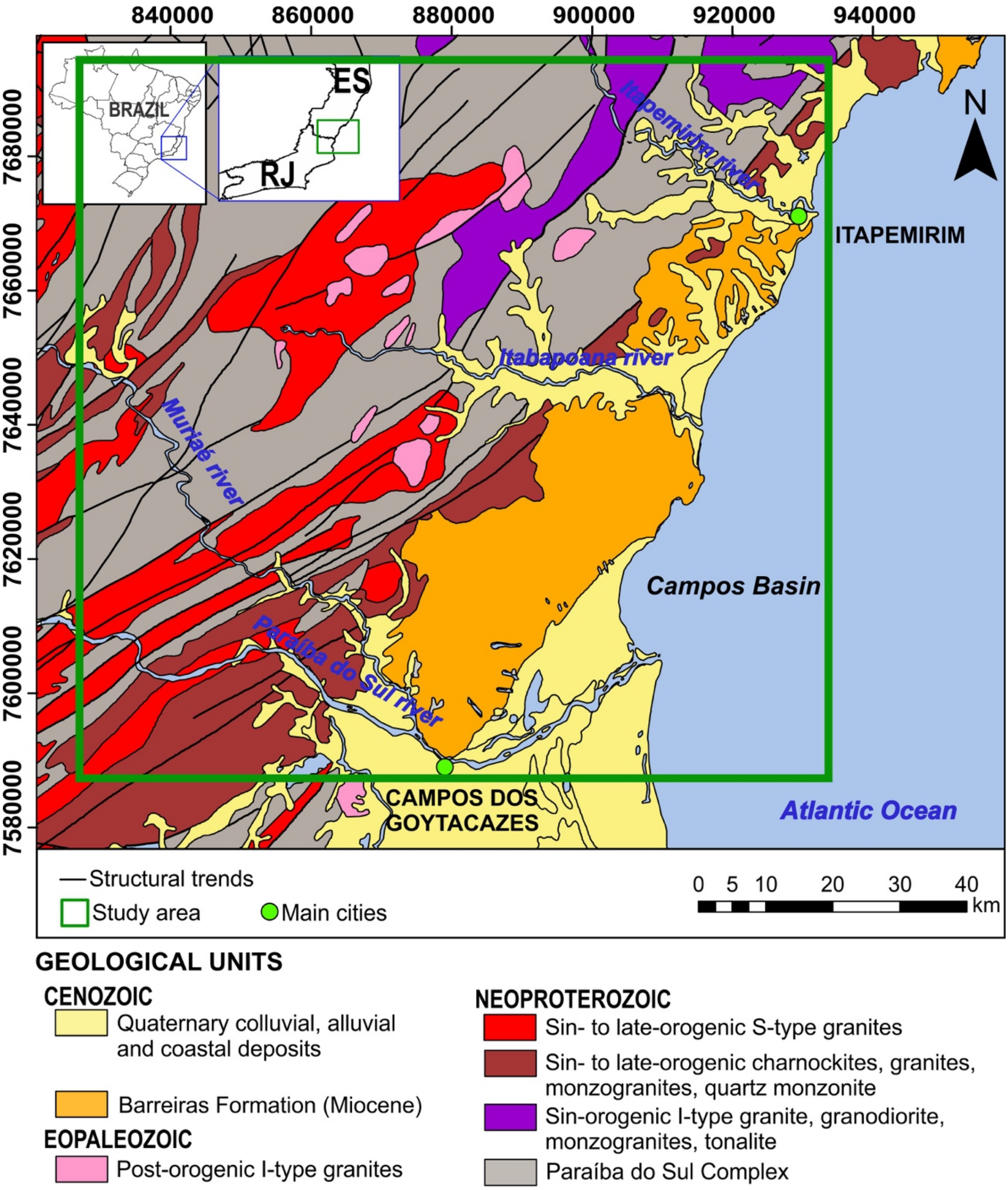


Figure 3. Geological map of the study area (modified from Bizzi *et al.* 2003), located in the limit of the Rio de Janeiro (RJ) and Espírito Santo (ES) states. See in Figure 1 the location of the area regarding the geomorphologic context of the Southeastern Brazilian Margin.

The basement rocks are predominantly composed of gneiss complexes and intrusive magmatic suites (Bizzi *et al.* 2003). The more representative geological unit in the study area corresponds to the Neoproterozoic Paraíba do Sul Complex (Fig. 3), which is composed of sillimanite-garnet-muscovite-biotite banded gneiss with intercalations of marble, calc-silicate rocks, gondite, amphibolite and quartzite.

Sin- to late-orogenic NE-SW-striking magmatic suites are distributed throughout the domain of basement (Fig. 3). They are composed of I-type and S-type granites, charnockites, monzogranites, quartz monzonites, granodiorites and tonalites. Post-orogenic I-type granites occur in restricted areas.

The sedimentary terrains in the study area correspond to the Barreiras Formation (Miocene) and Quaternary covers (Fig. 3). The Cenozoic deposits represent an important stratigraphic guide for neotectonic characterization along the Southeastern Brazilian Margin (e.g. Ribeiro 2010, Bricalli 2011). The Barreiras Formation is predominantly composed of ferruginized sandstones, with intercalations of mudstones and conglomerates. These deposits are related to braided river and alluvial fans environments (Morais *et al.* 2006, Winter *et al.* 2007, Brêda 2012, West 2019). Quaternary deposits in the study area correspond to alluvial and colluvial sediments and coastal deposits, more developed at the mouths of the main river courses (Bizzi *et al.* 2003).

MATERIALS AND METHODS

The investigation of the spatial variation of the paleostress field associated with the EW-DT tectonic event was carried out in three main methodological stages:

- lineament analysis;
- paleostress field analysis;
- numerical mechanical modeling.

In the first stage, a 1:500,000 scale map of lineaments produced by Brêda *et al.* (2018) was used, encompassing rectilinear features greater than or equal to 1 km long extracted from hillshades generated from the SRTM/NASA digital elevation model (available at http://srtm.csi.cgiar.org). Orientation, length and distribution of lineaments patterns were evaluated and compared to the geological map in order to characterize the structural framework of the study area and discuss the tectonic meaning of the lineaments. The structural framework used in numerical modeling was obtained in this step.

The paleostress field analysis was performed by using 86 fault-slip data compatible with the EW-DT tectonic event, distributed in 7 outcrops, available from previous works (Ribeiro 2010, Bricalli 2011, Rodrigues 2015). The extensional and compressional fields were obtained using Right Dihedra Method (Angelier and Mechler 1977). Then, the data were treated on the *Win-Tensor* (Delvaux and Sperner 2003), estimating the orientations of the paleostress field and the stress ratio ($R = \sigma2-\sigma3/\sigma1-\sigma3$). The paleostress fields obtained were spatialized in geological and lineament maps, which allowed to analyze patterns of paleostress trend variations.

The numerical mechanical modeling stage was based on the concepts of continuum mechanics, using the finite element method. This methodology enables the insertion of interface elements to represent discontinuities (such as lineaments), allowing to analyze structural reactivations. The model was performed in the TECTOS System (Petrobras software developed in partnership with the Tecgraf Institute of Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio)), which is able to simultaneously modeling hundreds of discontinuities. The model was based on elastic-plastic behavior and the Mohr-Coulomb criterion.

The model construction stages involved:

- loading of preexisting discontinuities from a text file with information on the initial and final coordinates of each tectonic structure;
- insertion of mechanical properties for material and discontinuities properties;
- generation of a semi-automatic triangular mesh of finite elements;
- insertion of boundary conditions;
- prescription of shear stress in successive steps (up to 20 MPa, with 1 MPa steps).

The properties attributed to the material and discontinuities are ideally obtained from mechanical testing of the investigated rocks, but parameters available in the literature for similar materials can alternatively be used. This study used values by Fjær *et al.* (2008) for the bearing rock (Tab. 1) and data available in Pariseau (2011) for discontinuities properties (Tab. 2).

The boundary conditions were defined in order to simulate the E-W dextral transcurrent movement, according to the tectonic event in study. The applied shear stress aimed to observe the progressive strain of the materials in order to investigate the orientation trend distribution of the paleostress field, considering the different orientations of the preexisting structural framework.

The building of the finite element mesh is the most arduous step in the model construction, being of great importance

Table 1. Mechanical properties used for material in numerical mechanical modeling.

Geologic framework properties	
Young module	20 GPa
Poisson coefficient	0.32
Biot coefficient	1
Internal friction angle	30°
Cohesion	20 MPa
Density	2,500 kg/m^3

Source: Fjær *et al.* (2008).

Table 2. Discontinuities properties used in numerical mechanical modeling.

Discontinuities properties	
Normal stiffness	10 MPa
Shear stiffness	0.1 MPa

Source: Pariseau (2011).

that it presents sufficient refinement and well-defined elements. It requires adjustment of inserted discontinuities to avoid areas with many intersections and narrowly spaced structures with similar orientations.

Finally, the generated numerical mechanical model was analyzed together with the results obtained from the paleostress field analysis by fault-slip data.

RESULTS

Lineament analysis

Based on a 1:500,000 scale map of lineaments involving a larger area than that covered in the present study, Brêda *et al.* (2018) recognized two main domains along the Southeastern Brazilian Margin: Domain of Basement and Domain of Cenozoic Deposits. The Domain of Basement in the area investigated in the present study was subdivided into two sectors (Fig. 4): northern sector, with NE-SW, NW-SE, N-S, and E-W-striking lineaments trends; and southern sector, with predominantly NE-SW-striking lineaments sets and, subordinately, E-W and NW-SE-striking lineament sets. The Domain of Cenozoic Deposits in the area shows predominantly NW-SE-striking lineaments trends, with minor sets of NE-SW and N-S-striking lineaments (Fig. 4).

Regarding the length of the lineaments in the area, the frequency histogram (Fig. 5) shows a change in the distribution pattern of the lineaments around 10 km. This pattern was also observed by Brêda *et al.* (2018) in a largest area. In the Domain of Basement, most of the lineaments

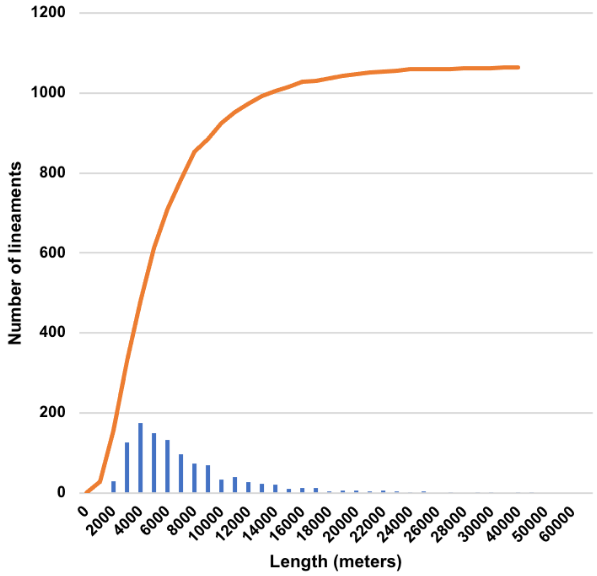


Figure 5. Histogram (in blue) and cumulative frequency graph (in orange) of lineaments length in the study area.

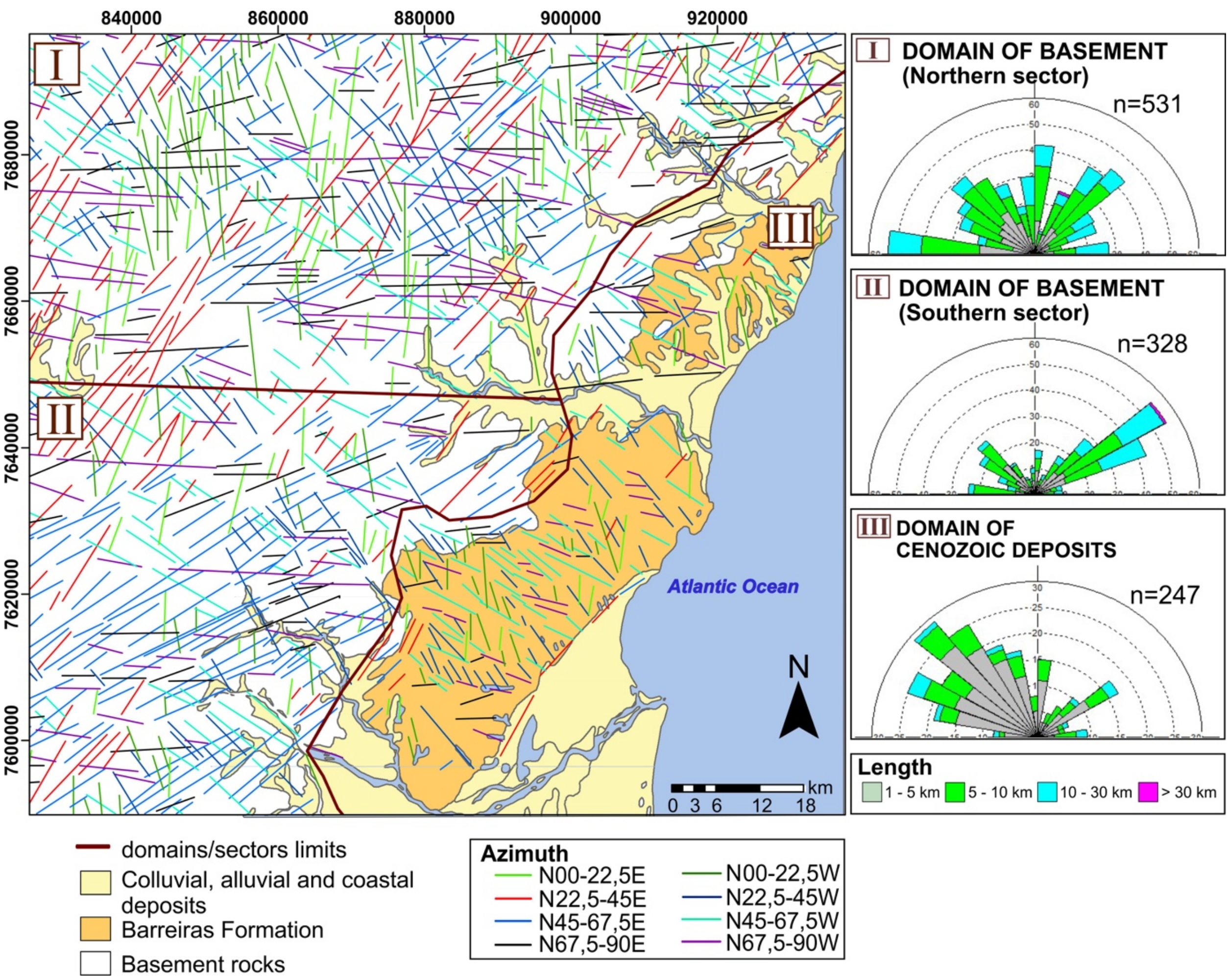


Figure 4. Map of lineaments (from Brêda *et al.* 2018) over a simplified geological map (from Bizzi *et al.* 2003) and rosette diagrams of orientation and length frequency of lineaments for each domain/sector. The limits of domains/sectors are also from Brêda *et al.* (2018).

greater than or equal to 10 km strike NE-SW (compatible with the main structural trend of Ribeira Belt), and there are also approximately N-S and E-W-striking sets in the northern sector (Fig. 6A). In this domain, lineaments smaller than 10 km (Fig. 6B) show, in addition to NE-SW-striking lineaments, expressive NW-SE and E-W-striking trends. In the Domain of Cenozoic Deposits, there is a very low frequency of lineaments greater than or equal to 10 km

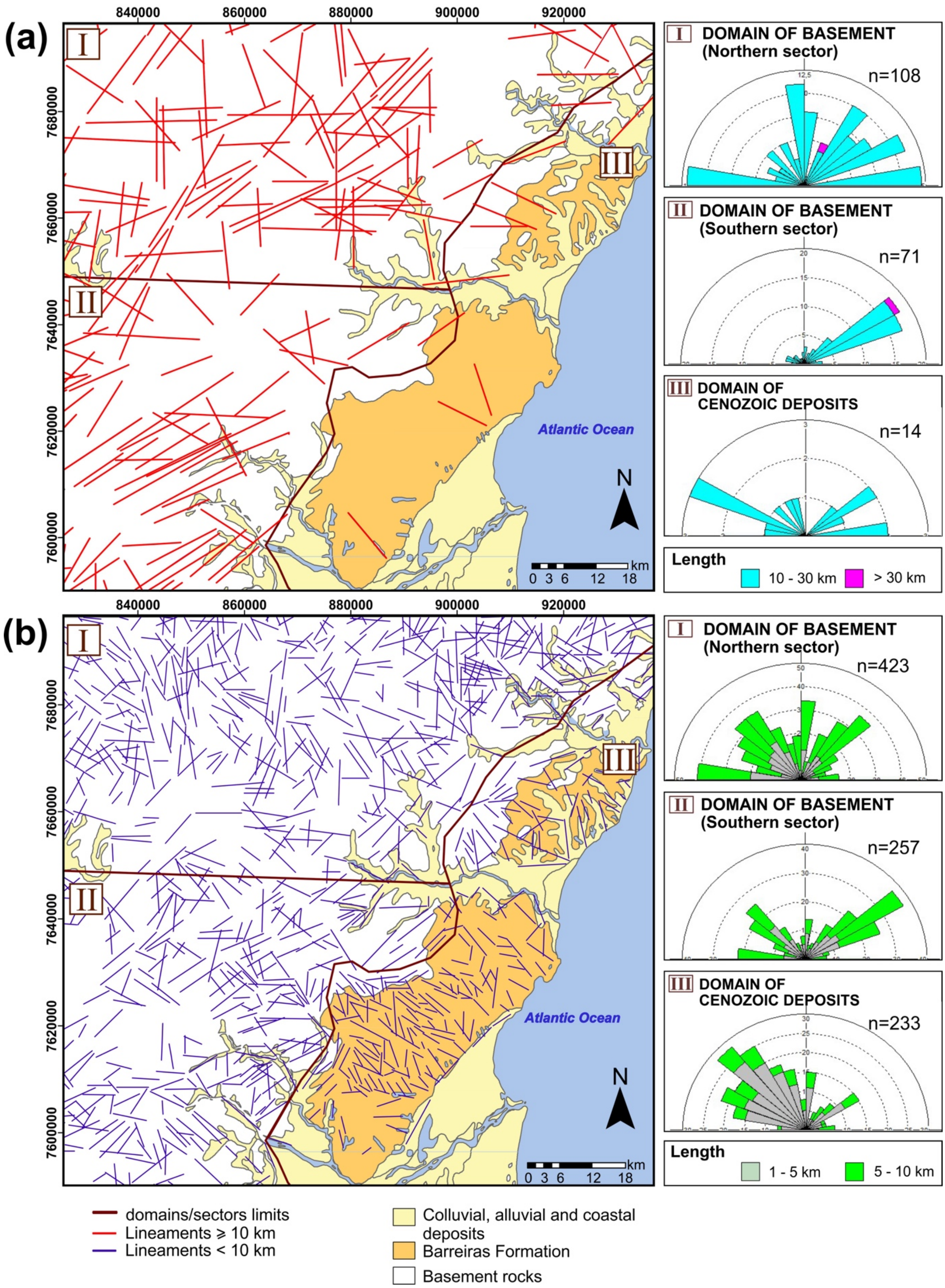


Figure 6. Maps of lineaments (A) greater than or equal to 10 km in length and (B) smaller than 10 km in length, indicating the boundaries between the domains/sectors of Basement and Cenozoic Deposits, including rosette diagrams of orientation and length frequency for each domain/sector. Maps of lineaments and domains/sectors limits are from Brêda *et al.* (2018). Geological units were simplified from Bizzi *et al.* (2003).

(Fig. 6A), while lineaments smaller than 10 km (Fig. 6B) are very frequent, with a predominant NW-SE-striking that contrasts with the basement structural trend. As discussed by Brêda *et al.* (2018), the frequency and orientation of the lineaments in the Domain of Cenozoic Deposits suggest a more recent genesis of lineaments smaller than 10 km in relation to larger ones.

Paleostress field analysis

The structural data compatible with the EW-DT tectonic event in the area are distributed in three outcrops in the Domain of Basement (MS-02/04, MC-CZ-01 and MC-02) and four outcrops in the Domain of Cenozoic Deposits (ITA-03, MC-04, MC-05 and RM-16) (Fig. 7).

In the Domain of Basement, WNW-ESE and NW-SE-striking normal faults, WNW-ESE and ENE-WSW-striking normal dextral faults, and ENE-WSW, NE-SW and WNW-ESE-striking dextral faults were analyzed. These structures were associated with a NW-SE-striking maximum horizontal stress (σ_H) ranging from N47W to N55W (Figs. 7 and 8). MS-02/04 site presents a predominance of dextral planes ranging from WNW-ESE to ENE-WSW-striking, which are associated with a N54W-striking σ_H. At MC-CZ-01 site, WNW-ESE to NW-SE-striking dextral and normal planes are predominant and associated with a N55W-striking σ_H. At MC-02 site, predominant NW-SE-striking normal planes and ENE-WSW-striking dextral planes are associated with a N47W-striking σ_H.

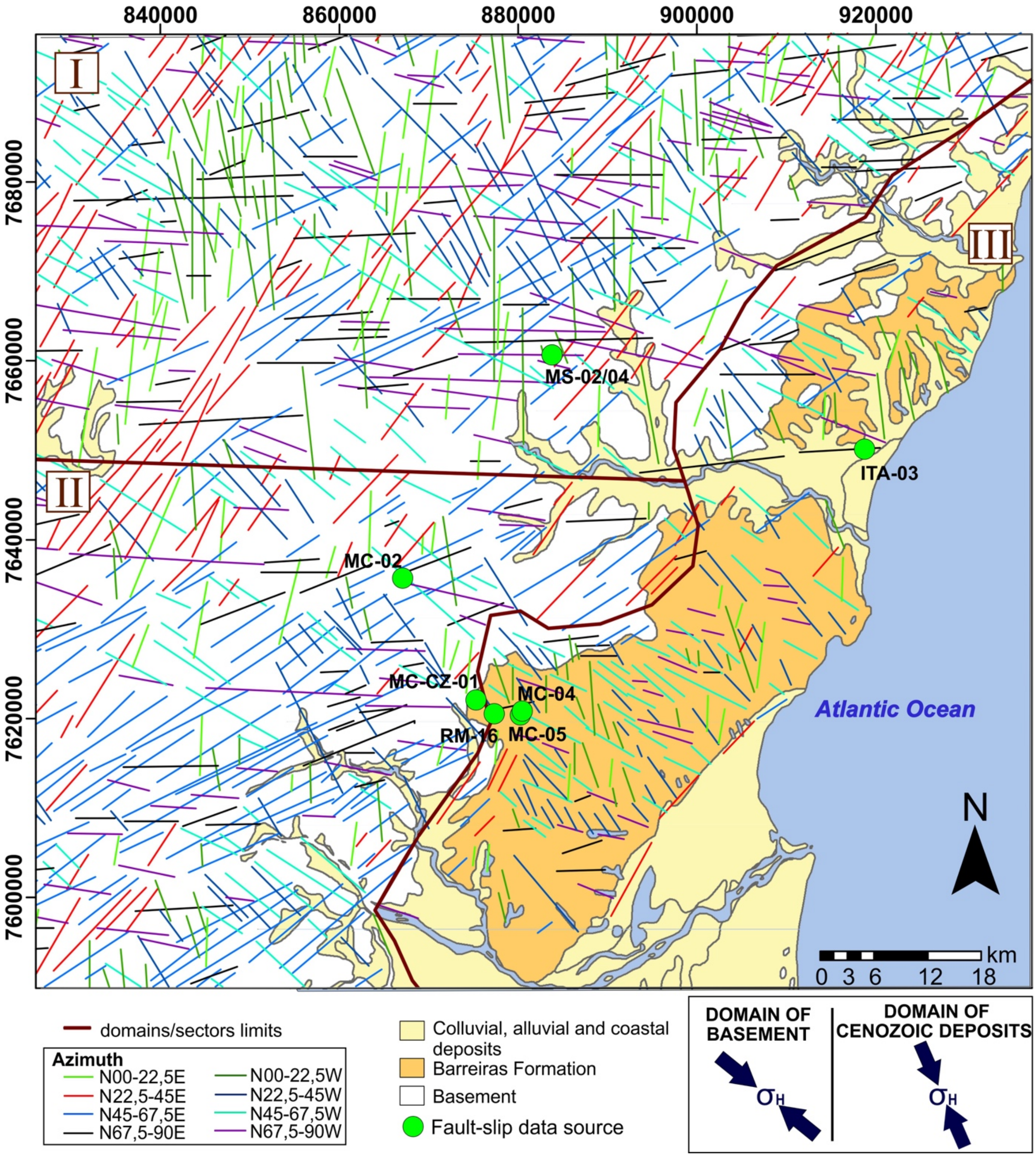


Figure 7. Distribution of the fault-slip data source over the map of lineaments (from Brêda *et al.* 2018) and general paleostress fields obtained for each domain. Geological units were simplified from Bizzi *et al.* (2003). Domains/sectors limits are from Brêda *et al.* (2018).

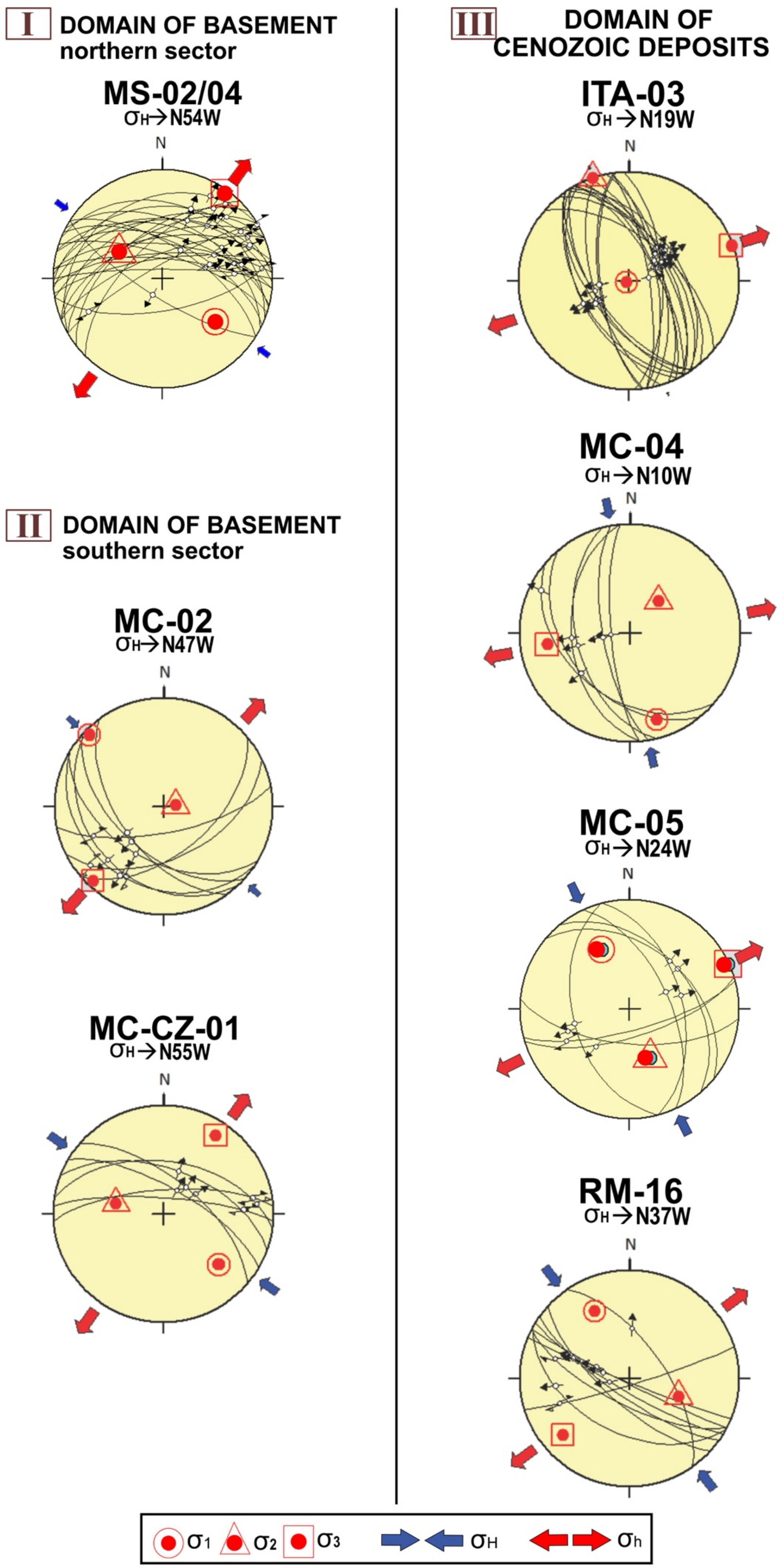


Figure 8. Paleostress fields estimated from fault-slip data source.

In the Domain of Cenozoic Deposits, NNW-SSE and NW-SE-striking normal faults, WNW-ESE, NW-SE and ENE-WSW-striking dextral normal faults, ENE-WSW-striking dextral faults, and NNW-SSE-striking sinistral normal faults to normal sinistral faults affect the Barreiras Formation deposits. Paleostress field analysis of these sets of structures indicates a NNW-SSE-striking σ_H (Figs. 7 and 8), ranging from N10W to N37W. The σ_H orientation varies more than that observed in the Domain of Basement. ITA-03 site presents a predominance of NW-SE-striking normal planes, which are related to a local extensional stress (N19W-striking σ_H) that is compatible to EW-DT tectonic event. MC-04 site presents a predominance of NNW-SSE-striking normal planes, which are associated with a N10W-striking $\sigma_{H.}$ At MC-05 site, NNW-SSE to NW-SE-striking normal planes and ENE-WSW to E-W dextral planes are predominant and related to a N24W-striking σ_H. RM-16 site presents a predominance of WNW-ESE-striking dextral planes, which are related to a N37W-striking $\sigma_{H.}$

The structural pattern at each point results on a local variation of the σ_H orientation, but prevailing an evident difference between the domains (Domain of Basement: N47-55W-striking σ_H; Domain of Cenozoic Deposits: N10-37W-striking σ_H).

The difference found for σ_H orientations between the Domain of Basement and the Domain of Cenozoic Deposits is associated with an influence of preexisting structural framework of basement rocks on the paleostress field related to the EW-DT tectonic event. A counterclockwise rotation is observed from the Domain of Cenozoic Deposits to the Domain of Basement. The σ_H orientation at RM-16 site (N37W) approaches the directions obtained in the Domain of Basement. This outcrop is located at the limit between the main domains and may also be influenced by the structural framework of the basement.

Numerical mechanical modeling

The numerical mechanical model that was performed for simulation of the E-W dextral transcurrent movement used 177 discontinuities representing the preexisting structures (Fig. 9).

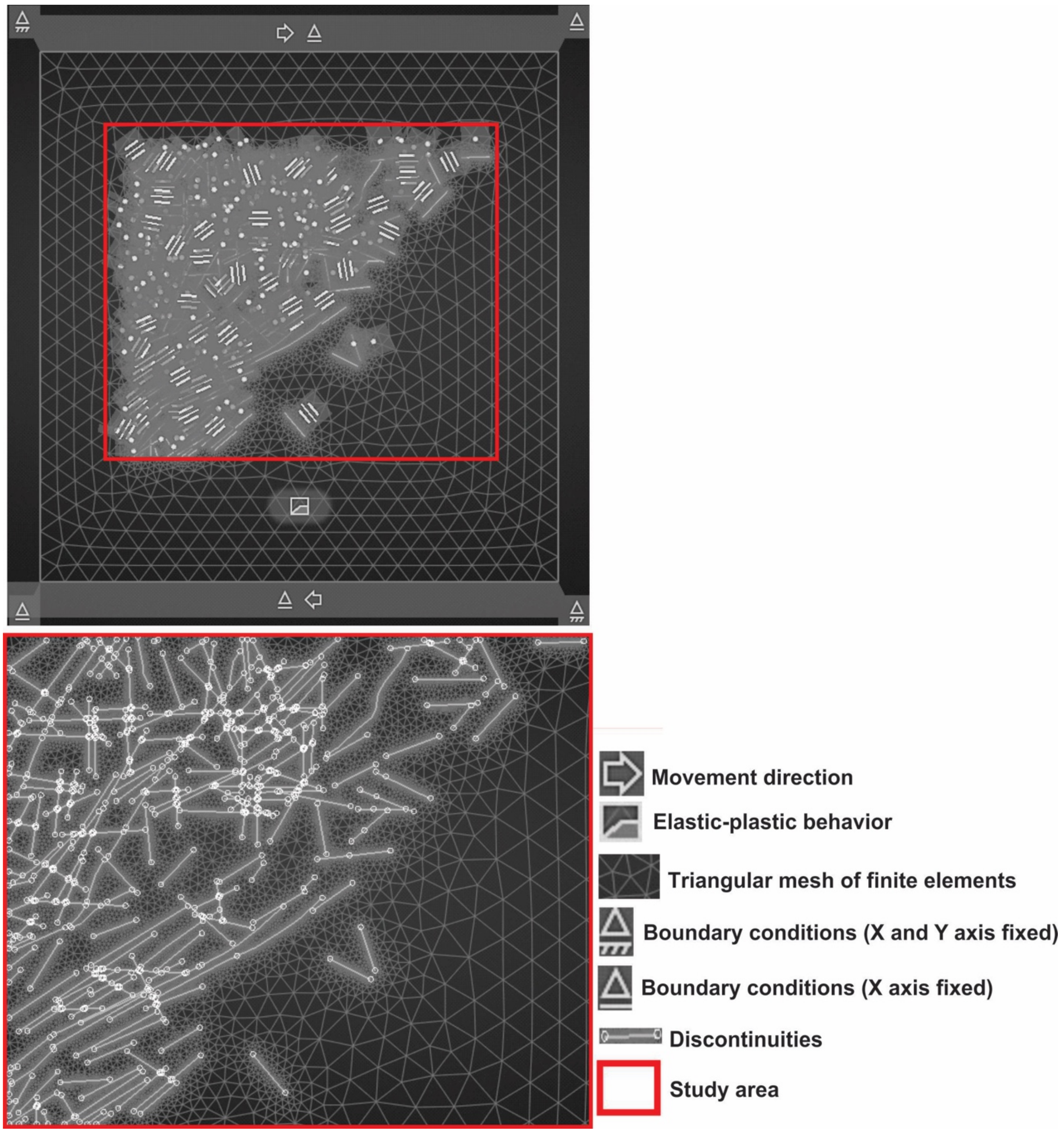


Figure 9. Geometric model generated for numerical simulation of the E-W dextral transcurrent movement in the studied area, outstanding the discontinuities (lineaments greater or equal to 10 km — from Brêda *et al.* 2018 and basement structures taken from the geological map — Bizzi *et al.* 2003), finite element mesh and boundary conditions.

These discontinuities correspond to lineaments greater than or equal to 10 km taken from Brêda *et al.* (2018) and basement structures taken from the geological map.

The TECTOS System provides several visualization modes to analyze the numerical models. Two parameters were more suitable for the analysis herein intended:

- the Ratio of Failure by Stress (RFS) parameter, which indicates the proximity of the accumulated stress to rupture considering the Mohr-Coulomb failure envelope, on a scale ranging from zero (0) to one (1), in which one (1) corresponds to the material rupture;
- the distribution of the orientation of the σ_H, which allows to observe the paleostress field variation along the studied area.

The RFS is sensitive to the parameters entered for both material and discontinuities, in addition to the kinematics prescribed in the model. The distribution of σ_H orientation is more directly related to the prescribed kinematics.

The RFS parameter map shows high values near NE-SW-striking structures, which was well evidenced between 5 and 12 steps of the model (Fig. 10). The RFS values remain lower close to approximately E-W-striking structures even under higher stress (Fig. 11). The distribution of the σ_H shows a general N45W-striking orientation. However, there is a locally tendency for σ_H to be parallel to E-W-striking features (Fig. 12). The distribution of E-W-striking features is more segmented in regions of greater interaction between discontinuities with different orientations and this distribution pattern may be influencing the RFS values obtained close to the E-W-striking trends.

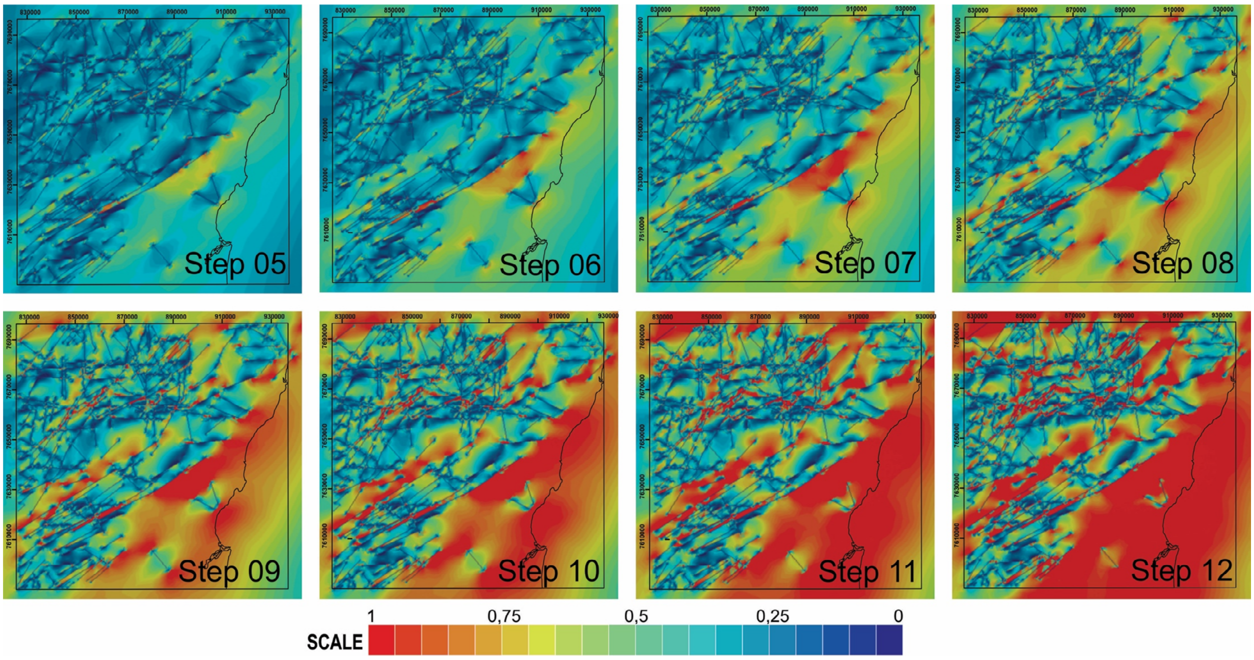


Figure 10. Ratio of Failure by Stress (RFS) parameter maps of the numerical mechanical model simulating E-W dextral transcurrent movement for the study area (from Step 5 to Step 12). The red color represents the RFS maximum value (material rupture/structural reactivation). Notice that the NE-SW structures are associated with higher RFS values.

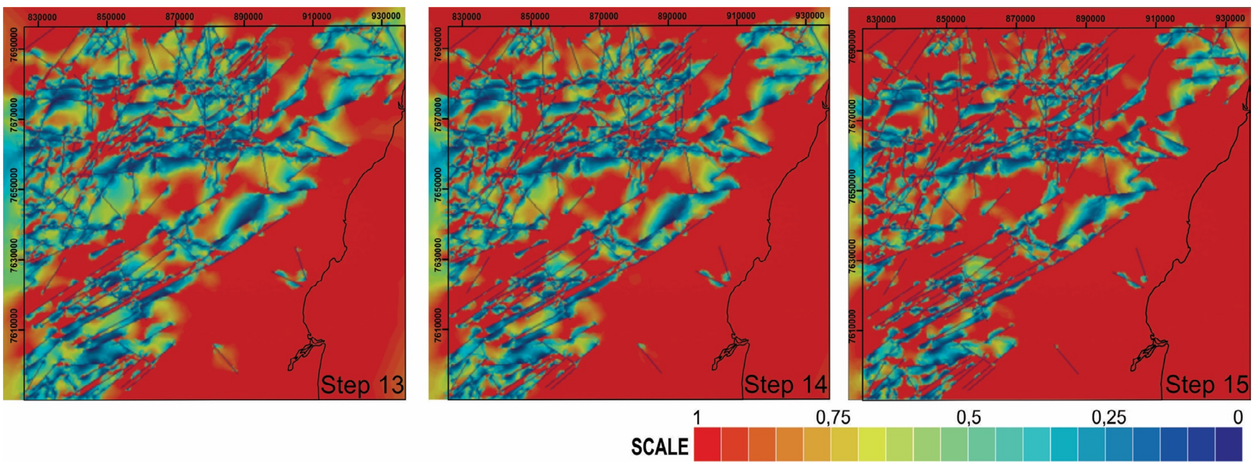


Figure 11. Ratio of Failure by Stress (RFS) parameter maps of the numerical mechanical model simulating E-W dextral transcurrent movement for the study area (from Step 13 to Step 15). The red color represents the RFS maximum value (material rupture/structural reactivation). Notice that the E-W structures are associated with lower RFS values.

DISCUSSION

The two approaches applied to estimate the stress field orientation related to the E-W dextral transcurrent tectonic event in the investigated area showed a good correlation, with complementary results. Paleostress field analysis from fault-slip data is dependent on the existence and the quality of outcrops, but it was possible to analyze sets of structures with different orientations and kinematics associated with the same stress field regime. Numerical modeling simulated the paleostress field variation over the entire area, allowing for both regional and local scale analysis. A difficulty with this approach is that it is not possible to represent in the model all the preexisting structural complexity.

Comparing the σ_H orientations obtained from fault-slip data and the σ_H distribution calculated by the numerical model, it is found that they are generally compatible (Fig. 12). Considering the sites investigated in the Domain of Basement, it could be verified that: the σ_H orientation at MC-02 site follows approximately the general trend of σ_H by the model (N45W); MS-02/04 site shows a small deviation from the general σ_H of the model (N45W), which is consistent with that presented by the model in its vicinity; the σ_H orientation at MC-CZ-01 site shows a minor coincidence with the general σ_H direction and also its near area. The observed variations in the results obtained for σ_H orientation according to the both approaches may be attributed to a different influence of the preexisting structural framework. Thus, the behavior observed at MS-02/04 site could be associated with the presence of E-W-striking structural sets. On the other hand, the behavior at MC-02 site may be attributed to lower concentration of lineaments in its proximity. The minor coincidence between the σ_H orientation data at the MC-CZ-01 site could be related to an influence of E-W-striking lineaments sets in its proximity (as observed on lineament maps in Fig. 7) that were not represented by the structural framework used in the model.

In the Domain of Cenozoic Deposits, the correlation between the paleostress field results by fault-slip data and by numerical model is hampered by the sparse σ_H data in the model. However, it is possible to verify a deviation (ranging from 21 to 35 degrees) between the σ_H orientations obtained in the investigated outcrops (ranging from N10W to N24W at ITA-03, MC-04 and MC-05 sites) and the overall σ_H trend calculated by the model (N45W). The RM-16 site presents a minor deviation (approximately 8 degrees).

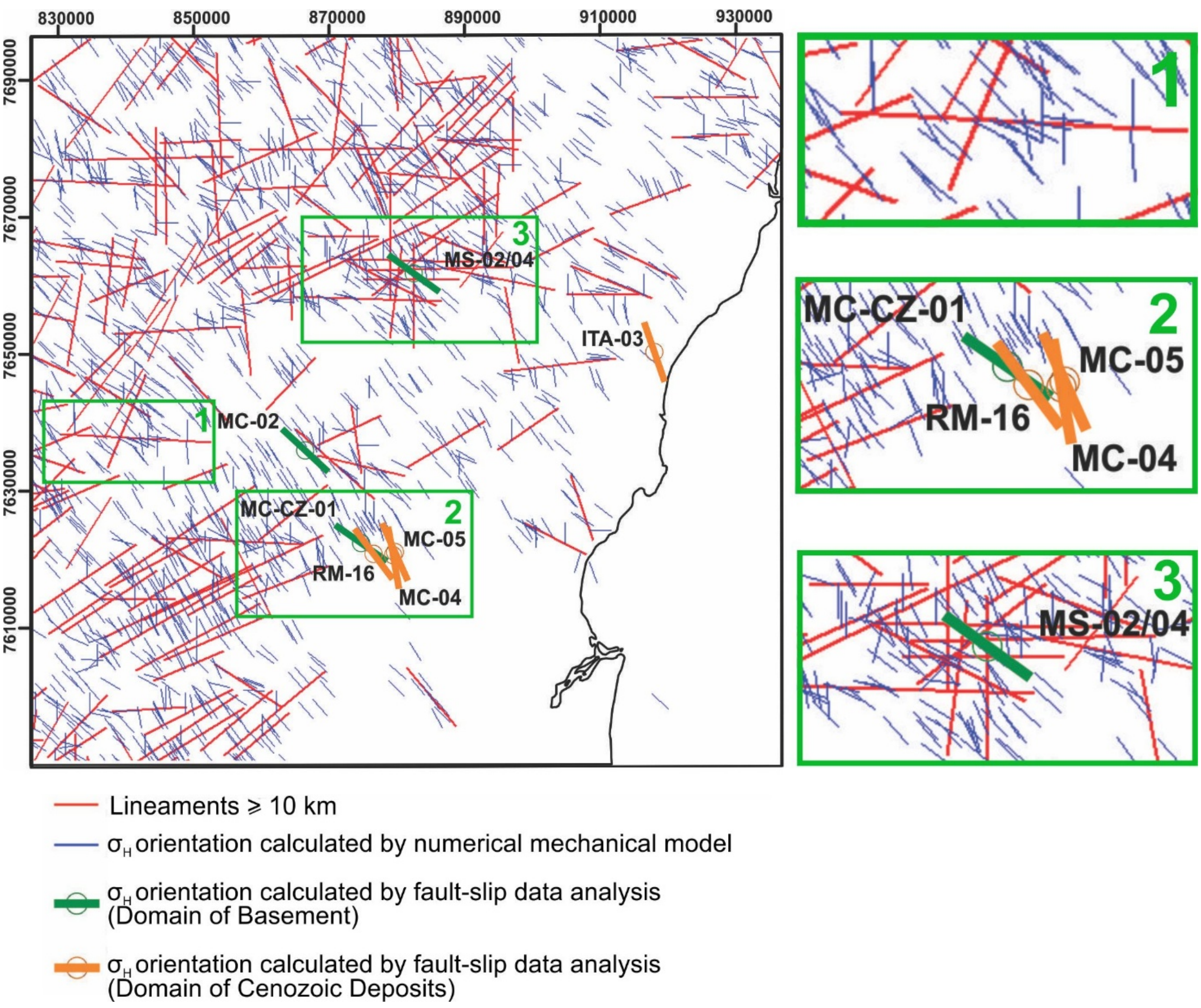


Figure 12. Distribution of the maximum horizontal stress (σ_H) orientation in the numerical mechanical model simulating an E-W dextral transcurrent movement, including lineaments greater than 10 km and the σ_H orientation identified from the paleostress field analysis by fault-slip data at the outcrops that were investigated. Zoom frames showing a locally tendency for σ_H to be parallel to E-W-striking features (zoom 1); and comparing the σ_H orientations obtained from fault-slip data and the σ_H distribution calculated by the numerical model (zoom 2 and 3).

CONCLUSION

The results of paleostress field obtained from the Domain of Cenozoic Deposits, which derived from fault-slip data in Miocene deposits, may be taken as a reference for the stress field related to the EW-DT tectonic event in the study area, presenting a NNW-SSE-striking σ_H. The counterclockwise rotation of the paleostress field in the Domain of Basement could be attributed to the reactivation of NE-SW-striking structures, which are typical of the Ribeira Belt.

The numerical mechanical model enabled a qualitative analysis of structural reactivation and of the influence of the preexisting structural framework on stress field reorientation along the area. The RFS maps corroborate the fault-slip data analysis regarding the preferential reactivation of NE-SW-striking structures under the stress field related to the EW-DT tectonic event. The analysis of σ_H orientation calculated by the model also indicated the influence of the structural framework on the reorientation of the paleostress field. Sets of approximately E-W-striking structures have been recognized as the main local control of counterclockwise rotation of the stress field, while sectors with minor lineament density reflect the regional stress field.

In the study area, it was not possible to discuss the influence of the NW-SE-striking trend because these features have a strong representation as lineaments smaller than 10 km, which were not inserted in the model because they were associated with a more recent genesis. It is recommended to reproduce the analysis in areas along the Southeastern Brazilian Margin where the NW-SE-striking structures are more evident, as well as on large regional scales, encompassing varied structural framework.

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T.C.B. developed all stages of the research, wrote the first draft of the manuscript, prepared the final manuscript and created all figures. C.L.M. guided the study in all stages, revised all the text and all the figures, improving the manuscript through discussions, corrections and suggestions. A.M. provided access to the TECTOS system, gave support to the modeling development and revised the final manuscript, improving the paper through suggestions.
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