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Papers

The Relationship between Lineament Patterns and Mass Movements in the Municipality of Vitória (Espírito Santo, Southeast Brazil)

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Keywords
Lineaments
Neotectonic events
Mass movements

Abstract

The main objective of this research is to analyze and relate lineament patterns to the occurrence of mass movements in the municipality of Vitória (Espírito Santo, Brazil). The methodology used consists of cabinet and field analyses. In a cabinet, Lineament Maps were made from the manual extraction technique, using ArcGIS 10.5 tools, on a Digital Elevation Model (DEM) with different artificial lighting (scale 1:110000) and Digital Orthophotos (scale 1:25000) and orientation rosettes generated. In the field, the geological structures were identified and analyzed from the lineaments identified in the cabinet, and their orientations were measured (Brunton compass). These data were integrated and analyzed from the Municipal Civil Defense mass movements records, referring to the period between 2006 and 2020. It was possible to verify the orientation patterns of dominant geological structures in the area (NNW-SSE and NW-SE, followed by NE-SW), including all measured fractures. At the regional scale, more mass movements occurred near NNW-SSE, NW-SE, and NE-SW orientation lineaments. At the local scale, these processes occurred more frequently in the vicinity of NNW-SSE, NNE-SSW, and NE-SW orientation lineaments. Data analysis demonstrates the important relationship between lineaments and occurrences of mass movements with regional geological structures and neotectonic events of the Espírito Santo in altered rocks of the Precambrian basement and Cenozoic deposits. The data revealed an association between the density of geological structures and the occurrence of mass movements since the increase in density is directly proportional to these processes, except for the Very High -density class, which presented little area representation.

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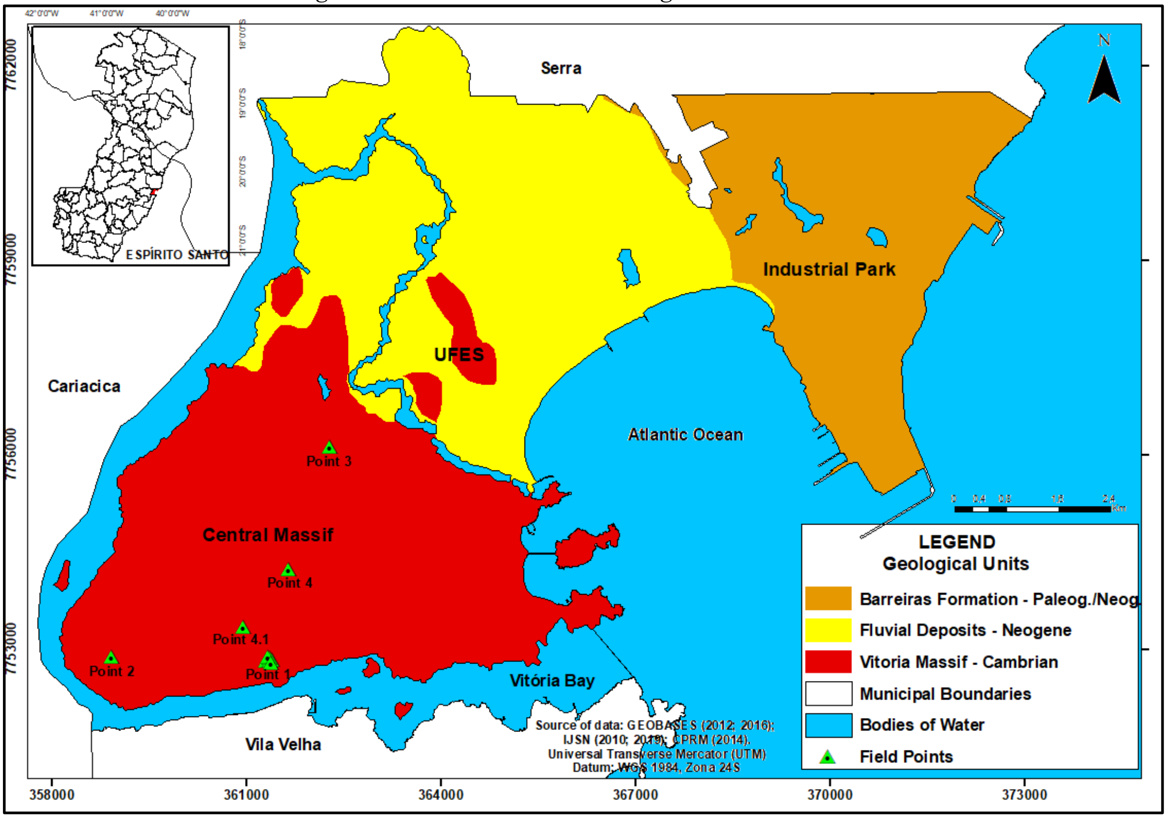
INTRODUCTION

This research was carried out in the municipality of Vitória (Figure 1), the capital of the state of Espírito Santo, with the main objective of identifying and relating the patterns of contours with the occurrence of mass movements. The area has three Geological Units: Vitória Massif, Recent clayey-sandy and sandy fluvial deposits, and Barreiras Formation (CPRM, 2014), and is also comprised of the Coastal Tableland Geomorphological Units, Coastal Hills and Massifs, and Coastal Plains (GATTO et al., 1983).

Figure 1 – Location and Geological Units of Vitória-ES



Source: The authors (2022).

The combination of physiographic factors, along with the disorderly growth of urban occupation in certain areas, without adequate land use planning and with the presence of buildings of low construction standards, has triggered accidents associated with mass movements, often causing disasters, which raises the need and importance of analyzing and understanding these processes (TOMINAGA; SANTORO; AMARAL, 2009).

In this sense, research on mass movements has intensified, especially in recent decades, since these processes are the main environmental problems in urban areas. In addition, some authors claim that combining natural triggering factors with those arising from hillside transformations by society can contribute to the evolutionary dynamics of relief (EFFGEN; COUTO; MARCHIORO, 2018).

In Brazil, a significant number of studies on mass movements have been carried out in the southeast of the country (TOMINAGA et al., 2007; FERNANDES et al., 2001; 2004; EFFGEN; MARCHIORO, 2017), with emphasis on the state of Espírito Santo, which has many areas with occurrences of these processes (EFFGEN et al., 2020; EFFGEN; COUTO; MARCHIORO, 2018; SANTOS; MARCHIORO, 2020).

An important aspect related to the occurrence of mass movements, not much addressed in studies of the subject, may be related to the influence of geological structures (faults and joints), which correspond to the lines of weakness of the crust of the earth (BRICALLI, 2011). The study of the relationship between lineament patterns and the occurrence of mass movements is practically scarce, thus being considered an unprecedented study for the municipality of Vitória and the state of Espírito Santo. However, the relationship of lineaments with the occurrence of mass movements has been investigated in Brazil and the world concerning research in the Asian continent

(ANBALAGAN; SIGH, 1996; NAGARAJAN, et al., 2000; SARKAR; KANUNGO, 2017) and European (ATKINSON; MASSARI, 1998; AMBROSI; CROSTA, 2006), also presenting studies in Brazil (GONTIJO, 1999; TOMINAGA, 2007).

Thus, based on this environmental and social problem that plagues the municipality of Vitória (ES), studies that can support the understanding and monitoring of mass movements, as well as decision-making for future and even emergency planning, are carried out needed.

MATERIAL AND METHODS

The methodological procedures for the elaboration of this research were composed of office analyses (scales 1:110000 and 1:25000) and field analysis (scale 1:1).

Office analyses

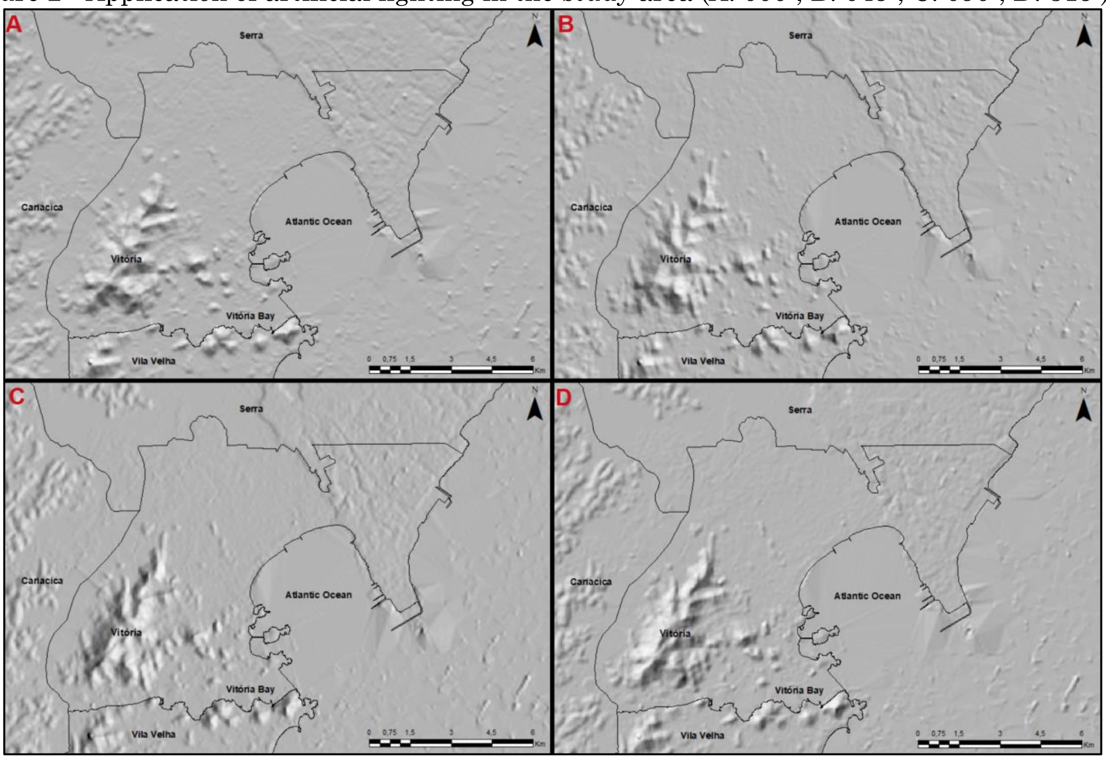
The cartographic bases used were processed in *ArcGIS™ 10.5 software* (ESRI, 2016). All maps were created or converted to Universal Transverse Mercator (UTM) projection, Horizontal Geodetic Datum WGS 1984, Time zone 24S.

Lineament analyses

Extraction of lineaments in Digital Elevation Model (DEM) - Scale 1:110,000

The lineament map was prepared using the manual extraction technique (BRICALLI, 2011), on a Digital Elevation Model (DEM) acquired from the North American Geological Survey (USGS), with a spatial resolution of 30m (VALERIANO, 2002), where 4 (four) artificial lightings were applied (000º, 045º, 090º, and 315º) – Bricalli (2011), as shown in Figure 2. The lineaments were identified following the methodology of Liu (1984) and traced in each of the illuminations on a scale of 1:110,000.

Figure 2 - Application of artificial lighting in the study area (A: 000º; B: 045º; C: 090º; D: 315º)



Source: The authors (2022).

Extraction of lineaments in digital Orthophotos - Scale 1:25,000

Orthophoto mosaics acquired from the Instituto Jones dos Santos Neves (IJSN - Jones dos Santos Neves Institute) (2019). The contours were traced over the images, again following the methodology of Bricalli (2011) and the definitions of Liu (1984), on a scale of 1:25,000.

Elaboration of guidance rosettes

To calculate the orientation of the lineaments, the Azimuth Finder app (2013).

The azimuth orientation values and lineament length were exported and plotted in tables present in the Oriana program (version 3.21, *license demo*) from Kovach Computing Services (2021), being represented in diagrams of rosettes.

Lineament Density and Structural Trends

The lineament density was produced from the lineaments identified with the manual extraction methodology over the study area on scales of 1:110,000 and 1:25,000, previously detailed, which were vectorized using *ArcGIS™ 10.5 software*.

The lineaments mapped on a Digital Elevation Model (DEM) scale of 1:110000, and those restricted on Digital Orthophotos, on a scale of 1:25000, were organized in a single *shapefile* with the structural data (CPRM, 2014) through the *Merge* tool.

The density calculation was performed using the *Line Density* pela tool, present in the *Arc Toolbox*, with cell size 45 and area unit in km/km². This tool calculates the density of linear features in the vicinity of each output raster cell and calculates in units of length per unit of area. The results were grouped into density classes: Very Low, Low, Medium, High, and Very High. Structural *trends* were plotted over the High and Very High-density classes.

Map of Geological Structures

The Map of Geological Structures was prepared from the lineaments modeled on the Digital Elevation Model (DEM), at a scale of 1:110000, from those demarcated on Digital Orthophotos, at a scale of 1:25000, and of the Geological Structures (CPRM, 2014), which were grouped into a single *shapefile* (organized in vector) using the *merge* tool, available in *ArcGIS™ 10.5*.

Some structures demarcated on Digital Orthophotos (scale 1:25000) were excluded from this product, as they were also identified on the map of lineaments demarcated on the Digital Elevation Model (scale 1:110000).

Density Map of Geological Structures and Structural trends

The Density Map of Geological Structures was prepared from the Map of Geological Structures. Density was calculated using the *ArcGIS™ 10.5* software, *Line Density* tool, present in *Arc Toolbox*, with cell size 45 and area unit in km/km².

The results were grouped into density classes: Very Low, Low, Medium, High, and Very High. Structural *trends* were plotted over the High and Very High-density classes.

Spatialization of occurrences of mass movements

Mass movement data were acquired in two different periods:

The mass movements recorded by the Defesa Civil Municipal de Vitória (Municipal Civil Defense of Vitória), which occurred from 2006 to 2011, were acquired on the interactive map of PROJETO MAPENCO (2021).

Those that occurred between 2012 and 2020 were acquired from the Municipal Civil Defense through access to inspection reports made available by the institution.

Structural analysis and occurrence of Mass Movements

The relationship of structural data in the area with mass movements was analyzed. These data were also analyzed based on the underlying lithological characteristics (CPRM, 2014) and structural data, neotectonics overcoats, defined for the area (BRICALLI, 2011).

Field Analysis

In the field analyses, 4 (four) study points were selected in the area where the presence of mass movements recorded by the Municipal Civil Defense in the vicinity of traced lineaments was identified in the office.

RESULTS

Lineament analysis

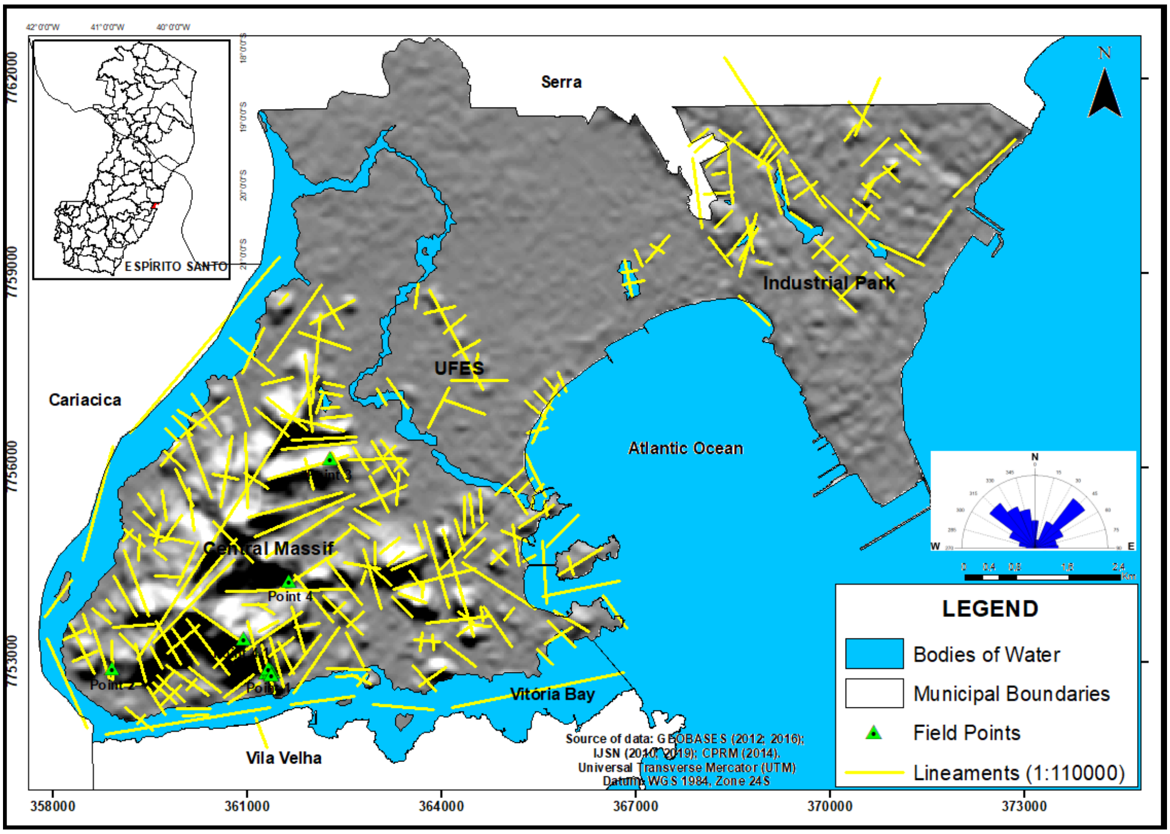
Lineaments in Digital Elevation Model (DEM) - Scale 1:110,000

In the lineament map prepared using the manual extraction technique on a Digital Elevation Model (DEM) for the municipality of Vitória (Figure 3), at a scale of 1:110000, 273 lineaments were identified in an area of 93.38 km².

It was possible to observe a greater concentration of NW-SE orientation lineaments, followed by NE-SW, NNW-SSE, ENE-WSW, and WNW-ESE directions, respectively, having E-W lineaments in smaller quantities.

The Vitória Massif Geological Unit has the largest mapped lineaments, followed by the Barreiras Formation. The lineaments are less expressive in the geological unit of recent clay-sandy and sandy river deposits.

Figure 3 - Map of Lineaments modeled on a Digital Elevation Model (DEM), at a scale of 1:110000



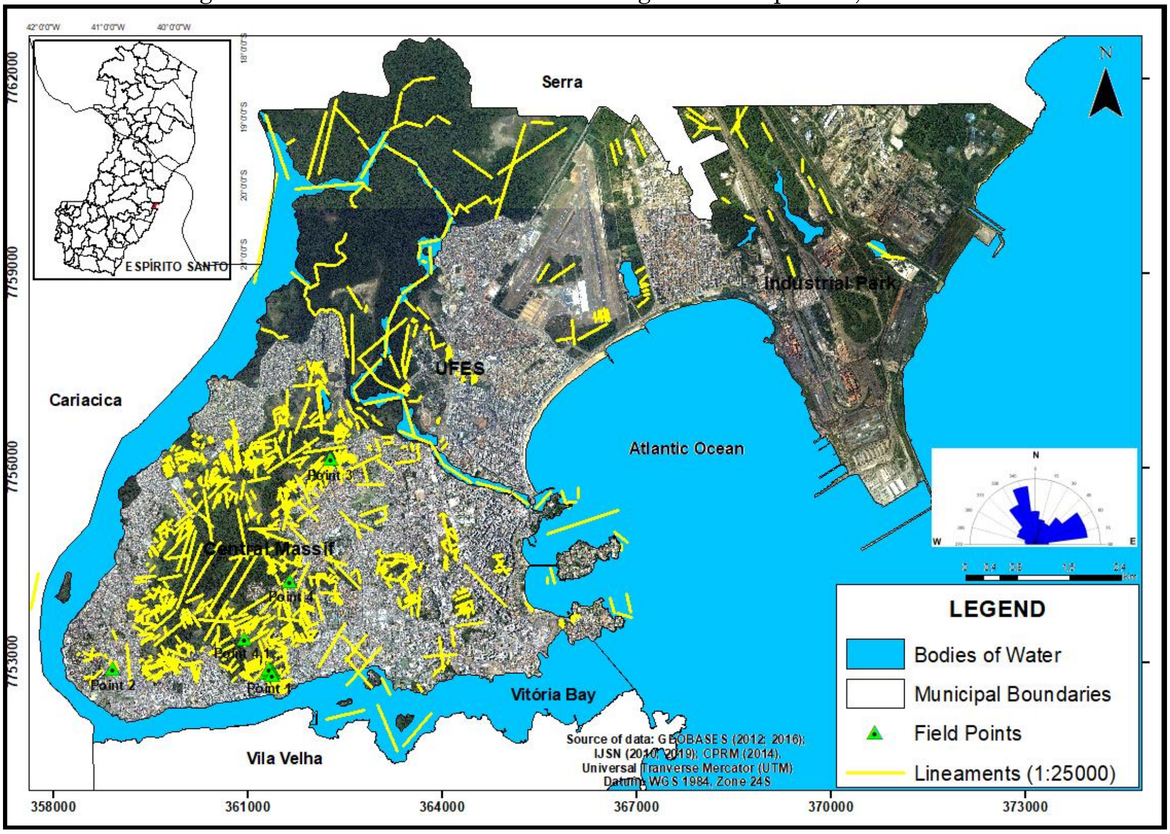
Source: The authors (2022).

Lineaments in Digital Orthophotos - Scale 1:25,000

The lineament map prepared using the manual extraction technique on Digital Orthophotos for the municipality of Vitória (Figure 4), on a scale of 1:25000, allowed for greater interpretation detail and thus identified a greater number of lineaments, totaling 1211 of these features, in an area of 93.38 km².

This scale shows a higher recurrence of NNW-SSE and ENE-WSW orientation lineaments, followed by E-W lineaments. As identified in the 1:110000 scale mapping, the highest proportions of mapped lineaments are found in the Vitória Massif Geological Unit, followed by the Barreiras Formation.

Figure 4 – Lineaments modeled on Digital Orthophotos, scale 1:25000



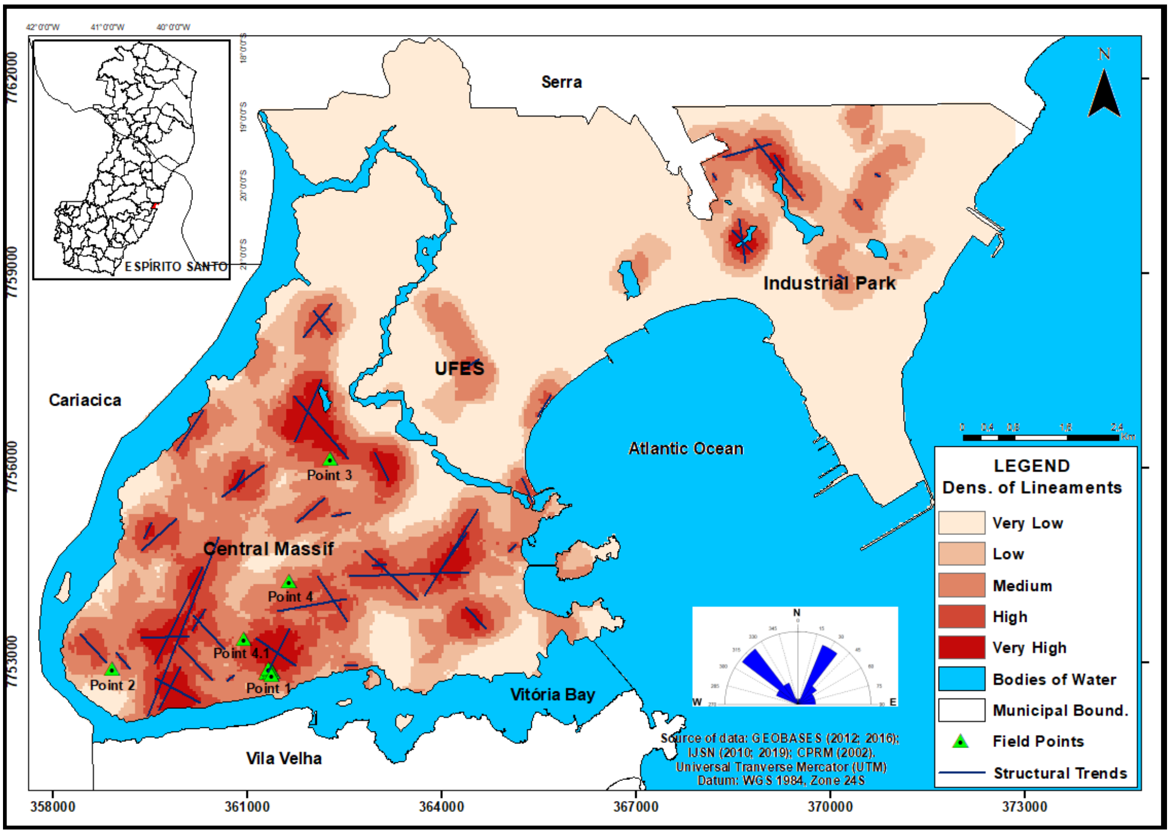
Source: The authors (2022).

Density of Lineaments and Structural trends

The density of the lineaments modeled on the Digital Elevation Model (DEM), at a scale of 1:110000 (Figure 5), demonstrates a greater concentration of these structures in the Vitória Massif Geological Unit, also showing areas of High and Very High density in localities of Barreiras Formation, even if to a lesser extent.

On this scale, the structural *trends* point to a greater amount of NW-SE and NNE-SSW orientations, also showing NE-SW, ENE-WSW, NNW-SSE, and WNW-SSE *trends* in a smaller proportion.

Figure 5 – Density of lineaments modeled on a Digital Elevation Model (DEM) at a scale of 1:110000 and structural *trends*

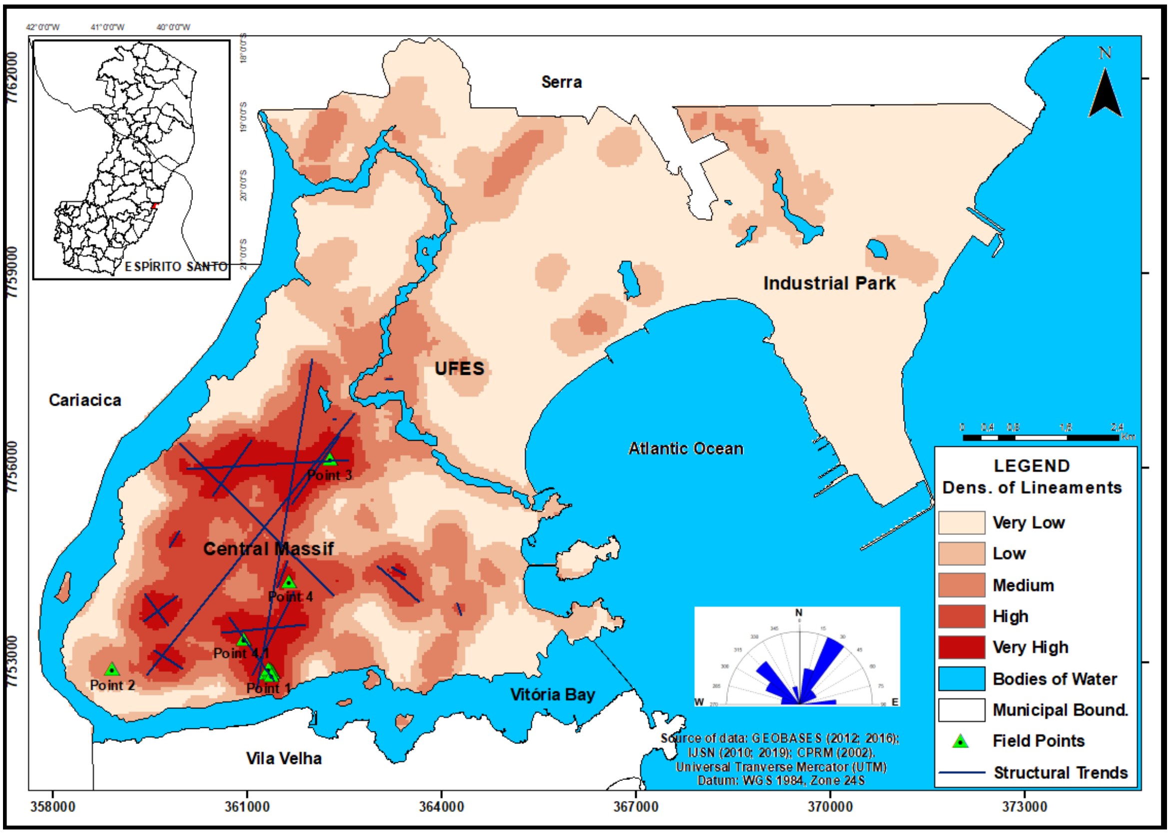


Source: The authors (2022).

The lineaments mapped on Digital Orthophotos, at a scale of 1:25000 (Figure 6), are concentrated in the Vitória Massif Geological Unit, appearing in a more dispersed way and smaller numbers in the Barreiras Formation and the recent sandy-clay and sandy river deposits.

The structural trends identified on this scale demonstrate structural patterns of predominantly NW-SE orientation, followed by NE-SW, NNE-SSW, NNW-SSE, WNW-ESE, ENE-WSW, and E-W orientations, in that order.

Figure 6 - Density of lineaments modeled on Digital Orthophotos at scale 1:25000 and structural *trends*



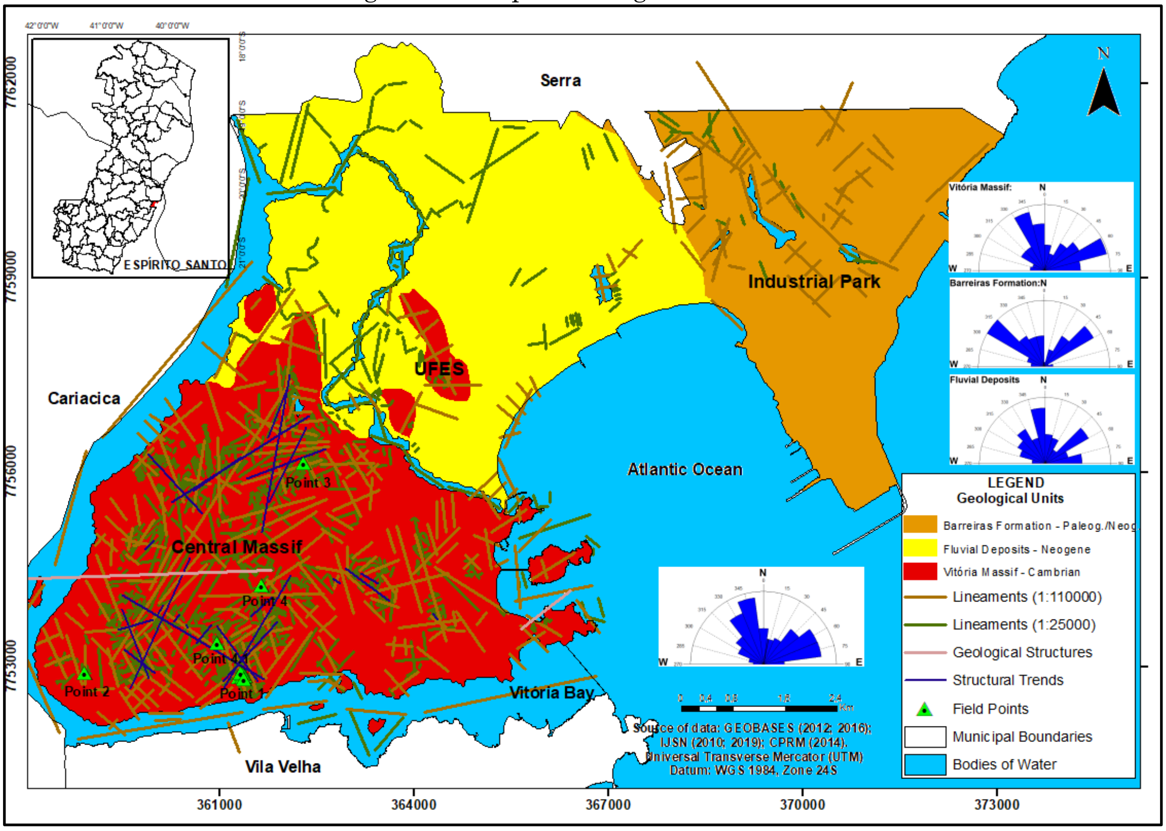
Source: The authors (2022).

Map of Geological Structures

The Map of Geological Structures, generated from the combination of lineaments modeled on a Digital Elevation Model, lineaments demarcated on Digital Orthophotos, and regional Geological Structures (CPRM, 2014), points to the predominance of NNW-SSE, NE orientation structures -SW and NW-SE, in that order (Figure 7).

The largest proportion of mapped structures is found in the Vitória Massif Geological Unit, followed by the Barreiras Formation. The structures are in smaller quantities in the Geological Unit of recent clay-sandy and sandy river deposits.

Figure 7 – Map of Geological Structures



Source: The authors (2022).

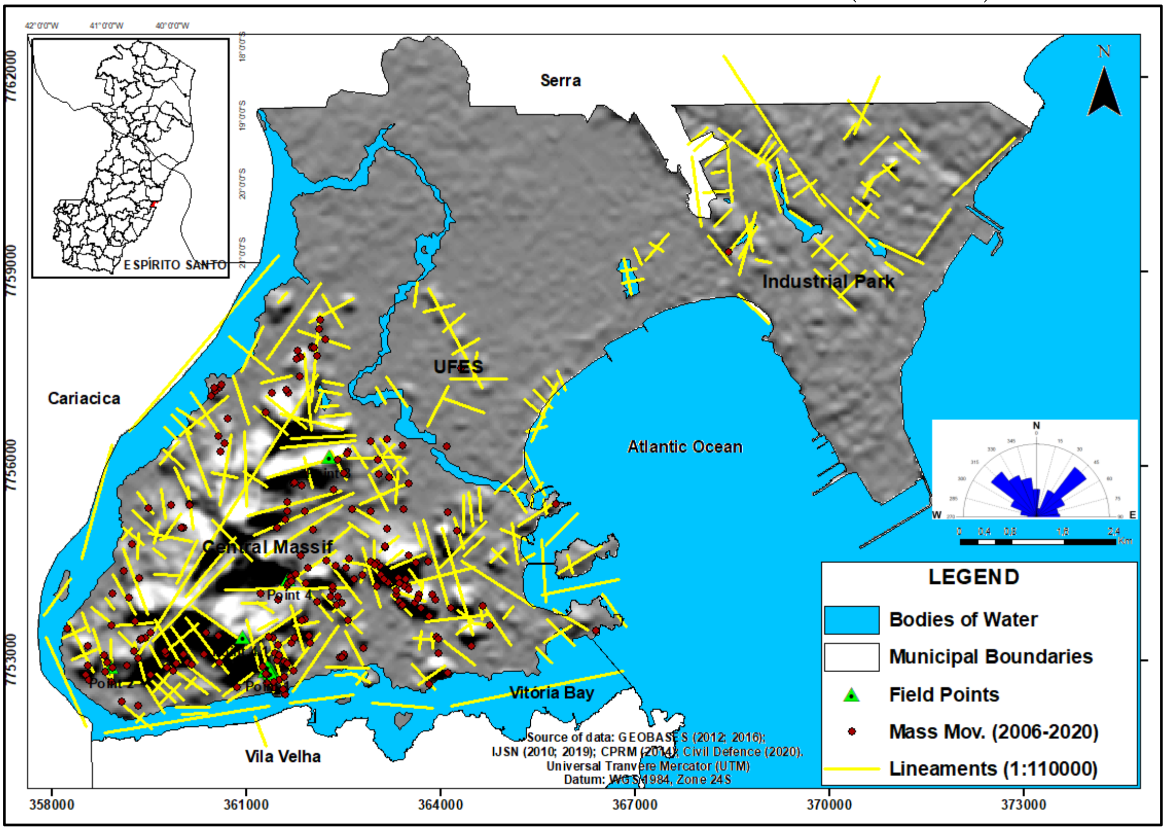
The rosette charts show the predominance of NE-SW and NNW-SSE structures in the Vitória Massif Geological Unit. In the Barreiras Formation, NW-SE and NE-SW orientations were identified more often. The NNW-SSE, NE-SW, and NW-SE directions are predominant in the geological unit of recent clay-sandy and sandy river deposits.

Lineaments, Structural Trends (1:110000), and Mass Movements

The lineaments modeled on the DEM, both in terms of orientation and the number of lineaments, have a strong spatial and orientation relationship with the mass movements that occurred in the area.

Of the 202 (two hundred and two) records of mass movements, 63 (sixty-three) occurred in the vicinity of NNW-SSE orientation lineaments, the most recurrent orientation, followed by NW-SE (35 occurrences of mass movements). The NE-SW orientations correspond to 27 records of mass movements, and the ENE-WSW, WNW-ESSE, and E-W orientations correspond to 20, 15, and 14 occurrences. Only 13 (thirteen) recorded mass movements did not occur near lineaments restricted in the scale above (Figure 8).

Figure 8 – Lineaments modeled on a Digital Elevation Model (DEM), at a scale of 1:110000, structural *trends* and occurrences of Mass Movements (2006-2020)



Source: The authors (2022).

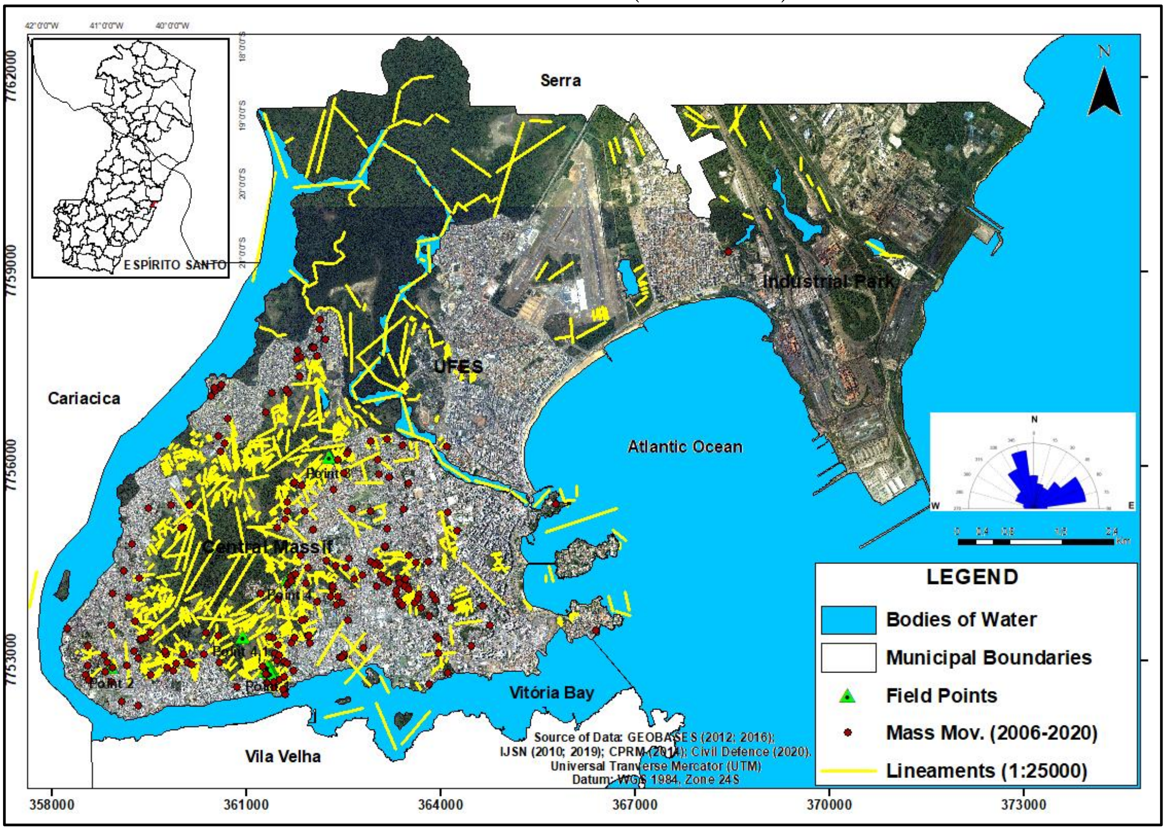
Mass movements occur predominantly in areas with high lineament density (Figure 5). Furthermore, the rosette plot of the structural *trends* shows a dominance of the NW-SE orientation, followed by the NNE-SSW and NE-SW orientations.

Lineaments, Structural Trends (1:25000), and Mass Movements

In terms of orientation and density, the lineaments modeled on the Digital Orthophotos have a strong spatial and orientation relationship with the mass movements in the area.

Of the 202 (two hundred and two) spatialized processes, 59 (fifty-nine) occurred close to NNW-SSE orientation lineaments, the pattern that presented the highest number of records, followed by NNE-SSW (39 records), NE-SW (23 occurrences), ENE-WSW (22 landslides), and NW-SE (19 occurrences). To a lesser extent, landslides close to the WNW-ESSE and E-W orientation lineaments were recorded (Figure 9).

Figure 9 – Lineaments modeled on Digital Orthophotos (1:25000), structural trends, and occurrences of Mass Movements (2006 - 2020)



Source: The authors (2022).

Of the processes studied, 36 (thirty-six) did not occur in locations close to the lineaments demarcated in the scale under analysis. Only 6 (six) mass movements did not occur near lineaments at scales 1:110000 or 1:25000.

Mass movements are predominant in high and very high lineament densities (Figure 6). The rosette plot of structural *trends* shows the prominence of the NW-SE orientation, followed by the NE-SW orientation.

Field analyzes

Four points were visited, located in the Centro (Point 1), Caratoíra (Point 2), Joana D'arc (Point 3), and Fradinhos (Point 4) neighborhoods. The field points are present in the Vitória Massif Geological Unit (CPRM, 2014), which corresponds to the region with the highest density of lineaments, geological structures, and incidence of mass movements between the years 2006 to 2020, and in the Geomorphological Unit Colinas e Massifs Coastal (GATTO et al., 1983). The fieldwork (Figures 8, 9, and 10) was important for identifying and validating the mass movements recorded by the Civil Defense, in addition to having made it possible to identify their occurrence in important and visible lineaments in the field.

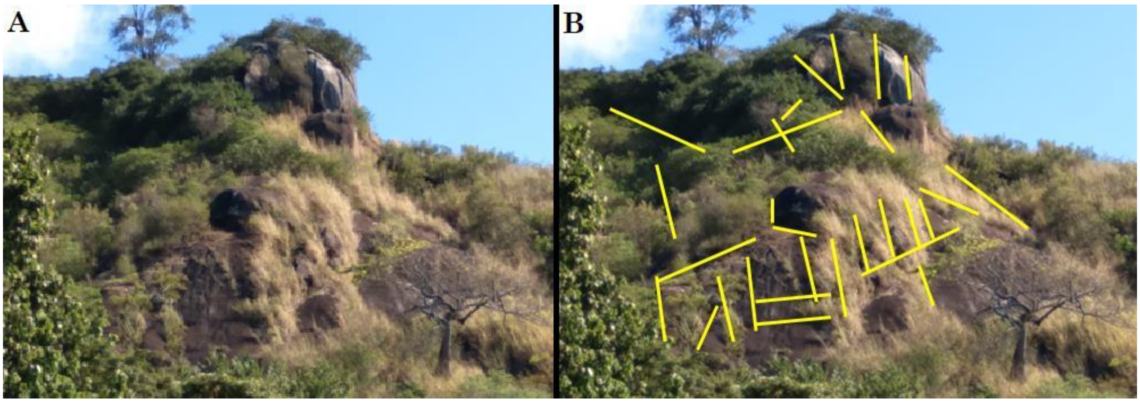
At Point 2 (Figure 10), in the Caratoíra neighborhood, it is possible to identify a rocky hillside with large fractures, which form a lineament with an ENE-WSW orientation and several smaller structures with an NNW-SSE orientation.

Figure 10 – A: Mass movement of large dimensions, which occurred in the Caratoíra neighborhood (Point 2); B: ENE-WSW (yellow line) and NNW-SSE (red line) fractures identified in the field

Source: Vitória (2020). Adapted and elaborated by the authors (2022).

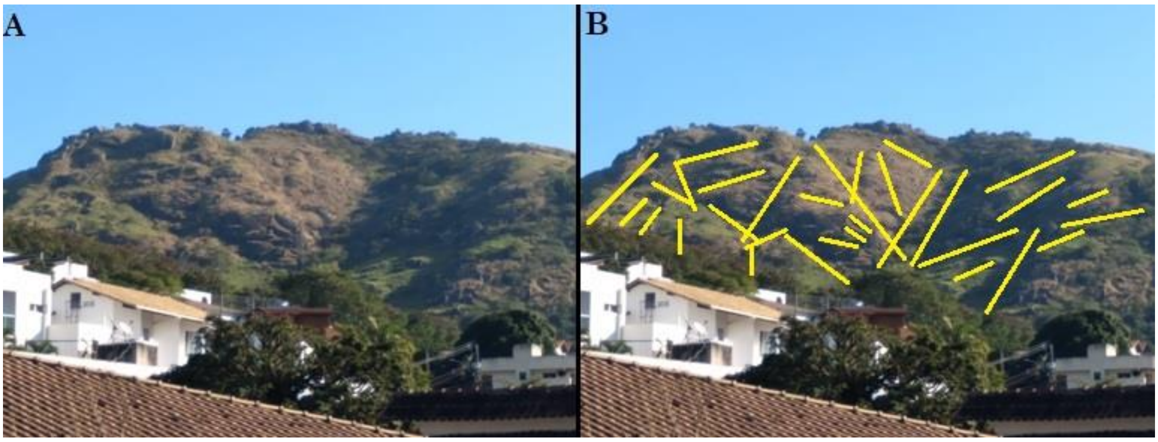
At Points 3 (Figure 11) and 4.1 (Figure 12), located respectively in the Joana D'arc and Fradinhos neighborhoods, hillsides with significant fractures were found in places with rolled blocks and landslide scars located during field campaigns.

Figure 11 – A: Hillside located in the Joana D'arc neighborhood (Point 3); B: Yellow lines represent fractures identified in the field



Source: The authors (2022).

Figure 12 – A: Hillside located in the Fradinhos neighborhood (Point 4.1); B: Yellow lines represent fractures identified in the field



Source: The authors (2022).

The fractures identified in Point 3 (Figure 11) have predominantly NW-SE and NNW-SSE orientations. The hillside at point 4.1 (Figure 12) has more structures with NE-SW and NW-SE orientations.

DISCUSSION

Structural analysis and occurrence of mass movements

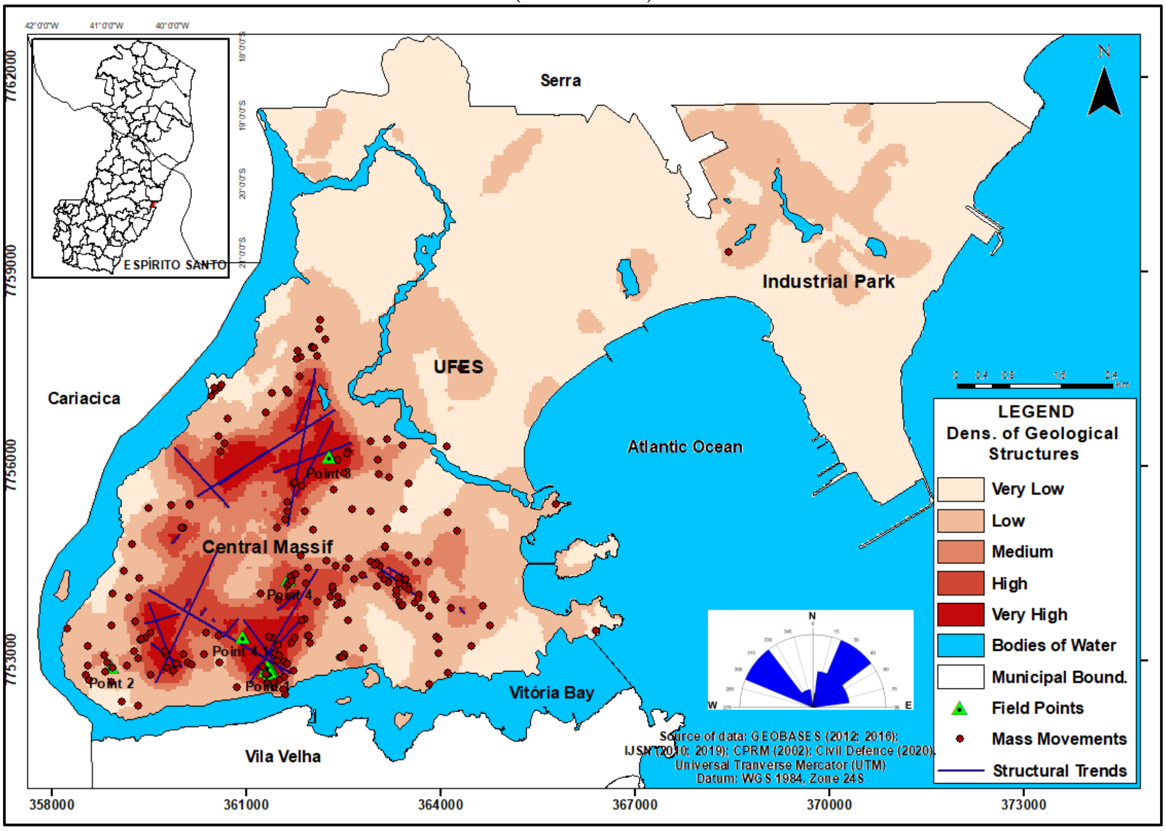
Density of Geological Structures, Structural Trends, and Mass Movements

Among the 202 (two hundred and two) registered mass movements, 62 (sixty-two), which correspond to 30.7% of the total, occurred in areas of high density, representing only 5.3% of the territorial extension of Vitória. In very high-density locations, representing 3.1% of the area, 18 (eighteen) mass movements were recorded, 9% of the total number of phenomena, as shown in Figure 13 and Table 1.

In medium-density polygons (6.5%), 49 (forty-nine) mass movements were recorded, a proportion of 24.3% of these processes for the analyzed period.

In the areas of very low density, representing more than half of the municipality (50.9%), 26 (twenty-six) mass movements were recorded, 12.8% of the total occurrences. In places of low density, which correspond to 34.2% of the territory, there were 47 (forty-seven) mass mobilizations, 23.2% of the total.

Figure 13 – Density of Geological Structures, structural *trends*, and occurrences of Mass Movements (2006-2020)



Source: The authors (2022).

Table 1 – Relationship between density of geological structures and mass movements.

Density of geological structures	Area of the municipality of Vitória (%)	Mass movements (%)
1 – Very low	50.9%	26 (12.8%)
2 – Low	34.2%	47 (23.2%)
3 – Medium	6.5%	49 (24.3%)
4 – High	5.3%	62 (30.7%)
5 – Very high	3.1%	18 (9%)

Source: The authors (2022).

The above data analysis demonstrates that the greater occurrence of mass movements is related to the Medium (24.3%) and High (30.7%) densities – table 1 and figure 13. It is also observed that as the density of lineaments increases, mass movements increase (Table 1 and Figure 13), except for the Very High-density, which presents a smaller number of occurrences of mass movements. The Very High-density class can explain this data is present in areas of small territorial extension, in small nuclei distributed in the area. In addition, these areas represent places of high declivity and high altitude, thus representing places with little inhabitation and little or no action by the Civil Defense, which is the body responsible for collecting data on the occurrence of mass movements in the area.

The rosette chart of the structural *trends* points to dominance in the NNE-SSW orientation, followed by the NW-SE, NE-SW, NNW-SSE, and ENE-WSW orientations.

Analysis of the relationship among geological structures, structural trends, and mass movements

Based on the results obtained, the predominance of the orientations of the NNW-SSE and NW-SE lineaments and the predominant occurrence of mass movements in these orientations are observed, both on the scale of 1:110000 and the scale of 1:25000. These orientations are the most recurrent in Geological Units Fluvial Deposits sandy clayey and recent clayey and Barreiras Formation, in addition to being highly representative in structures identified in the Vitória Massif.

The NNW-SSE and NW-SE orientation lineaments also predominate in the lineament map made for the state of Espírito Santo (BRICALLI, 2011), and coincide with the orientation of the Faixa Colatina, thus demonstrating the important relationship between the orientation of the area's lineaments and regional lineaments and the most important geotectonic structure in the state of Espírito Santo (Faixa Colatina). Additionally, the structural *trends* of both analysis scales also reproduce the same relationship, orientation, and predominance of mass movements (NW-SE orientation). In this way, it is observed that the mass movements that occurred in the area in the analyzed period have a strong and important relationship with the regional structures.

In addition to the important relationship between the occurrence of mass movements and the structure, there is an association between these predominant orientations mentioned and the occurrence of mass movements with the orientations of the neotectonic faults in the state of Espírito Santo, corresponding to the NW-SE orientations of the geological faults characteristics of the Dextral E-W Transcurrent regime (BRICALLI, 2011).

The orientation of the NE-SW lineaments, which correspond to the second most predominant orientation in the area and the most identified in the Vitória Massif Geological Unit, is also the second orientation in which more occurrences of mass movements were identified in the analyzed period. This orientation corresponds to the predominant direction of the Araçuai orogen (TUPINAMBÁ et al., 2007).

It is observed, as well as in the NW-SE orientation, an important association of the NE-SW orientations with the occurrence of mass movements and with the orientations of the neotectonic faults of the state of Espírito Santo, corresponding to the NE-SW orientations of the geological faults of the Distension NW-SE regimes and Sinistral Transcurrent E-W (BRICALLI, 2011).

In this sense, on a scale of 1:110000, considering the neotectonic events present in the state of Espírito Santo (BRICALLI, 2011), most of the recorded mass movements (55.4% of the total) occurred in the vicinity of lineaments whose orientation is related to the neotectonic event of E-W Dextral Transcurrent, from Pleistocene to Holocene age, as mentioned above. A significant fraction of the processes recorded in the period (23.26%) also occurred in the vicinity of lineaments whose orientations are associated with the neotectonic regime of Distension NW-SE, of Holocene age, or the regime of Sinistral Transcurrent E-W, of Neogenic age.

On a scale of 1:25000, considering the neotectonic events associated with the state of Espírito Santo (BRICALLI, 2011), a significant amount of mass movements (39.6%) occurred in the vicinity of lineaments influenced by the Dextral E-W Transcurrent. Among the spatialized processes, the highest proportion (41.5%) of mass movements culminated in the vicinity of lineaments whose orientation is associated with NW-SE Distension or E-W Sinistral Transcurrent.

FINAL CONSIDERATIONS

The analysis of the lineaments and other elaborate cartographic products, as well as the field and office identification of mass movement processes, demonstrate that there is a strong relationship between litho-structural control (local and regional) and regional neotectonic with the occurrence of mass movement processes, even though it is not possible to state whether this relationship occurs directly or indirectly.

The predominant orientations of lineaments, lineament trends, and geological structures (joints and faults) were identified, in addition to lineament density at different scales, significantly contributing to studies on the subject in the municipality of Vitória and the state of Espírito Santo.

Most research on mass movements either does not consider or attaches little relevance to the structural influences implicit in these processes. Thus, this research brought a different approach to the subject and presented results that allowed for new discussions.

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AUTHORS CONTRIBUTION

Thiago Borini Pimentel conceived the study, collected and analyzed the data, wrote the text and prepared the cartographic products. Luiza Leonardi Bricalli wrote the text, helped with the interpretation of the data and guided the entire production of the research.