Article

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APPLICATION OF MORPHOMETRIC INDICES FOR THE INVESTIGATION OF THE STRUCTURAL AND TECTONIC INFLUENCES ON THE LANDFORM OF THE ATLANTIC-TYPE CONTINENTAL MARGIN, PARAÍBA - BRAZIL

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Abstract

Understanding the structural and tectonic influences on the formation of the landscape and drainage network is essential for geomorphological studies of continental margins of the Atlantic type, in which seismic activities have been discounted in the past, as they did not cause immediate changes to the landform. However, with the expansion of seismographic networks and the better understanding of the development of geomorphological processes, it is now possible to understand that the structures of some landforms are consistent with the patterns imposed by tectonic processes. In this context, the principal objective of the present study is to analyze the structural and tectonic influences on the geomorphological configuration of the northeastern extreme of the state of Paraíba, in northeastern Brazil. In this research, morphological analyses were conducted and morphometric indices were applied to the interpretation of the current geomorphology configuration. The results indicate the existence of major morphological and morphometric anomalies of the landform and the drainage network of the study area. The morphological and morphometric characteristics presented here are considered to be sufficient to affirm that the configuration of the landform and the drainage network of the study area have been influenced by lithological structures and tectonic activity resulting from the ongoing tectonic separation of the continents of Africa and South America.

Keywords: Morphometry; Drainage Network; Structural Dome; Mamanguape Graben.

Resumo / Resumen

APLICAÇÃO DE ÍNDICES MORFOMÉTRICOS PARA ANÁLISE DE INFLUÊNCIA ESTRUTURAL E TECTÔNICA NO RELEVO DE MARGEM CONTINENTAL TIPO ATLÂNTICA, PARAÍBA - BRASIL

Compreender as influências estruturais e tectônicas na elaboração do relevo e da rede de drenagem é necessário nos estudos geomorfológicos da margem continental do tipo Atlântico, onde as atividades sísmicas eram praticamente negadas no passado, por não causarem mudanças imediatas no relevo. Porém, com a expansão das redes sismográficas bem como um melhor entendimento do desenvolvimento dos processos geomorfológicos, é possível compreender hoje que algumas formas de relevo estão de acordo com estruturas e padrões impostos pela tectônica. Nesse sentido, o objetivo principal deste trabalho é analisar as influências estruturais e tectônicas na configuração geomorfológica do Nordeste do Estado da Paraíba - Brasil. Nesta pesquisa, foram realizadas análises morfológicas e aplicados índices morfométricos para interpretar a configuração geomorfológica atual. Os resultados obtidos atestam fortes anomalias morfológicas e morfométricas do relevo e da rede de drenagem da área de estudo. Por fim, entende-se que as características morfológicas e morfométricas apresentadas são suficientes para afirmar que a configuração do relevo e da rede de drenagem da área de estudo são influenciadas pelas estruturas litológicas e pela atividade tectônica decorrente do contínuo afastamento da América do Sul em relação ao continente africano.

Palavras-chave: Morfometria; Relevo; Rede de Drenagem; Domo estrutural; Gráben do Mamanguape.

APLICACIÓN DE ÍNDICES MORFOMÉTRICOS PARA LA INVESTIGACIÓN DE LA INFLUENCIA ESTRUCTURAL Y TECTÓNICA EN EL RELIEVE DEL MARGEN CONTINENTAL TIPO ATLÁNTICO, PARAÍBA - BRASIL

Comprender las influencias estructurales y tectónicas en la elaboración del relieve y la red de drenaje es necesario en los estudios geomorfológicos de margen continental de tipo Atlántico, donde las actividades sísmicas fueron prácticamente negadas en el pasado, ya que no provocaron cambios inmediatos en el relieve. Sin embargo, con la expansión de las redes sismográficas, así como una mejor comprensión del desarrollo de los procesos geomorfológicos, es posible entender hoy, que algunos accidentes geográficos están de acuerdo con las estructuras y patrones impuestos por la tectónica. En este sentido, el objetivo principal de este trabajo es analizar las influencias estructurales y tectónicas sobre la configuración geomorfológica del noreste del Estado de Paraíba - Brasil. En esta investigación se realizaron análisis morfológicos y se aplicaron índices morfométricos para interpretar la configuración geomorfológica actual. Los resultados obtenidos atestiguan fuertes anomalías morfológicas y morfométricas del relieve y la red de drenaje del área de estudio. Finalmente, se entiende que las características morfológicas y morfométricas presentadas son suficientes para afirmar que la configuración del relieve y la red de drenaje del área de estudio están influenciadas por estructuras litológicas y por la actividad tectónica resultante del distanciamiento continuo de América del Sur en relación al continente africano.

Palabras-clave: Morfometría; Red de drenaje; Domo estructural; Graben del Mamanguape.

INTRODUCTION

Historically, the Brazilian Atlantic continental margin has been considered to be an area of reduced tectonic activity. In the past, this led to the understanding that tectonics would not have had a significant influence on the configuration of the landform and its drainage network. However, the results of a number of studies in the field of geology and geomorphology in Brazil in general and in the state of Paraíba in particular, including those of Hasui (1990), Mabesoone and Alheiros (1993), Lima (2000), Barbosa and Lima Filho (2006), Furrier et al. (2006), Brito Neves et al. (2008), Andrades Filho (2010), Bezerra (2011), Andrades Filho and Rossetti (2012), Silva and Furrier (2013), Bezerra et al. (2014) and Silva and Furrier (2019), have changed this understanding over the years.

Given the advances in geomorphological research and the availability of the seismic data collected by the monitoring networks installed throughout Brazil, Bezerra et al. (2014) concluded that some regions of Northeast Brazil can be considered to be the seismically most active in the eastern continental region of South America. One of these regions is the northern border of the Paraíba Sedimentary Basin, which makes up the eastern sector of the present study area.

The principal objective of the present study is to analyze how lithological structures and tectonic activity have influenced the configuration of the landform and the drainage network in the northeastern extreme of the Brazilian state of Paraíba. These influences may trigger a series of processes, such as subtle vertical and horizontal displacements, which can be interpreted and measured through the application of standard morphometric indices.

The studies of Furrier et al. (2006), Mantovani et al. (2008), Andrades Filho (2010), Alves and Rossetti (2015; 2016), Barbosa and Furrier (2012), Furrier et al. (2014), Barbosa and Furrier (2017), Silva and Furrier (2019), and Furrier and Silva (2020) provided further evidence that corroborates the occurrence of structural and tectonic controls on the geomorphological configuration of the study area. Given this, the present study, in addition to applying morphometric indices to the analysis of a number of hydrographic basins in the study area, confirmed the altimetric variation and slope of its landforms. These analyses were supported by extensive and meticulous fieldwork, which identified the location and recorded the typical geological structures that corroborate the influence of structural and tectonic processes on the configuration of the local landforms.

To analyze these attributes of the study area, standard morphometric indices of structural and tectonic parameters were used, following Etchebehere et al. (2004), Etchebehere et al. (2006), Font et al. (2010), Hartwing and Riccomini (2010), Furrier and Vargas-Cuervo (2018), and Figueiredo et al. (2019). This approach, combined with the morphological and morphometric analysis of the relief of the study area, and a detailed field investigation, provides valuable insights into the configuration of the landforms and drainage networks of environments influenced by structural and tectonic processes.

STRUCTURAL AND TECTONIC CONTEXT

Within the scope of regional geology, Hessel and Barbosa (2005) stated that the Paraíba Sedimentary Basin is one of the least well-known Brazilian marginal sedimentary basins due to its lack of oil or gas reserves. Mabesoone and Alheiros (1993) had already attributed the scarcity of research in this region to the lack of fossil fuels, which led to a lack of interest in investing in the area. These authors also pointed out that this region represents the last terrestrial link between the South American and African continents.

For Mabesoone and Alheiros (1988), the separation of South America from Africa was due to South America's clockwise rotation in relation to Africa, which has been the principal cause of the formation of sedimentary basins on the south Atlantic margin and their associated structures. In this context, the origin and evolution of the Paraíba Sedimentary Basin (which is currently covered primarily by poorly-consolidated sediments of the Miocene Barreiras Formation in its emerged portion) are linked entirely to the separation of South America from Africa, and the consequent widening of the Atlantic Ocean (ASMUS, 1975).

The evolutionary processes of the Paraíba Sedimentary Basin, combined with the reactivation of pre-existing Precambrian faults during the continuous distancing of South America from Africa, originated typical structures that had a direct influence on the configuration of this area's landform (FURRIER, et al., 2006; BRITO NEVES et al., 2008; ANDRADES FILHO; ROSSETTI, 2012; MAIA; BEZERRA, 2014; LIMA, et al., 2017). These events gave rise to a succession of grabens and horsts, in addition to narrowly embedded river valleys (FURRIER et al., 2006; FURRIER, 2007).

Hasui (1990) dates the initial finalization of the deposition of the Brazilian marginal basins (and associated magmatic manifestations) to the Middle Miocene (13 Ma), which defines the beginning of the Neotectonic period in Brazil. According to Carneiro et al. (2012), the continuous rotational distancing of South America from Africa generated compressive and distending effects in a large part of the Brazilian territory, which reactivated the old geological faults of shear zones throughout Brazil. This reactivation generated considerable crustal adjustments and, consequently, tremors and even some earthquakes in the states of Rio Grande do Norte, Minas Gerais, Mato Grosso, Rio de Janeiro, and São Paulo, providing unmistakable evidence of the occurrence of conspicuous tectonic activity in Brazilian territory.

Similar reactivations also took place in the Patos Lineament (BRITO NEVES, et al. 2004), which traverses the present study area from east to west. It is a crustal limit formed by a cluster of ductile shear zones, more than 900 km in length, which continues to Africa as the Adamaoua-Garaoa Lineament (BRASIL, 2002). Medeiros (2004) reported that this structure may reach depths of 6–16 km.

Bezerra and Vita-Finzi (2000) used the detection of earthquake-induced liquefaction fields and the radiocarbon dating of rock to infer the occurrence of prehistoric Holocene earthquakes, some with a magnitude of Ms > 6.8 in the Northeast region of Brazil. Rossetti et al. (2012) observed evidence of Neogenic and Quaternary tectonic activity in the Paraíba Sedimentary Basin, such as seismites, as well as late Pleistocene faults and an abundance of tectonic lineaments.

Analyzing the central portion of the emerged part of the Paraíba Sedimentary Basin, Andrades Filho and Rossetti (2012) highlighted lineaments with an E-W orientation, which predominate, with secondary NE-SW and NW-SE lineaments, and to a much lesser extent, N-S, features. Lima Neto (2013) reviewed the seismic data from the Borborema Province and the surrounding area, for the period between 1720 and 2010, obtained from the Brazilian Seismographic Network, together with a simplified map of the lithology and the main geological structures (Fig. 1).

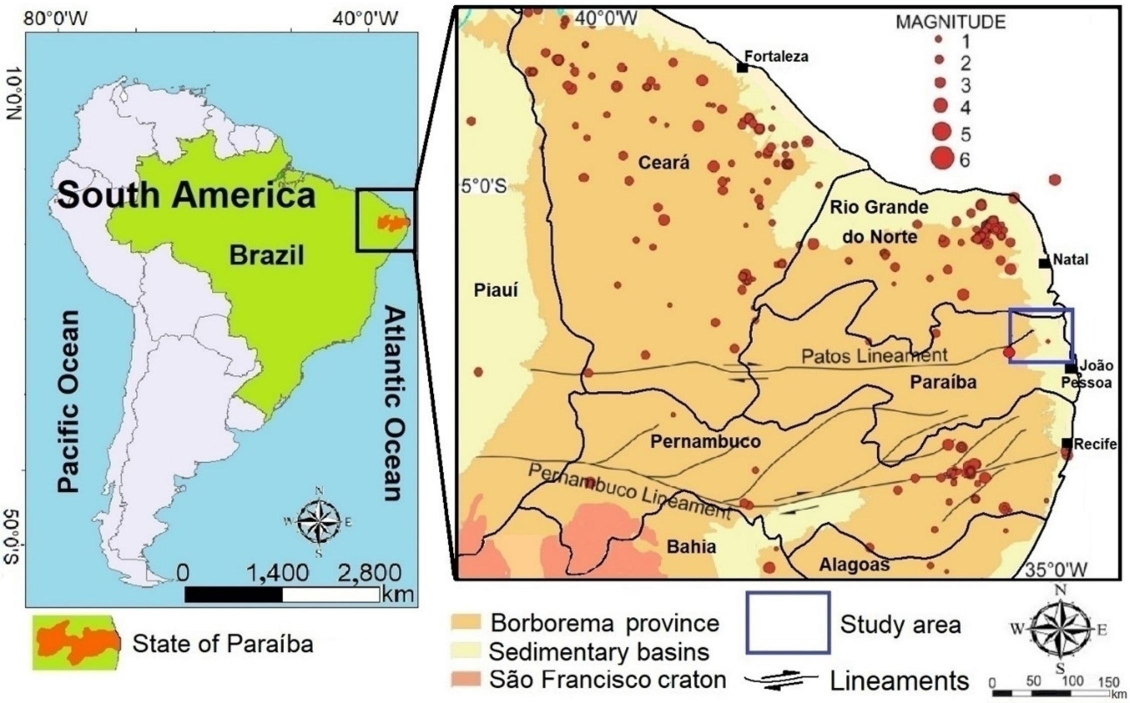

Figure 1 - Location of the study area and the distribution and intensity of the principal earthquakes (red circles) that occurred in the Borborema Province and the surrounding area between 1720 and 2010 (adapted from LIMA NETO, 2013).

The present study area is located in the northeast of the state of Paraíba, between the Province of Borborema, to the west, and the Paraíba Sedimentary Basin to the east (Fig. 1). This region has a mean annual rainfall of 1,600 mm in the areas closest to the Atlantic, decreasing to 1,000 mm in the extreme west of the region, with a mean annual temperature of 26ºC (FRANCISCO; SANTOS, 2017).

The pioneering geomorphological studies in the Brazilian Northeast date to the 1950s with the studies of Gilberto Osório de Andrade, although the first structural and tectonic analyses were conducted in the state of Sergipe by Pontes (1969) and Leite (1973). These researchers observed and mapped considerable altimetric variations in the surface of the coastal tablelands formed over the Barreiras Formation (Miocene), which represent the interference of the tectonic reactivation on the layout of the different levels.

In the state of Paraíba, Furrier et al. (2006) observed a sequential altimetric differentiation of the surface of the coastal tablelands structured with horsts and grabens, and considered these features to be a direct link between the modelling of the relief and the drainage network, with vertical and horizontal crustal movements that indicate recent tectonic forces. For Andrades Filho (2010), these forces may have affected the central portion of the Paraíba Sedimentary Basin, by as late as the Pleistocene.

Alves and Rossetti (2015) consider the morphostructural analysis of the drainage network and relief forms, based on both qualitative and quantitative data, to be an important diagnostic tool. This analysis may facilitate the identification of the influence of tectonic activities at varying degrees of intensity on the geomorphological configuration of the Paraíba Sedimentary Basin, as reported by Andrades Filho and Rossetti (2015).

In general, these structural, tectonic, and seismological features of northeastern Paraíba attract considerable attention for the development of geomorphological studies. This region is located on a continental margin of the Atlantic type, and it has two morphological structures of enormous relevance: the Paraíba Sedimentary Basin and the Patos Lineament. These two elements have had a major influence on the configuration of the landforms and the drainage network of the study area.

METHODS

The morphometric data on the study area were extracted from the 1:25 000 scale topographic charts produced by SUDENE (Superintendência de Desenvolvimento do Nordeste) in 1974. These charts were produced using aerophotogrammetry with technical field support, and are highly accurate. All the contour lines are 10 m equidistant, with spot elevation, and the entire hydrographic network was vectored manually.

Subsequently, the cartographic products were developed with a high level of precision, which served as the baseline for the research and fieldwork. The free software QGIS version 3.12.3 was used in the elaboration of all the cartographic products.

For the preparation of the altimetric map, classes were established with an initial interval of 0–10 m to better represent the coastal plain and floodplain. Subsequently, classes of 10–20 m and 20–60 m were applied for the more precise delimitation of the cliffs that separate the coastal plains abruptly from the coastal tablelands. From the 60 m mark, fixed intervals of 40 m were proposed, up to the maximum limit of 380 m, to represent the foothills of the Borborema Plateau in the far west of the study area.

The slope classes suggested by the Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA) were used to elaborate the slope map (BRASIL, 2006). The analysis of the slope classes and their relationship with the morphostructure of the study area and its morphotectonics have been discussed extensively by Furrier et at. (2006), Hartwig and Riccomini (2010), Silva and Furrier (2013), Santos et al. (2013), Furrier, Nobrega and Souza (2014), Barbosa and Furrier (2015), Lima et al. (2017), Silva and Furrier (2019), and Furrier and Silva (2020).

For a more detailed morphometric analysis, three widely-used morphometric indices were applied to the hydrographic basins of the Roncador, Itapororoca, Tinto, and Estiva rivers. These indices were the Stream-Gradient Index (SL), the Valley Floor Width - Valley Height Ratio (Vf), and the Asymmetric Factor (AF).

The choice of the hydrographic basins for the application of these morphometric indices was based on preliminary analyses of the cartographic products and the results of the field research. This included the basins with the largest number of elements indicative of the influence of structural and tectonic factors, such as waterfalls, directed drainage, straight channels, marked channel inflections, and faults, mapped in previous geological studies.

STREAM GRADIENT INDEX (SL)

A number of studies of the longitudinal profile of rivers have been published since the 1950s, including Leopold and Wolman (1957), Hack (1973), Howard (1980), and Christofoletti (1981). In this context, the SL index proposed by Hack (1973) enables the correlation of the lithological substrate with the incidence of crustal movements and the formation of knickpoints along the river channel (ETCHEBEHERE et al., 2004; ANDRADES FILHO, 2010).

To determine the SL, the index is applied initially to all the selected stretches (SLtotal - SLt) and, subsequently, to the different segments of the river channel (SLsection - RDEs) (Fig. 2). Once the SLs values have been obtained, Martinez et al. (2011) establishes that they should be divided by the SLt (SLs/SLt), with the sections of the channel with a resulting value equal to or greater than 2 being considered tectonic. The expression SL corresponds to the Stream Gradient index in Figure 2.

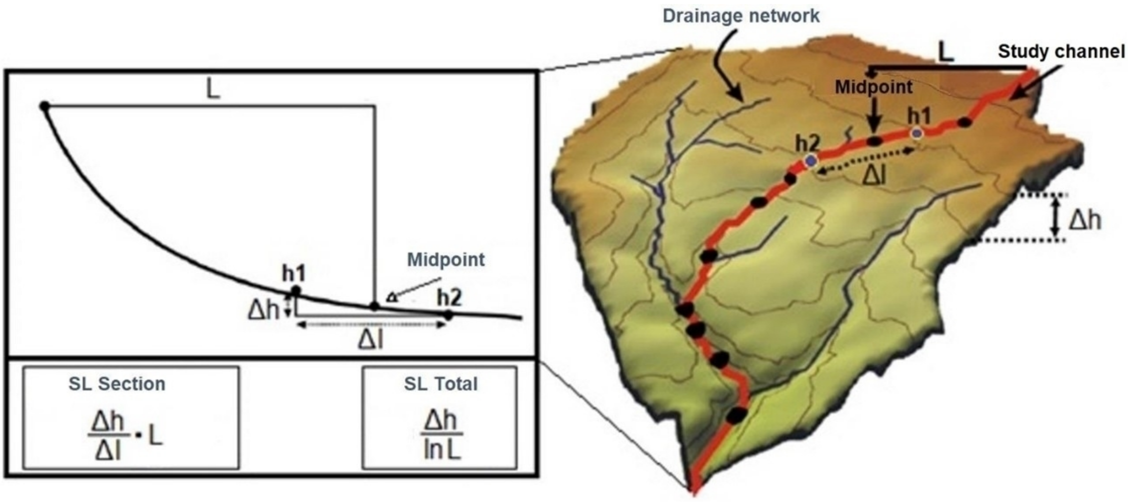

Figure 2 - Parameters used to calculate the SL index (modified from Font and Lagarde, 2010).

To obtain the SLt, Δh is the altimetric difference between the headwater and the mouth, ln corresponds to the natural logarithm of the total length of the channel, and L is the total length of the channel, considering its sinuosity. In the equation for the SLs, Δh represents the altimetric difference between the two points of the segment of the study channel, Δl corresponds to the length of the segment, and L is the total length of the watercourse upstream from the midpoint of the stretch for which the index is being calculated.

Sebeer and Gornitz (1983) established two categories of intensity for the SLs/SLt values. The values equal to or greater than 2 and less than 10 represent 2nd-order anomalies, while the values of 10 or more reflect 1st-order anomalies. For any value greater than 2, then, the researcher must verify, in the field, evidence of tectonic events or structural legacy that may have influenced the development of the channel (HARTWIG; RICCOMINI, 2010).

VALLEY FLOOR WIDTH–VALLEY HEIGHT RATIO (VF)

The Valley Floor Width–Valley Height Ratio (Vf) can be used to investigate the relationship between the depth of the river channel and its lateral coverage. Bull and McFadden (1977) proposed this ratio as a means of showing when the river is exercising an accelerated deepening of its bed through an increase in the energy of its current that may have resulted from tectonic uplifts. It is necessary to exercise due caution, however, and, in particular, determine the existence of any lithological differentiation in the length of the study channel, where less resistant rock has been eroded more intensely, which would not be an effect of tectonic uplift. This ratio can be calculated using the equation and parameters shown below (Fig. 3).

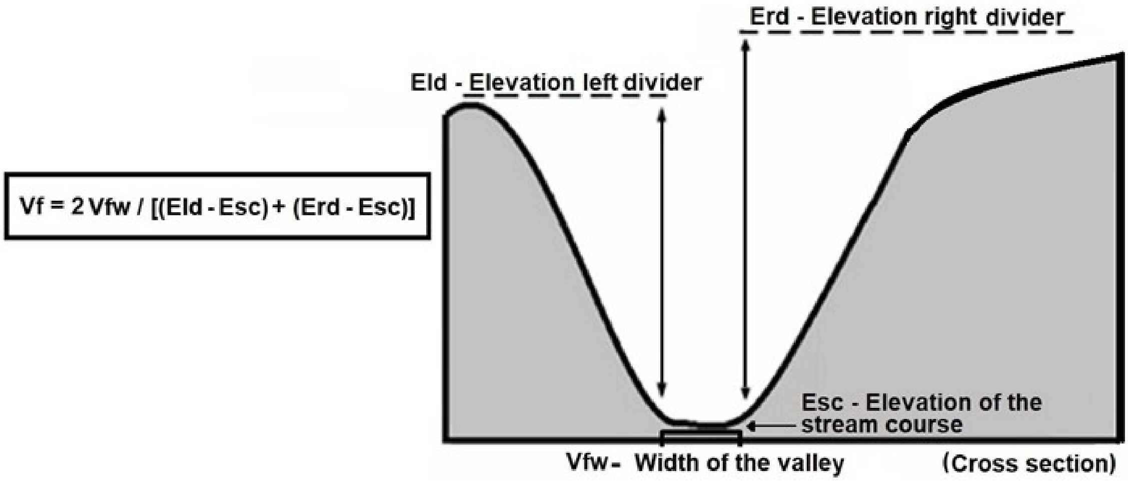

Figure 3 - The mathematical formula and parameters used to obtain the Vf ratio (adapted from Grant and Swanson, 1995).

In this equation, Vfw represents the width of the valley floor, Eld is the altimetric difference between the height of the left water divider and the height of the valley floor, Erd is the altimetric difference between the height of the right water divider and the height of the valley floor, and Esc is the elevation of the valley floor in relation to sea level. Lower values of Vf indicate a greater imbalance in the river channel (EL HAMDOUNI et al., 2008). Silva et al. (2003) considered values below 1 to be anomalous, indicating that the channel has suffered some tectonic influence, which has exacavated its bed. Values above 1 indicate lateral erosion and tectonic stability.

ASYMMETRIC FACTOR INDEX – AF

The Asymmetry Factor (AF) index establishes a direct relationship between the location of the principal river in a watershed and the total area of the watershed. Asymmetrical watersheds are considered to have main channels that are displaced markedly to the right or left of the area of the basin (Fig. 4).

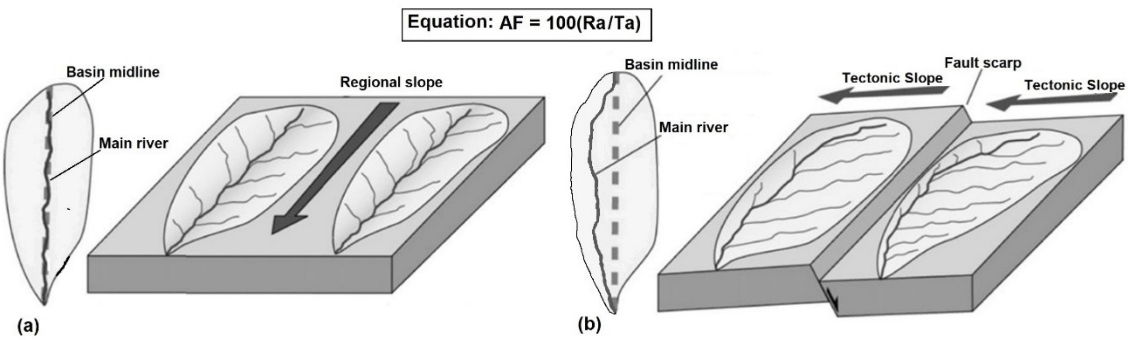

Figure 4 - Response of the drainage network to tectonic activity: a) regional slope in the absence of any tectonic influence, b) displacement of the main channel by tectonic tipping (adapted from Mahmood and Gloaguen, 2011).

In this formula, AF is the Asymmetry Factor, Ra is the territorial extension of the right area of the river, and Ta is the total area of the drainage basin. Soares and Fiori (1976) consider that the presence of tributary channels of different forms on the two sides of the main channel reinforces the intensity of the asymmetry of the basin (Fig. 4b).

Values of AF close to 50 indicate that the configuration of the basin has not suffered any major tectonic influence. When the value is much less than 50, it indicates tilting toward the left margin of the watershed and when it is much greater than 50, tilting toward the right margin (HARE; GARDNER, 1985; RINCÓN; VEGAS, 2000).

Andrades Filho (2010) established three intensity classes for the AF, in which values that are up to 7 points apart (higher or lower) from the equilibrium value of 50 are considered to represent low levels of asymmetry. By contrast, AF values 7–15 points from the equilibrium midpoint are considered to be moderately asymmetric, while those more than 15 points apart are considered to be highly asymmetric.

RESULTS AND DISCUSSION

MORPHOLOGICAL ANALYSIS OF THE STUDY AREA

The structural and tectonic configuration of the study area has been influenced strongly by the widening of the Atlantic Ocean, and the formation of the Patos Lineament and its shear zones. These characteristics have had a direct effect on both the crystalline lithology and the sedimentary rocks of the Barreiras Formation (Fig. 5).

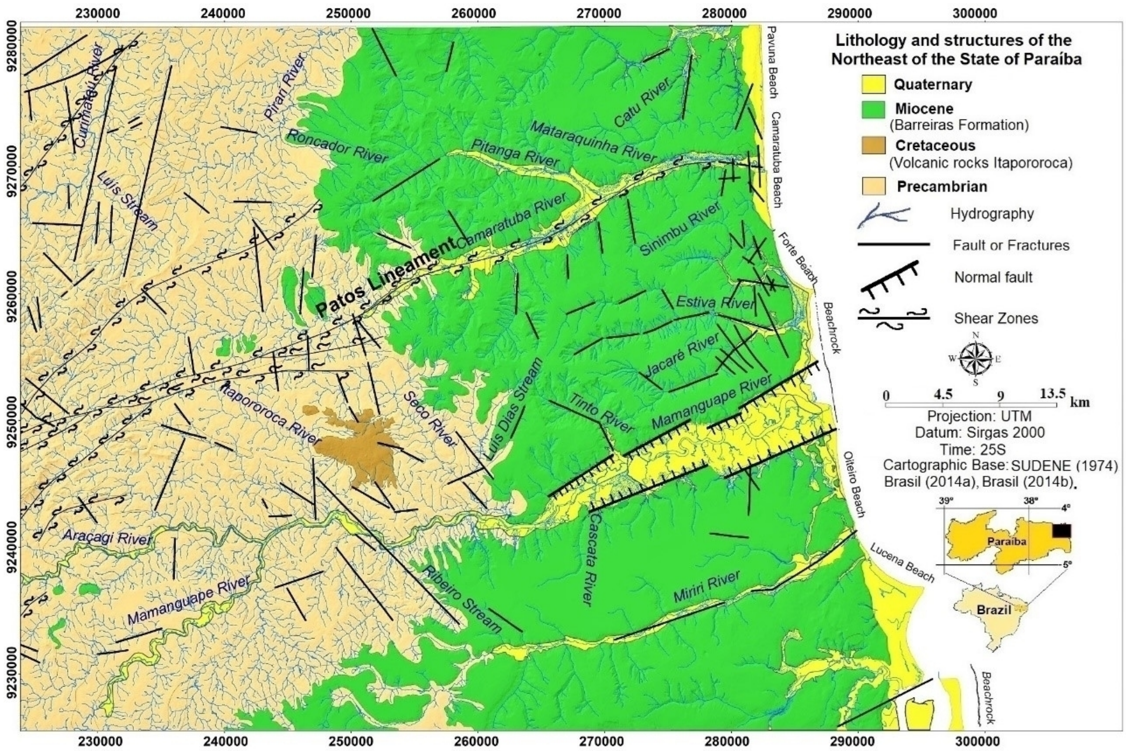

Figure 5 - Simplified geological map of the study area, showing its principal geological structures (modified from SUDENE, 1974; Brasil 2014a; Brasil 2014b).

The low-lying course of the Mamanguape River is a prominent feature of the lithological and structural context of the study area. Brito Neves et al. (2004), Furrier et al. (2006), Furrier et al. (2014), and Alves and Rossetti (2016) have suggested that this area represents a graben, formed by the reactivation of pre-existing faults in the Precambrian crystalline base.

Geomorphologically, the delimitation of the Mamanguape graben can be better observed in the altimetric and slope maps. The altimetry map (Fig. 6) shows clearly that this tectonic morphology is responsible for the advance of elevations of less than 10 m to approximately 25 km inland from the coastline.

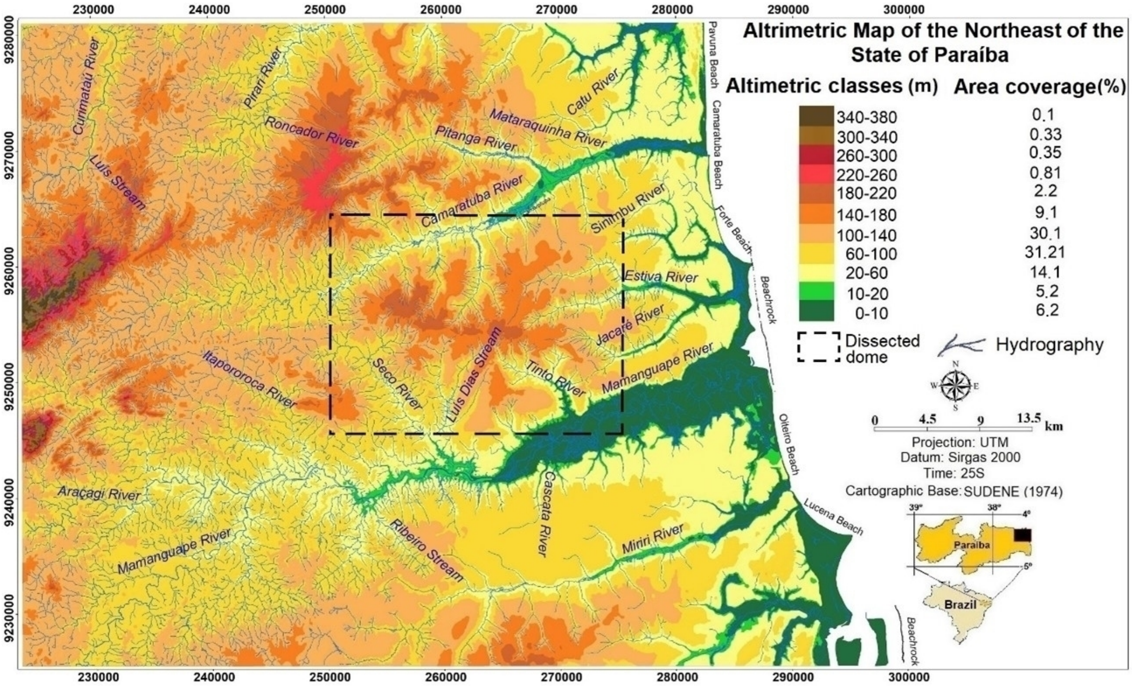

Figure 6 - Altimetric map of the study area.

An abrupt discontinuity in the pebble lines was observed, for the first time, in the western limit of the Mamanguape graben, on its left margin, close to the BR-101 highway, which can be interpreted as a result of tectonic movement, due to the presence of a normal fault in this region (Fig. 7a). This finding, together with the abrupt delimitation of the edge between the graben and the coastal tablelands, is a strong indication of the typical graben characteristics of this area. Other morphological characteristics of this graben will be discussed below.

At Oiteiro beach, a cliff of the coastal tablelands that separate the Mamanguape and Miriri rivers, is further evidence of vertical displacements in the pebble lines (Fig. 7b), which reinforce the evidence that this region was affected by normal post-Miocene faults. In addition to these characteristics, it is noted that the tableland that separates the watersheds of the Mamanguape and Miriri rivers has a much lower elevation levels in comparison with the other interflows in the area (Fig. 6).

Other evidence of tectonism can be seen in the upper course of the Pitanga River (Fig. 7c), where a 4-meter high waterfall (knickpoint) is located in the Barreiras Formation (Miocene). This waterfall was established over the Barreiras Formation, which reinforces the recent nature of tectonics in the area.

It is important to note that the Barreiras Formation is composed of poorly consolidated sand-clay sediments, and that the presence of considerable altimetric unevenness in this formation can be considered to be much more recent, up to the Quaternary. Knickpoints established in this extremely fragile, non-resistant lithology would have easily been erased or minimized by the intense erosive processes that occur in this region of hot and humid climate, with a mean annual rainfall of 1,600 mm (FRANCISCO; SANTOS, 2017).

In the western sector of the study area, where Precambrian crystalline rocks predominate, the configuration of the relief and the drainage network provide strong structural evidence of tectonic processes. In this area, the river channels are confined within narrow valleys and oriented by the lithological configuration. The predominant hydrographic orientations are in the NW-SE and NE-SW directions, established by the geological faults mapped by Brasil (2014b; Fig. 7d).

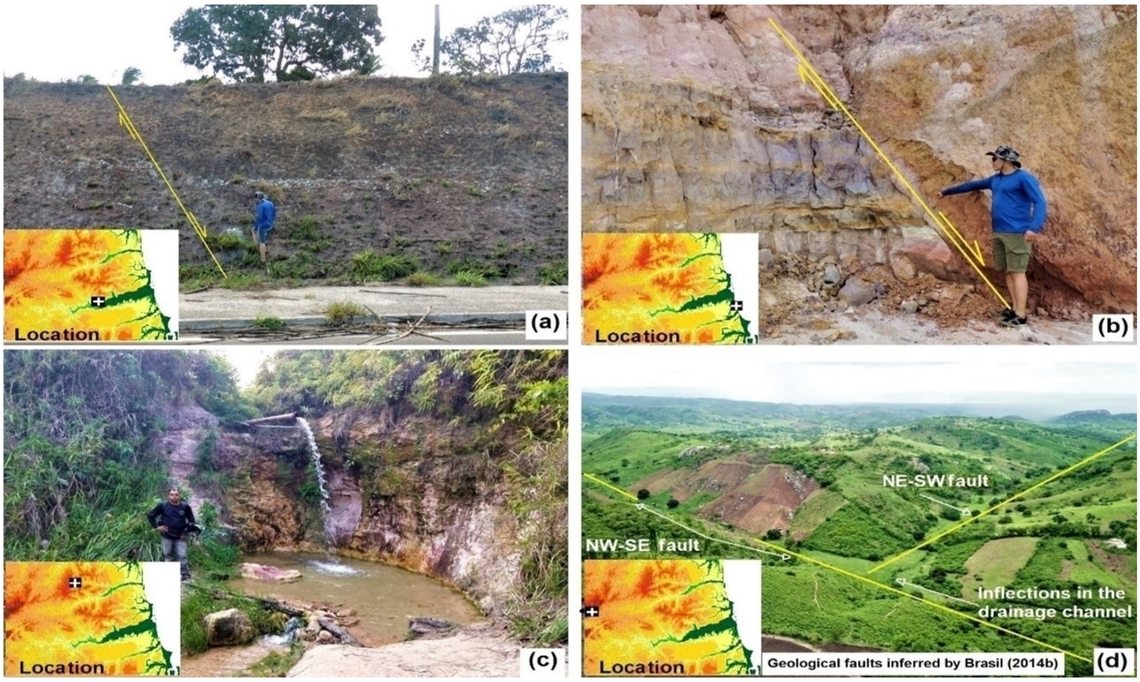

Figure 7 - Lithological structures and landforms indicative of tectonism in the study area: (a) Vertical displacements of pebble lines in the lower course of the Mamanguape River, (b) Vertical displacements in pebble lines in cliffs of the Barreiras Formation, on Oiteiro Beach, (c) Knickpoint in a stream located within the Barreiras Formation in the Pitanga Watershed, and (d) Relief and hydrography established under the influence of the geological faults mapped in the municipality of Serra da Raiz, in the western limit of the study area.

The elaboration of the slope map proved to be very useful for the delimitation of the structural systems and fault lines that have a direct influence on the relief and the precise delimitation of the geomorphological compartments. The Mamanguape graben is delimited clearly in the slope map, as are the slopes that delimit this graben. The northern sector has slopes of up to 75%, while the southern slopes reach no more than 45%.

To the north, the Camaratuba River is set deeply into a valley with very steep slopes whose morphology is linked directly to the Patos Lineament (Fig. 5). In the lower course of the Camaratuba River, many tributaries are located practically perpendicular to the principal river, with more tributaries on the southern margin. All the tributaries in the southern sector have steeply-sloping valleys, ranging from 45–75%, with a slope of more than 75% in some sectors.

A closer analysis of both the altimetric (Fig. 7) and slope maps (Fig. 8) reveals a dome in the central-eastern sector of the tableland that divides the Mamanguape and Camaratuba watersheds. This dome shape has influenced the entire hydrographic network that surrounds it in a centrifugal configuration that involves the streams of the hydrographic basins of both the Mamanguape and the Camaratuba rivers.

In addition to being completely anomalous for the coastal tablelands of the Barreiras Formation, this dome-shaped structure is consistent with the evolution of the adjacent fluvial structures, where rivers and streams have carved out their beds intensively, producing slopes greater than 75% in some sections and with an intense retraction toward the headwaters (Fig. 8).

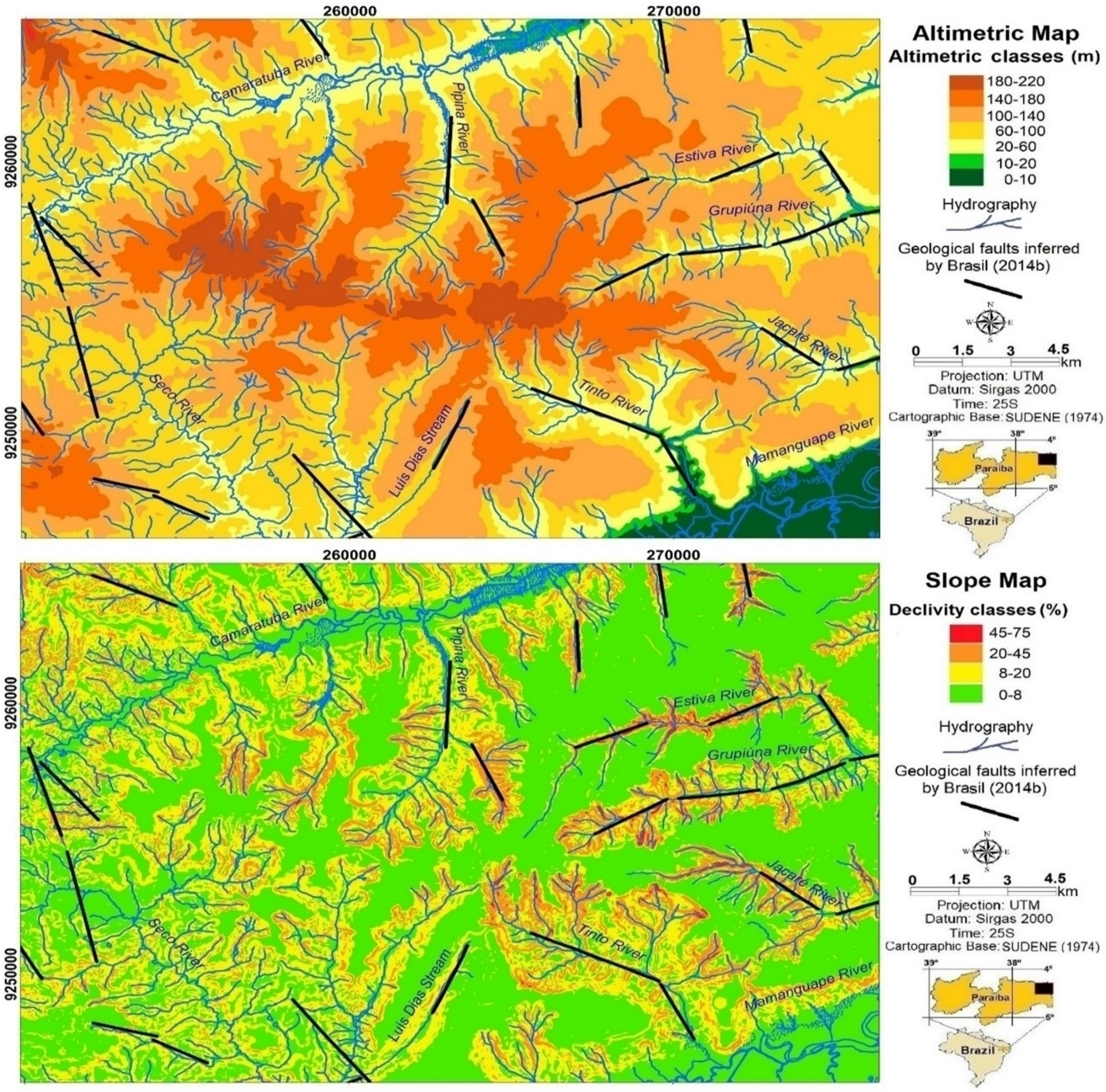

Figure 8 - Altimetric and slope maps showing the presence of a dome in the Barreiras Formation with a centrifugal drainage network and strong fluvial dissection.

Another dome shape can also be observed in the northern sector of the study area, which is also surrounded by a centrifugal drainage network with streams that have carved out their beds intensively. The rapid gouging process has produced slopes of greater than 75% with a strong backwater drainage, contributing to the accelerated evolution of these drainages. These domes are reported here for the first time in this area, but other similar structures forms have already been described in the Barreiras Formation by Brito Neves (2004) and Furrier et al. (2006).

The predominant slope class in the study area is 0–8%, which represents the flattened tops of the coastal tablelands, the fluvial and coastal plains, and the low-lying hills of the Eastern Borborema Depression. The highest altitudes are located to the west, where the foothills of the Borborema Plateau are located. With the exception of the foothills of the Borborema Plateau, the steep slopes found throughout most of the study area, especially in the coastal tablelands, are strong evidence of structural control and, probably, of recent tectonic action (Fig. 9).

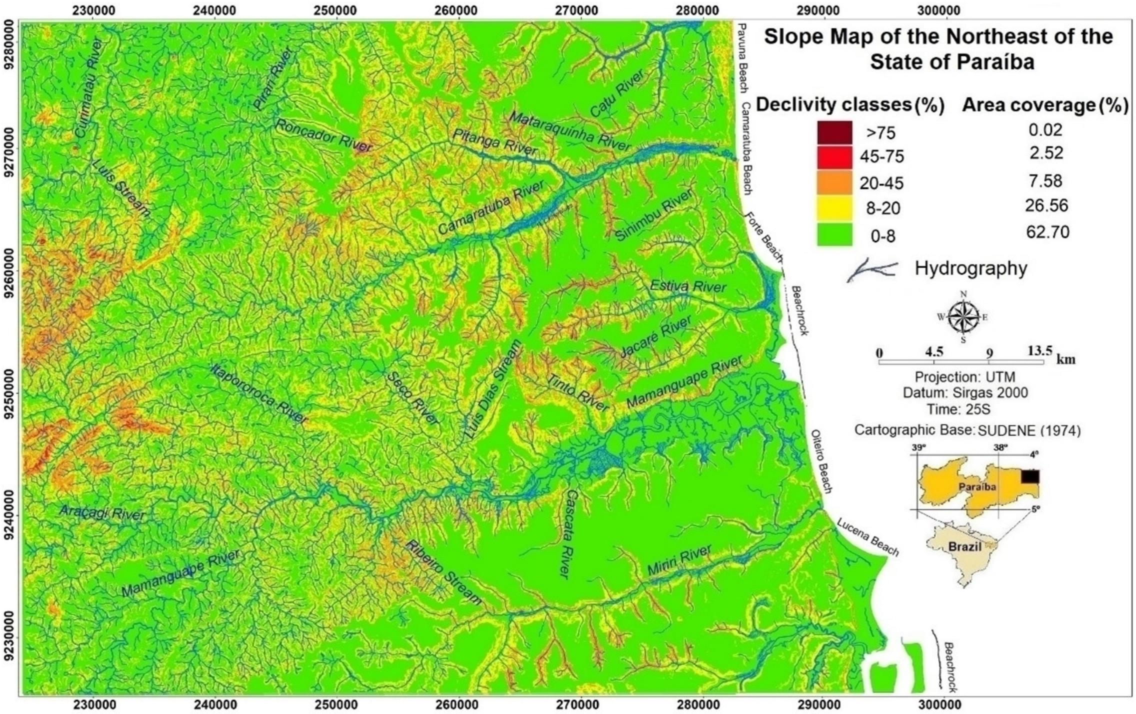

Figure 9 - Slope map of the study area.

The lithology, altimetry and slope maps of the area to the north of the Mamanguape River all indicate a greater density of geological faults, coastal tablelands of higher altitudes and steeper slopes, in addition to the dome structure mentioned above. One explanation for these characteristics may be the closer proximity of the Patos Lineament and its reactivated shear zones, which have affected the crystalline basement directly and, indirectly, the overlying Barreiras Formation, resulting in the dome-shaped morphology that has streamlined the fluvial processes.

As proposed by Hartwig and Riccomini (2010), the integration of the analysis of the slope of the terrain with other morphometric variables, such as altimetry, provides a sound preliminary characterization of the study area. Given this, the mapping of slope patterns contributes to the precise delimitation of the configuration of the landforms and the drainage network, considering that regions which have suffered structural or tectonic impacts tend to have their own unique characteristics, such as the formation of grabens and horsts, which can be delimited accurately through their altimetry and slopes.

MORPHOMETRIC ANALYSIS OF THE WATERSHEDS

The application of the morphometric indices revealed that the watersheds selected for analysis had values consistent with a marked structural influence of post-Miocene tectonics on their development and present-day configurations (Fig. 10).

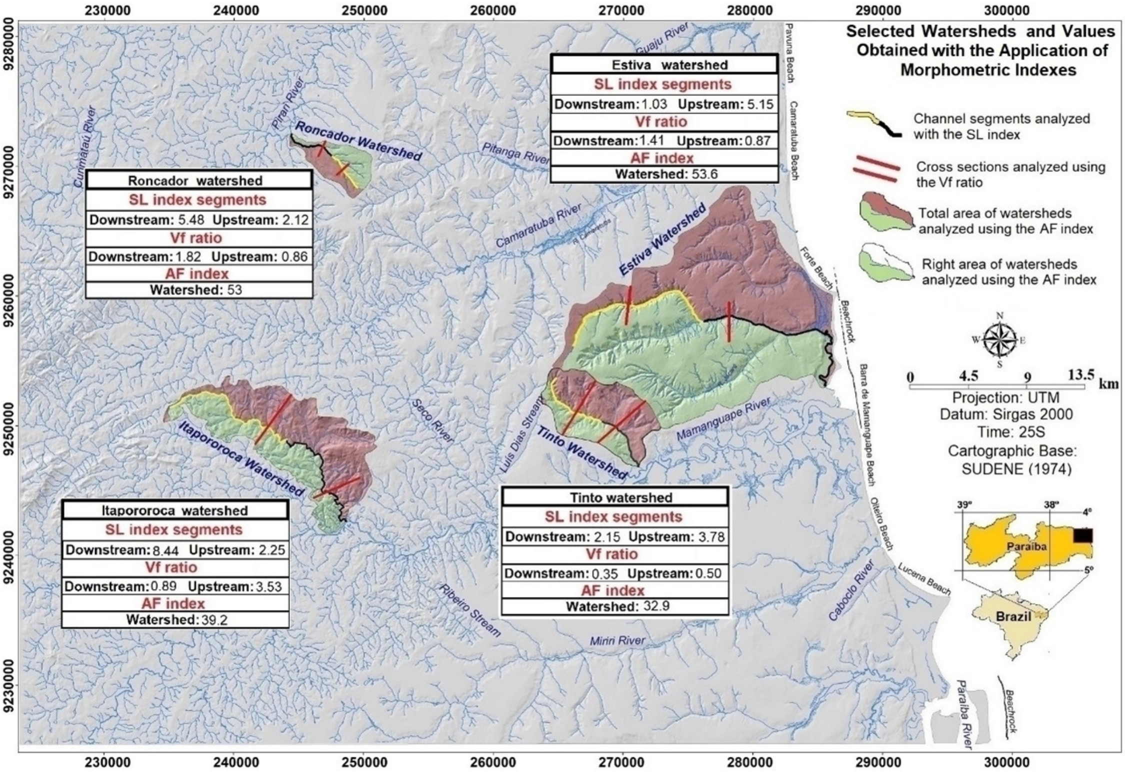

Figure 10 - Watersheds analyzed in the present study, and their respective morphometric indices.

RONCADOR RIVER

The Roncador River flows in a SE–NW direction, which is atypical of the predominant orientation of the principal rivers in the study area, which mostly flow eastward into the Atlantic. This river forms a 3rd order hydrographic network, based on Strahler's (1952) classification, and is a tributary of the Pirari River. Its watershed covers an area of 15.04 km2 in an area of lithological transition between the sedimentary rocks of the Barreiras Formation, in the upper basin, and crystalline Precambrian rocks, in its middle and lower courses.

In the upstream segments, the SL index (2.12) and the Vf ratio (0.86) indicate a reduced probability that the development of this area of the watershed was influenced directly by tectonic activities, which is further corroborated by the lack of elements indicative of these deforming activities in the configuration of the relief and the drainage of the upper course (Fig. 11a).

In the middle to lower course of the Roncador River, the SL was 5.48 and the Vf was 1.82. This SL index is consistent with the possibility of the existence of a longitudinal anomaly in this stretch of the river. The triggering element of this longitudinal anomaly has not yet affected the transverse morphometry of the channel, which justifies the non-anomalous Vf ratio. The SL value of this sector can be explained by the knickpoints found in the lower course of the Roncador River (Fig. 11b).

It is possible to observe that the formation of the knickpoint furthest down the channel, in the crystalline rock of the Precambrian, is indicative of a fault mirror. In this structure, there is a polished face resulting from vertical movement and reduced weathering, given that the exposed rock is extremely well-preserved, which is likely the result of the short period of time that has passed since the occurrence of this tectonic event and the exposure of the rock (Fig. 11c).

The AF index was 53.0, which demonstrates a certain stability, with little evidence of tipping within the watershed. This reinforces the conclusion that tectonic activity has only affected its lower course, as detected by the SL index and the field data.

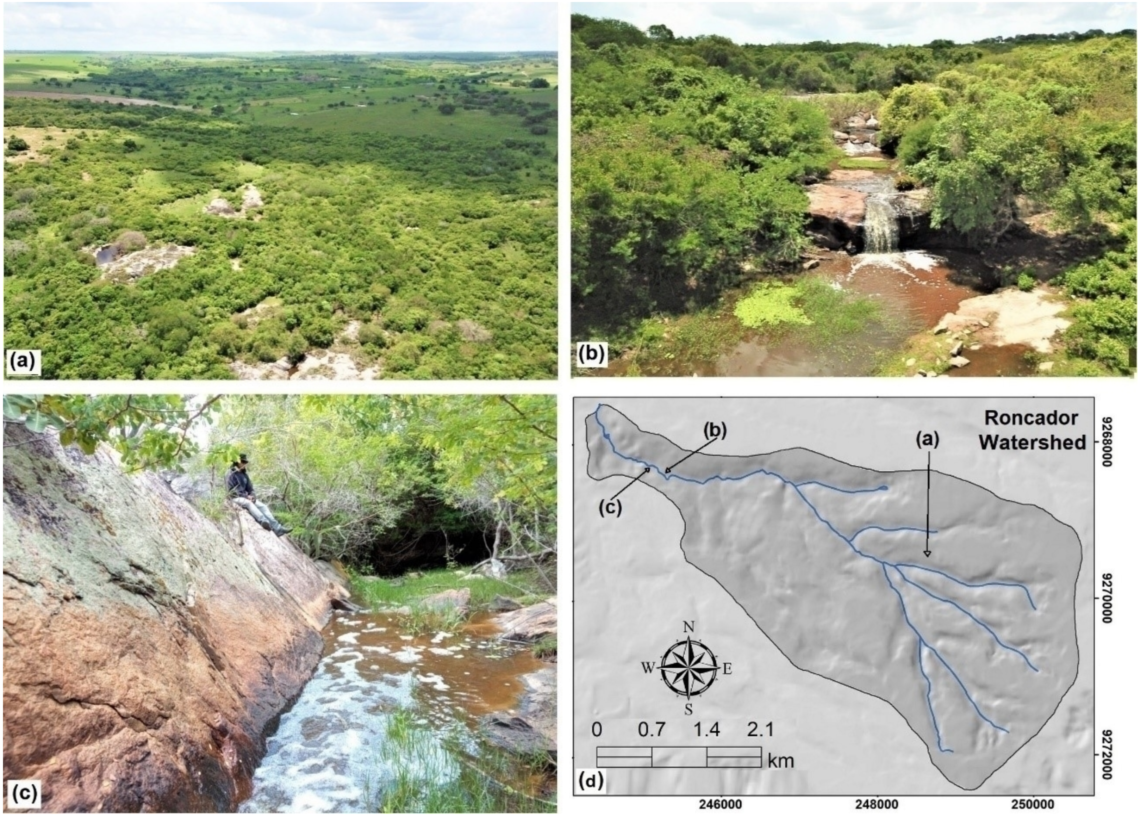

Figure 11 - Principal landforms in the Roncador River watershed: (a) relief of the middle and upper course of the Roncador River, (b) knickpoint in the lower course, (c) preserved form indicating a fault mirror, and (d) watershed of the Roncador River showing the points photographed.

ITAPOROROCA RIVER

The Itapororoca River is a 4th-order tributary of the middle Mamanguape River and has a watershed of 80.01 km2, with a dendritic drainage pattern. This watershed is located on volcanic Cretaceous and crystalline Precambrian rocks. The morphometric indices obtained for this watershed are consistent with a high probability of structural and tectonic impacts in its middle and lower courses.

The SL index (2.25) and the Vf ratio (3.53) recorded in the upper sector of the watershed are compatible with a stable environment, controlled primarily by lithological processes. In the lower sector analyzed, however, both the SL (8.44) and Vf (0.89) are consistent with the tectonic control of the drainage network. This conclusion was supported by morphological evidence from the field. Two knickpoints were mapped within the lower basin, and evidence of drainage capture was found near the mouth of the Itapororoca River (Fig. 12).

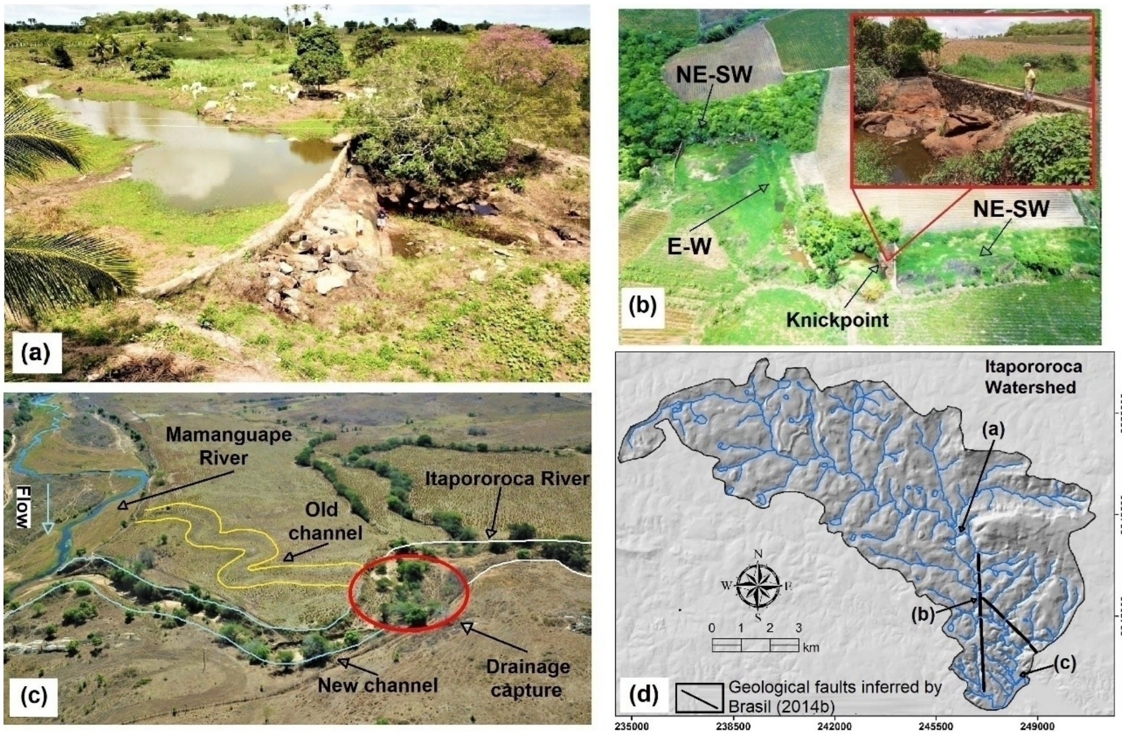

Figure 12 - The principal landforms of the Itapororoca River watershed: (a) knickpoint in the middle course where a small dam has been built on the outcrop, (b) small stretch of straight channel in an EW direction, with a knickpoint (with small dam) in the lower course, (c) evidence of drainage capture near the mouth of the Itapororoca River, and (d) the Itapororoca River Watershed showing the points photographed.

In order to take advantage of the natural barriers formed by the knickpoints, local residents have built small masonry walls on these structures (see Figs. 12a and 12b), which form small reservoirs used to meet their water needs for agricultural practises during periods of low rainfall. In addition to these morphometric and morphological data, Brasil (2014b) mapped a number of geological faults in the middle and lower course of the Itapororoca River, which further reinforce tectonic character of this basin (Fig. 12d). In this context, the value of the AF index (39.2) also indicates the influence of tectonic activity in the Itapororoca River watershed, with tipping to the left side of this basin.

ESTIVA RIVER

The Estiva River watershed is a 5th-order drainage, with the largest area of the four watersheds analyzed here (223.06 km2). The principal drainage pattern is dendritic and its lithology is formed by rocks of the Barreiras Formation and Quaternary sediments in the plains of the most well-developed channels.

In the upper sector, the SLs/SLt index was 5.15, which is compatible with the existence of a tectonic anomaly in the channel. The Vf ratio was 0.87 in this sector, which further reinforces the tectonic character indicated by the SLs/SLt index.

The main channel of the Estiva River near its source has a weak incision that increases substantially going downstream. The upper course of the Estiva River flows SW-NE and is aligned with the upper Tinto River which flows NE-SW. Brasil (2014b) mapped a geological fault exactly in this area, which also conditions the NE-SW flow of the Luís Dias stream (Fig. 8).

The weak incision of this segment of the channel can be associated with its relatively recent formation, with its direction being controlled by tectonic forces. As this stretch is recent, the soft rock of the Barreiras Formation has not yet been eroded noticeably. This scenario can also be observed on the upper Sinimbu River (Fig. 13b) and the upper stretches of the Cascata, Tinto, Estiva, and Mataraquinha rivers, which are all located on the Barreiras Formation.

In the lower Jacaré River, a tributary of the southern margin of the Estiva River, where a sequence of faults running NW-SE was mapped by Brasil (2014a), an unevenness in the channel was found, which gives rise to a section of rapids was recorded in the field, together with the formation of river terraces. These characteristics can be interpreted as a response of the drainage network to the movement of the mapped faults (Fig. 13a, 13c, and 13d).

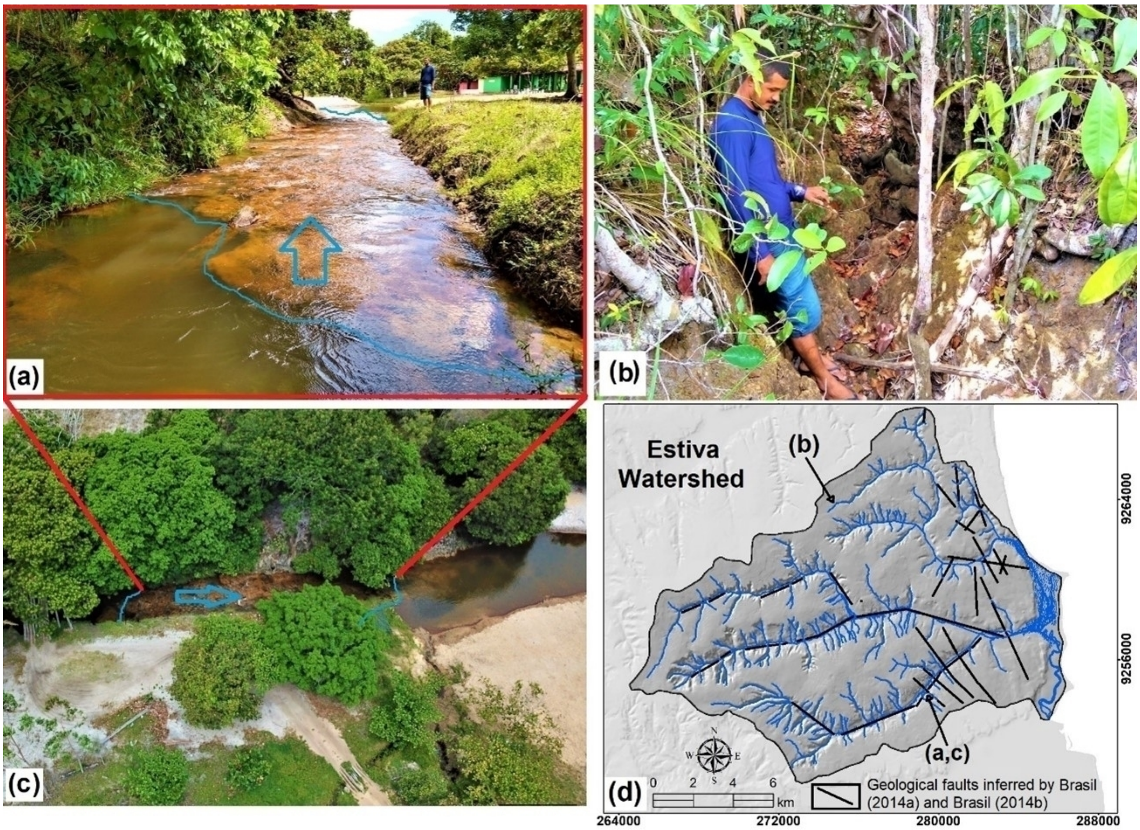

Figure 13 - Principal morphological characteristics of the Estiva River watershed: (a) and (c) stretch of rapids in the soft rock of the Barreiras Formation in the lower course of the Jacaré River, (b) low incision in the 1st-order drainage of the upper Sinimbu River, aligned in a NE-SW direction, (d) watershed of the Estiva River, the geological faults mapped by Brasil (2014a), and the points photographed here (a, b, c).

Despite a high concentration of geological faults, the erosive processes observed on the lower Estiva River are much less intense in comparison with its middle and upper stretches. The SL index (1.03) and Vf ratio (1.41) were not consistent with the presence of morphometric anomalies that represent tectonic impacts, although it should be noted that lower stretches will always have lower morphometric indices, reflecting the natural evolution of any watercourse. It is nevertheless worth noting the high concentration of mapped faults.

As Font and Lagarde (2010) stated, in areas with low rates of elevation determined by tectonic processes, the channels will have lower SL values, while the channels located in areas with more intense elevation rates will have higher indices. The slopes in the lower Estiva River are shallow, rarely more than 20%, which is very different from the middle and upper course, where the slopes, in some sectors, may exceed 75%. This basin had an AF of 53.6, with only a slight asymmetry to the right side.

TINTO RIVER

The Tinto River is a tributary of the lower Mamanguape River and its watershed covers an area of 39.86 km2, with a 4th-order drainage, and a dendritic drainage pattern. The drainage channels of this watershed are inserted in the sedimentary lithology of the Barreiras Formation and the direction of its main channel is influenced strongly by the geological faults mapped by Brasil (2014b).

The Tinto River watershed was the only one of the four analyzed here to present morphometric indices that were all compatible with the influence of tectonic activities. In the upper segments, the SL index was 3.78 and the Vf ratio was 0.50, while in the lower segments they were 2.15 and 0.35, respectively. These results are corroborated by the AF index, which was 32.9.

These findings indicate that the development of the hydrography of the Tinto River watershed was influenced extensively by tectonic processes. A marked inflection of the channel was found in the upper course of the river, which is aligned with other drainages from nearby channels in a NE-SW direction, which is the same orientation as the geological fault mapped by Brasil (2014b) in the Luís Dias stream (Figs. 14b and 14c). At this tipping point there is a marked knickpoint, which forms a waterfall with an abrupt drop of 4 meters (Fig. 14a), which due to the fact that it is aligned with a geological fault and located on the friable lithology of the Barreiras Formation, which can only be explained by recent tectonic activity.

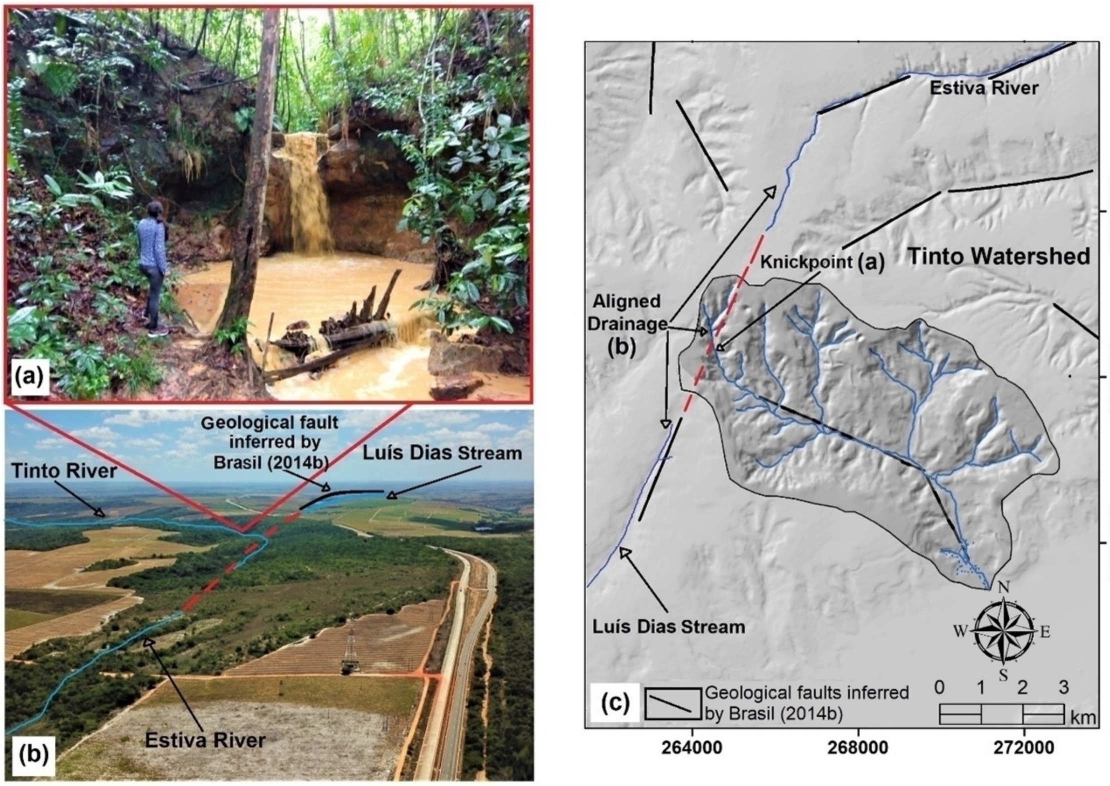

Figure 14 - Principal features of the relief of the Tinto River Watershed: (a) knickpoint 4 meters in height in an area of unevenness in soft rock of the Barreiras Formation, (b) drainage alignments of the Tinto, Estiva, and Luís Dias rivers with a geological fault, (c) watershed of the Estiva river showing the points photographed and the drainage alignments.

In addition to these observations, the main channel of this watershed has been diverted by the tectonic faults mapped by Brasil (2014b), with part of the upper segment and the entire middle course are aligned in a NW-SE direction and the lower course, in NNW-SSE direction. These alignments with regional lithological structures, together with the morphometric indices, reinforce the conclusion that structural and tectonic processes have been the most prominent factors in the development of the relief and drainage network in this watershed.

Watershed	Index	Reference value for anomalies	Value recorded
Roncador lower	SL	> 2	**5.48**
Roncador upper	SL	> 2	2.12
Itapororoca lower	SL	> 2	**8.44**
Itapororoca upper	SL	> 2	2.25
Estiva lower	SL	> 2	1.03
Estiva upper	SL	> 2	**5.15**
Tinto lower	SL	> 2	2.15
Tinto upper	SL	> 2	**3.78**
Roncador lower	Vf	< 1	1.82
Roncador upper	Vf	< 1	**0.86**
Itapororoca lower	Vf	< 1	**0.89**
Itapororoca upper	Vf	< 1	3.53
Estiva lower	Vf	< 1	1.41
Estiva upper	Vf	< 1	**0.87**
Tinto lower	Vf	< 1	**0.35**
Tinto upper	Vf	< 1	**0.50**
Roncador	AF	deviation (+/-) from 50	53
Itapororoca	AF	deviation (+/-) from 50	**39.2**
Estiva	AF	deviation (+/-) from 50	53.6
Tinto	AF	deviation (+/-) from 50	**32.9**

Table 1 - Results obtained of the morphometric indices for the four watersheds analyzed in the present and the respective reference values used to infer the influence of structural and tectonic processes. Values in bold script are consistent with the influence of tectonic processes (in the case of the AF index, only major differences were considered relevant).

CONCLUSION

SUMMARY

The results of the present study provide substantial evidence that the configuration of the watersheds and, consequently, the relief of the northeastern extreme of the Brazilian state of Paraíba has been influenced fundamentally by structural and tectonic processes resulting from the adjustments of the regional geology established by the ongoing separation of South America from Africa. This continuous distancing has reactivated ancient structures inherited from the Pre-Cambrian, such as the Patos Lineament, as well as generating new geological structures linked directly to the widening of the Atlantic Ocean and, consequently, to the formation of the Paraíba Sedimentary Basin.

In the morphological analyses based on geological, altimetric and slope maps, it was possible to verify areas of abrupt altimetric unevenness in the coastal tablelands carved out of the Barreiras Formation, with relatively tall structures in the form of domes, accentuated erosion processes in some rivers and streams with strong recoil erosion of the headwaters, abrupt channel inflections related to the presence of faults, in addition to the graben of the Mamanguape River. These features cannot be explained adequately by climatic factors and erosive planing processes alone.

The morphometric analyses of the river channels based on the SL index recorded values that were often compatible with the influence of tectonic processes, which was confirmed by the observation of the knickpoints in the field. The morphology of many of these knickpoints is typical of preserved fault mirrors and waterfalls in the homogeneous lithology of the soft rock of the Barreiras Formation, which is consistent with the occurrence of recent tectonic events. The Vf ratios were higher in the valleys in which erosive processes were more intense, regardless of whether the valley is located in the upper of lower stretch of the channel, thus demonstrating the sensitivity of this parameter to the variation in the relief. The AF indices also proved to be effective for the morphometric analysis of the watersheds, with values that indicated some areas have undergone tectonic tipping, given the lack of lithological differences that could account for the displacement of the river channel.

Overall, the results of the morphological and morphometric analyses show clearly that the study region has undergone conspicuous structural and tectonic processes, given that the observed configuration cannot be explained by climatic conditions or the static structural framework alone. It is hoped that this study will contribute to further geomorphological research in other sectors of the Atlantic Continental Margin.

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