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Geomorphology, morphometry and evidence of tectonics in the Araçaji Chart, Eastern Edge of Paraíba

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ABSTRACT

The present article has as objective to analyse the interrelations between the relief, the lithology, the hydrography and the conspicuous evidence of tectonics on the area covered by the Araçaji 1: 25.000 chart, State of Paraíba, Northeast Brazil. The results showed the existence of anomalies in the study area, such as altimetry with disproportionate dimensions to the regional average, strong channel inflections, rectilinear channels and modified patterns in the drainage network influenced mainly by the local geological framework and possibly the Cenozoic tectonics. Allied to this qualitative analysis, morphometric indices were applied, for which the values obtained corroborate the tectonic influence in the area. The methodology used in this article requires a greater comparison to results obtained in other areas of the Atlantic continental border.

Keywords: Structural Geomorphology; Watershed; Mamanguape River; Drainage network.

Geomorfologia, morfometria e evidências de tectônica na Folha Araçaji, Borda Oriental da Paraíba

RESUMO

O presente artigo tem como objetivo analisar as interrelações existentes entre o relevo, a litologia, a hidrografia e a conspícua evidência tectônica da área da folha Araçaji na escala de 1:25.000, Estado da Paraíba, Nordeste do Brasil. Os resultados mostraram a existência de anomalias na área em questão, como altimetria com cotas desproporcionais à média da região, fortes inflexões na direção de canais, canais retilíneos e padrões modificados na rede de drenagem influenciados, principalmente, pelo arcabouço geológico local e, possivelmente, pela tectônica cenozoica. Aliados a essa análise qualitativa, foram aplicados índices morfométricos, nos quais os valores obtidos corroboram com a influência tectônica na área. A metodologia empregada neste artigo carece de maior comparação com resultados obtidos em outras áreas da borda continental atlântica.

Palavras-chave: Geomorfologia Estrutural; Bacia Hidrográfica; Rio Mamanguape; Rede de drenagem.

Introduction

This article addresses the mutual relations of lithology, hydrography and tectonics in the configuration of relief in the Araçaji topographic chart, eastern border of the State of Paraíba. This topographic chart has a scale of 1:25,000 and equidistance of the 10m contour lines. It was elaborated by the *Superintendência de Desenvolvimento do Nordeste* (SUDENE) in 1974, through triangulation aerophotogrammetry and technical support on the ground, which gives it high precision, much higher than the images of the Shuttle Radar Topography Mission (SRTM) with resolution of 30m.

This chart provides several attributes necessary for accurate morphological and morphometric analysis, such as contour lines with 10m equidistance, rated points and a very detailed hydrographic network. The choice of the referred topographic chart is due to the fact that it is an integral part of the regional project of geomorphological mapping of the eastern border of the State of Paraíba, developed by the Laboratory of Geological and Environmental Studies of the Federal University of Paraíba.

Morphometric analyzes are being investigated in the watersheds of the Guadu, Itapororoca, Seco and Araçaji rivers, all tributaries of the Mamanguape River that crosses the chart

from west to east in addition to being the main river on the north coast of the State of Paraíba and being confined, in its medium and low course, in a Cenozoic graben (Furrier, Nóbrega and Souza, 2014).

Rodrigues and Adami (2009) affirm that these charts are very important for data collection for further morphometric analysis. Although the vectorization of your data is an arduous and expensive task, the resulting precision proved to be quite satisfactory.

In Brazil, doctoral theses by Bezerra (1998), Furrier (2007), Barbosa (2017) and Silva (2020), in addition to several published articles, suggest that the tectonic stability of the Brazilian Continental Margin is only relative, and that this tectonic cannot be neglected more in geomorphological works, mainly those of a morphostructural nature.

In the past, geomorphological studies on the coastal rear of Northeast Brazil were strongly based on processes of climatic planing. This research tries to demonstrate that there is a tectonic factor that cannot be neglected and must be addressed with other technical and methodological biases.

The current challenges are to try to measure this tectonics through data obtained in the thematic maps generated and the use of morphometric calculations in the drainage network to, in this way, obtain relative dates regarding the movements and the derived morphologies and, mainly, confront data obtained in other regions of Brazil and other countries bordering the Atlantic Ocean.

Geological and structural characterization

The study area is located in the Geotectonic Province of Borborema (Figure. 1), east of the Borborema Plateau, more precisely in the morphological region called the *Superfície Pré-Litorânea (SPL)*, defined and delimited by Costa et al. (2020). This flattened surface is located between the eastern edge of the Borborema Plateau and the Coastal Tablelands sculpted on the Barreiras Formation, in the State of Paraíba.

Its division into tectono-stratigraphic terrains comes from the Brasiliana orogenesis that affected the entire Borborema Province until the beginning of the Ordovician (~ 490 Ma), indistinctly marking all of its terrains with a strong system of flowing shear zones and remarkable granitic plutonism. In the domains of this province, rocks of Archean ages can be found, but rocks with Paleo to Mesoproterozoic ages predominate, which are grouped in the northern, transversal and meridional sub-provinces, separated by the Patos and Pernambuco lineaments that have E – W direction (Brito Neves et al., 2008).

Much of the Province of Borborema, including the area covered by the *Superfície Pré-Litorânea (SPL)*, would be formed by reworking the Paleoproterozoic crust during the Brazilian cycle. These structures, after reaching their tectonic stability, underwent new tensions during the last major tectonic event that took place in South America and West Africa, which was the separation of these continents in Mesozoic (Bezerra et al., 2001). In recent studies, Maia and Bezerra (2020) stated that these reactivations of Precambrian fault zones, caused by the continuous movement of South America towards the west, caused deformations in sedimentary deposits of Neogene to Quaternary.

Figure 1. General geology and location of the study area (Source: Adapted from Sudene (1974); modified by Santos, Ferreira and Silva Júnior (2002) and Brito Neves *et al.*, (2008).

Several studies point to indications of fault reactivations in the geological context where the Araçaji 1: 25,000 chart and its surroundings are inserted, including in the Patos Lineament and in the Mamanguape River Graben (Furrier; Araújo; Meneses, 2006; Mantovani *et al.*, 2008; Brito Neves *et al.*, 2008; Silva, 2020). Such reactivations would have affected rocks belonging to crystalline basement, which, in turn, affected rocks generated and deposited in relatively recent periods, ranging from the Cretaceous to the Neogene.

With the continuous separation of the South American Plate from the African Plate, there is a continuous adjustment of the lithology of the entire area, which is substantially reflected in the arrangement and morphology of the drainage network, showing patterns incompatible with a classic hydrographic evolution proclaimed in tectonically stable zones.

Materials and methods

The methodological structuring of this article is based on two investigative lines: a qualitative bias, which investigates the forms of relief and its interrelationships with hydrography and geology and a quantitative analysis, which studies the relationship between geomorphology/tectonics/hydrography through application of morphometric indices very widespread today.

Florenzano (2008) reports that in geomorphological studies the qualitative aspects refer to the descriptive analyzes of the relief, represented by its forms and appearance, such as, for example, flat, hill, mountainous etc. Qualitative aspects of the relief can also be understood as its spatial organization, genesis, chronology and explanation. Quantitative data refer to morphometry, represented by variables related to measures of height, length, width, surface, volume,

inclination (slope), curvature, orientation, density and frequency of its forms.

The structural and tectonic character in understanding the configuration of the relief has been gaining scope in Brazil since the pioneering works of Pontes (1969) and Leite (1973), who observed abrupt altimetric unevenness delimiting parallel levels, suggestive of reactivation by faults in the Coastal Boards of the State of Sergipe due to the constant separation between South America and the African continent.

These more recent studies, such as Lima (2000) and Bezerra et al., (2001), for the Northeast coast; Hiruma et al., (2001), in the Southeast region; Costa et al., (1996), for the Amazon region, corroborate the structural and tectonic character in the configuration of the relief for several Brazilian geographic regions. Maia and Bezerra (2020) conspicuously demonstrate that much of the relief of the Northeast Region has a strong structural character in its configuration.

For Hartwig and Riccomini (2010), the morphometric analyses applied on reliefs with a strong structural character may allow the identification of anomalies in the relief pattern that may show recent tectonic movements, and which are not always visible on the surface. For the authors, in general, these analyses precede the fieldwork and aim at the preliminary identification of areas with a higher probability of structural-tectonic occurrences.

Marques (2012) states that it was the work of R. E. Horton and A. N. Strahler towards morphometry that opened new horizons for geomorphology, allowing to obtain results based on the attribution of numerical values regarding the ordering of river channels.

In Brazil, since the 1980s, several studies have used morphometric parameters to analyze the relief and its interrelationships with hydrography and geology, the most used being the Stream-Gradient Index (SL) (Etchebehere et al., 2004; Passarella et al., 2016; Andrades Filho and Rossetti, 2018). For Passarella et al. (2016), the morphometric parameters of the relief are essential for the characterization and understanding of the formation of a landscape, especially in regions where the erosive and tectonic processes are well marked in the relief, a very noticeable situation in the region where the present study was developed.

In the present study, much attention was paid to what Andrades Filho and Rossetti (2018) warn, because, for the aforementioned author, the application of morphometric indices requires a careful analysis, since the relief forms can present morphometric results, that indicate recent tectonic activity, but that are related to structures elaborated

and maintained in prominence by the lithological resistance or by actions of past and current climatic processes.

In addition to the Brazilian studies previously presented, several authors of international works attest to the validity of the application of morphometric indices in interrelated studies of relief and hydrography. Among them we can mention the works of Jordan (2003), in Hungary; Kaur et al. (2014) and Kulkarni (2015), in India; Furrier and Cuervo (2018), in the region of Cartagena de Indias, Colombia and Ivanov and Yermolaev (2018), in Russia.

It is worth noting that works of a structural and tectonic nature are being developed in Portugal and realizing that the morphology of the relief of several regions of this country is under strong influence of the lithological structure and the tectonic structure. These works are being carried out by geologists and geographers, such as Barbosa (1995), Martins (1999) and Martins et al. (2009) in the Tagus Basin; Dias (2001), for the Algarve region and Teixeira (2006) for the Center-North of the country.

The fieldwork, as well as the previous analysis of satellite images and, mainly, of the topographic map, are essential in the qualitative investigation, since they can reveal morphostructural and morphotectonic performance in the general configuration of the relief and in the morphology of the hydrographic network as sudden inflections, channel straightness, asymmetric and centrifugal or centripetal drainages (Howard, 1967; Lima 2000; Peulvast and Claudino-Sales, 2002; Martinez, 2005; Furrier, 2007).

Leopold and Maddock Jr. (1953) corroborate the importance of applying quantitative analysis when they state that the qualitative approach to geomorphology has really been constructive, but it would be desirable to analyze some of the concepts quantitatively. Hack (1973), in this context, states that drainage networks have regular geometric properties and can also be described quantitatively. In the present study, the indices used for quantitative analysis were: a) Stream Gradient Index (SL), b) Valley Floor Width-Valley Height Ratio (Vf) and c) Asymmetric Factor (AF).

For Etchebehere et al. (2016), the SL can be applied to the entire length of the main river (SL_{total} or SL_t), which allows, for example, a regional assessment of large areas. Another way of using the SL concerns the analysis of drainage segments (SL_{section} or SL_s), which has a more local relationship, applying to the analysis of possible detail tectonic deformation in drainage

segments. These sections can be chosen using morphological parameters of an anomalous section of the channel, such as a sudden inflection, for example. The calculation of SL_t or SLs can be done through the mathematical expressions exposed inside figure 2.

In the formulas presented to obtain the SL_t, Δh is the altimetric difference between two extreme points of a section along the watercourse, In corresponds to the natural logarithm of the total length of the river and L is the distance between the extreme points of the channel considering the sinuosity of the river. The anomalous segments detected in the application of the SL index would be out of this evolutionary balance, being considered knickpoints.

Similarly, for SLs, Δh is the altimetric difference between two points in the channel on which the index is being calculated, Δl is the length in horizontal projection of the highlighted section and L is the total length of the watercourse, upstream the midpoint of the section for which the index is being calculated.

This was the principle applied by Volkov et al. (1967), who studied the Russian platform seeking to detect crustal movements by applying mathematical equations from the parabolas that best fit the longitudinal profiles of the rivers. The anomalous stretches represented curve segments with greater distance, positive or negative, in relation to the longitudinal profile of each watercourse.

Figure 2. Parameters for calculating the Stream Gradient Index (SL)

Note: Points h1 and h2 represent two subsequent altimetric isolines (adapted from Font and Lagarde, 2010).

For Andrade Filho (2010), this index indicates significant changes in the declivity of the river channel, which can be associated with tributary outlets, different resistance to hydraulic erosion of the rocky substrate and/or to tectonic activity. The value of SLs considered anomalous will be that which, divided by SL_t, obtains a value equal to or greater than 2 (Martinez, 2005). There are also two categories of anomalies: 2nd order, with SL values equal to or greater than 2 and less than 10; and 1st order anomalies, with values equal to or greater than 10 (Sebeer; Gornitz, 1983).

According to Bull and McFadden (1977), the Vf ratio indicates whether the water flow is rapidly eroding the valley as a result of some modification of the base level resulting from tectonic activity, or if lateral erosion of the channel slopes is occurring, indicating thus, tectonic stability. El Hamdouni et al. (2008) also state that low Vf values indicate incision processes, which are commonly associated with tectonic uplifts. The following equation shows how to calculate this index (Figure. 3).

Figure 3. Mathematical formula and measurement procedures to obtain the values of the Vf ratio (Bull and McFadden, 1977).

For Bull and McFadden (1977), the element Vf represents the ratio between the width of the bottom and the elevation of the valley. Vfw is the width of the valley floor; Eld is the altimetric difference between the height of the water left divisor and the height of the valley floor of the interfluvial line in the left portion of the valley; Erd corresponds to the elevation in the interflow line of the right portion of the valley; and Esc is the value of the average elevation of the valley floor.

For Silva et al. (2003), in general, the Vf values considered as indicators of uplift and, consequently, of recent tectonic activity, are low (<1.0 - V-shaped valleys), while the values that indicate tectonic stability are higher (> 1.0 - U-

shaped valleys). The authors also affirm that, as the Vf values vary, depending on the size of the watershed, the flow discharge and the type of rock, they must be obtained in places with similar geological characteristics, with the same lithological resistance to the denudational processes.

According to Souza and Rosseti (2011), the AF is primarily based on the measure of asymmetry, defined by the ratio of the areas occupied by the right and left banks of the main river. The Asymmetric Factor is defined by the equation $AF = 100 (R_a/T_a)$. Figure 4 illustrates how a tectonic tipping can affect the symmetry of a watershed.

Figure 4. Drainage response to uplift along a fault line (Mahmood & Gloaguen, 2016).

The expression AF corresponds to the Asymmetric Factor, while Ra is the right sector of the watershed and Ta corresponds to the total area of the drainage basin. According to Ricón and Vegas (2000), the closer to 50 the values of the Asymmetric Factor obtained are, the smaller the possible influence of tectonic activity will be and vice versa. Therefore, a watershed with an AF = 50 would be a perfectly symmetrical watershed.

For Andrades Filho (2010), AF values much above or below 50 indicate, respectively, tipping on the right or left of the hydrographic watershed. This author also points out that watersheds with low asymmetry correspond to values of AF varying between 0 – 7 of AF = 50, which would be a perfectly symmetrical watershed. For medium asymmetry, the values vary between 7 – 15 of the AF = 50, and high asymmetry, where AF register values < or > 15. As an example, if a watershed has an AF = 66, that has a high asymmetry of 16.

To analyze the geomorphology of the study area, a cartographic material was made up, composed substantially of the hypsometric and

slope charts and the Digital Elevation Model (DEM). The thematic maps and the DEM were elaborated from data extracted from the topographic chart Araçaji 1: 25,000, through the values attributed to the contour lines and the quoted points.

The chart was digitized by means of a scanner and the following elements were vectored: contour lines with an equidistance of 10 meters; hydrography; rated points; road network and administrative limits. After digitization, vectorization and the preparation of cartographic materials was performed in the Spring 5.2 software.

It is worth noting that, due to the fact that several drainage channels in the study area, especially first-order channels, do not have their nomenclature presented on the Araçaji chart, numerical values were inserted to identify them. Such a procedure was necessary because it is necessary to mention a lot of these channels for the important roles they play in the configuration of the relief and for presenting, in some cases, significant anomalies in the network and drainage patterns. In

addition, alphanumeric codes have been assigned to these channels to identify them. It is known that such identification is not usual, however, considering the interpretative value of this attribution, it was decided to proceed.

Results and discussions

Qualitative analysis

The highest altitudes of this chart occur at the Residual Level Itapororoca (~ 200 m). It is an oblong structure inclined in the E–W direction and strongly dissected in its W side by the Timbó stream. Such altimetric differentiation may be related to the lithological composition of this unit, formed, by Cretaceous felsic rocks with a high concentration of silica, which would provide greater resistance to erosive processes.

The hydrography verified in this sector is centrifugal, forming extremely tight valleys (Figure 5a). This geological structure is a remnant

of the felsic phenomena of the opening of the Atlantic and, therefore, its lithology is totally different from the adjacent lithology in terms of age and composition. It is noticed in the relief sculpted in this geological structure, altitudes disproportionate to the average local elevation, sudden inflections in the adjacent river channels and very steep slopes that can be seen in the clinical chart with slopes greater than 45% (Figure. 5b).

At Residual Level Itapororoca, the altitude reaches the maximum elevation of the chart (198m), with the minimum elevation of this felsic structure being around 120m. The highest levels of slope (classes 20% to 75%) are also seen in the relief developed over this lithology. Such characteristics put this unit in a prominent position in the topographic configuration and slope of the study area, since the altimetric predominance of the relief of the Araçaji chart area generally presents levels below 120 meters in areas composed of granitic and gneiss rocks of the Precambrian.

Figure 5. a) Altimetric chart of Araçaji; b) Slope chart of Araçaji.

The drainage network of the watershed in the study area, especially those of the Itapororoca and Guandu rivers, presents as the basic drainage pattern, the dendritic, however, in its configuration

various signs of anomalies are observed that sometimes modify this pattern and give origin, for example, in centrifugal, annular, subparallel and sub-dendritic radial patterns, as occurs in the

Tanques stream, west of the Araçaji chart (Figure 6).

In the Guandu River, the basic pattern seen is the dendritic (Figure 6) and the general direction of flow of this river is NW – SE. However, this channel suffers some sudden inflections, assuming N – S directions between the confluence of stream

23 and the Tanques stream and, between the confluence of stream 25 with the mouth of the Guandu River, on the Mamanguape River. Structural formations of drainage patterns are also observed, such as a radial pattern, with annular and subparallel characteristics in the hydrography of the chart area (Figure 6).

Figure 6. Drainage patterns of the Araçaji chart 1: 25,000 with emphasis on the main anomalies presented in its configuration.

Quantitative analyses

Stream Gradient Index (SL)

Stream Gradient index was applied in streams 40, Marmelada, Timbó, 17, Tanques and in stream 33 (Fig.7). The results obtained with the SL, in its entirety, with the exception of segment 1 of stream 17 and segment 2 of stream Tanques, revealed values that correspond to second order anomalies.

In the Marmelada stream channel, which has uniform lithology, the results show that the two

segments analyzed show values that correspond to channels that have a relevant tectonic influence. In segment 1, downstream, the SL_s/SL_t value of 3.75 was obtained; in segment 2, upstream of the channel, this value was lower, at 2.65, which represents a channel segment with less intensity, without large altimetric variations from tectonic movements or differentiated lithological resistance (Table 1).

Figure 7. Channels with segments selected for calculating the Stream Gradient index (SL).

In the Timbó stream (Figure 7), all analyzed segments showed values that correspond to anomalies. In its low course, the value obtained was 3.41. This segment is located on the metamorphic rocks of the São Caetano Complex. The second segment of the Timbó stream presented an intermediate value of SLs/SLt (2.42) and, when analyzing the geological map (Figure 1), it is observed that this segment is eroding two distinct geological units: the São Caetano Complex, in its low course and the Itapororoca Volcanic Felsic unit in its high course. In addition to these characteristics, its direction is completely anomalous to the other courses with sense W.

In the segments studied in stream 17, the existence of two distinct realities in the values of SLs/SLt were verified. In section 1, low course,

which flows over Quaternary sediments deposited by the Mamanguape river (Figure 1), the value obtained was 1.15 (Table 1). This value does not represent evidence of recent tectonic activity in the configuration of the longitudinal profile of the drainage channel. In section 2, the value of SLs obtained was the highest in the Araçaji chart (3.90). Although this sector is eroding two distinct geological units: the São Caetano Complex, upstream, and the alluviums, downstream, the value of SLs presented must be considered adequate, since this stretch is inserted in an area where several anomalies occur, such as channel inflections, dome formation, centrifugal radial drainage pattern and subparallel pattern (Figure 6).

Table 1. Values obtained with the application of the SL index in the studied watershed

Main channel / sections	Upper quote (m)	Inferior quote (m)	Altimetric difference (m)	Total channel length / channel sections (m)	Extension from midpoint to channel upstream (m)	SLs	SLt	SLs/SLt
Marmelada Stream	120.1	90	30.1	2694	-	-	3.76	-
Marmelada (1)	100	90	10	1403	1992	14.1	3.76	3.75
Marmelada (2)	120	100	20	1291	645	9.99	3.76	2.65
Timbó Stream	153.7	75.2	78.5	6238	-	-	8.99	-
Timbó (1)	95	75	20	3060	4708	30.7	8.99	3.41
Timbó (2)	110	95	15	1627	2365	21.8	8.99	2.42
Timbó (3)	153.7	110	43	1551	775	21.4	8.99	2.38
17 Stream	60.2	24.8	35.4	4731	-	-	4.18	-
17 (1)	27.4	24.8	2.6	1997	3733	4.86	4.20	1.15
17 (2)	60.2	27.4	32.8	2734	1367	16.4	4.20	3.90
40 Stream	134.6	77.4	57.2	2646	-	-	7.25	-
40 (1)	90	77.4	12.6	1292	2000	19.5	7.25	2.68
40 (2)	134.6	90	44.6	1353	676	22.8	7.25	3.14
Tanques Stream	110.2	55.1	55.1	4663	-	-	6.20	-
Tanques (1)	70.1	55.1	15	2104	3611	25.7	6.20	4.14
Tanques (2)	104	80.3	23.7	1350	675	11.8	6.20	1.91
Tanques (3)	110.2	70.1	40.1	2558	1279	20.5	6.20	3.23
33 Stream	110.2	40.2	70	5009	-	-	8.22	-
33 (1)	70.1	40.1	30	2618	3700	42.3	8.22	5.14
33 (2)	110.2	70.1	40.1	2391	1195	20.0	8.22	2.43

Note: The values in bold represent the four channels with the most significant anomalies in SLs/SLt.

Valley Floor Width-Valley Height Ratio (Vf)

The Vf ratio was applied in the main channels of the watershed of the streams Marmelada, Timbó, Tanques and stream 30 and in the rivers Guandu, Itapororoca and Araçaji, in addition to a profile applied in a valley where no type of drainage is specified in the Araçaji chart, that was conventionally called in this work the Seco valley (Figure 8).

In the two profiles applied in the Timbó stream valley, profile 1 and profile 2, the lowest values of Vf in the Araçaji chart area were obtained, respectively, 0.56 and 0.36. These Vf values, added to the qualitative characteristics and the results of the SLs index applied in the area of the Itapororoca Volcanic Felsic, reinforce the idea that this geological unit has evidence of recent

tectonic activity. These indices found attest to a strong fluvial notch with accelerated headland retreat, that is, a morphometric result, corroborating with a morphological analysis.

In the channel of stream 30 and Guandu River, Vf values of 0.63 and 0.76 were obtained, respectively. The Vf value obtained in the Itapororoca River channel (0.57) should be interpreted with greater caution, because in the profile applied in this channel, the left and right margins are represented by different lithotypes. However, it is worth noting that the results presented in this location should not be discarded, since they were obtained in an area of the chart where the qualitative analysis and other indices showed evidence of anomalies in the drainage network.

Figure 8. Selected channels with plotted profiles for the calculation of the Valley Floor Width-Valley Height Ratio (Vf).

Table 2. Morphometric variables and values obtained with the application of the Vf ratio in the watershed studied.

Watersheds	Valley bottom width (m)	Elevation of the left divisor (m)	Elevation of the right divisor (m)	Average valley floor elevation	Vf
Marmelada Stream (1)	63,3	116,8	115,0	95,3	3,07
Timbó Stream (1)	50,0	196,4	180,3	100,0	0,56
Timbó Stream (2)	13,0	177,0	180,3	142,7	0,36
Tanques Stream (1)	144,6	108,0	112,1	89,3	6,96
Tanques Stream (2)	47,6	117,5	113,1	100,0	3,11
30 Stream (1)	30,8	91,3	105,1	50,0	0,63
Guandu River (1)	38,0	130,3	129,6	80,3	0,76
Itapororoca River (1)	40,0	186,1	93,1	70,1	0,57
Araçagi River (1)	49,0	79,2	84,3	35,1	1,05
Seco Stream (1)	27,0	70,1	70,1	40,2	0,90

Note: The values in bold represent the four channels with the most significant Vf anomalies.

Asymmetric Factor Index

The Asymmetric Factor index was applied to seven little watersheds of the Seco, Itapororoca and Mamanguape rivers. The little watershed of the streams Marmelada, Timbó, Tanques, Várzea das Cobras, stream 40, stream 29 and stream 17 were chosen to apply the index (Figure 9).

The highest AF values, considered to be high asymmetry, were recorded in the watersheds of the Tanques streams, with values of 70.49, distancing 20.49 from the standard symmetry (50); and the Várzea das Cobras stream, with values of 22.96 and a distance of -27.04 from the symmetric

watershed (50) (Table 3). These values, added to the straight and arcuate forms visualized in the drainage channels and the data obtained through the application of other morphometric indices and

qualitative analysis, reinforce the hypothesis that the asymmetric configuration of these watersheds are the result of the performance of recent tectonic events (Figure 9).

Figure 9. Watersheds selected to apply the AF index.

Looking at figure 9, there is a marked asymmetry of the drainage network with three tributaries on its right margin and no tributary on its left margin, attesting to a considerable tipping.

The AF values obtained are also compatible with the values obtained by El Hamdouni et al. (2008) in southern Spain, a region considered tectonically active.

Table 3. Values obtained with the application of the AF index in the studied.

Watersheds	Right area of the watershed (km ²)	Total area of the watershed (km ²)	AF	AF-50	Anomaly intensity class AF
Mamelada Stream	1,12	2,61	42,91	- 7,09	Medium
Timbó Stream	4,88	9,06	53,86	3,86	Low
Tanques Stream	4,42	6,27	70,49	20,49	High
V. das Cobras Stream	0,93	4,05	22,96	- 27,04	High
40 Stream	0,83	1,89	43,91	- 6,09	Low
29 Stream	1,46	3,79	38,52	- 11,48	Medium
17 Stream	1,68	3,10	54,19	4,19	Low

Note: The values in bold represent the four watersheds with the most significant AF anomalies.

Final considerations

From the results obtained, it was found that the analyzes performed responded satisfactorily to the expectations raised in the introduction of this work. It was found, from the thorough analysis of the hypsometric, slope and DEM charts, that the regions with the greatest evidence of tectonic action on the Araçaji chart 1: 25,000 are located in the Northeast sector, due to the influence of the Itapororoca Volcanic Unit; in the Southwest sector, in the valleys of the Guandu and Araçaji rivers, and in the lower course of the Itapororoca River, in the Southeast sector.

In the qualitative analysis of the patterns and drainage network, it was observed that the drainage patterns of the study area were configured by morphostructural influence. The first refers to the different lithologies in the area that determine fluvial processes of different intensities. The second element refers to the configuration of the relief itself, which is conditioned by lithology and, probably, also linked to the tectonism originated due to the constant separation between South America and the African continent.

This constant spacing causes an adjustment of the crust of the entire area that is attested by the intra-plate earthquakes that occurred in Brazil, mainly on the Atlantic margin. Unfortunately, the correlation between these earthquakes and the configuration of the relief still needs further

investigation and, therefore, this relationship was not addressed in this article.

Regarding the results obtained with the application of the morphometric indices, it can be seen that they were satisfactory, but more applications are needed in other regions of the Atlantic border in order to compare the obtained data. It is worth noting that such indices need adjustments to be applied in regions of passive continental margin, such as the Brazilian eastern border, since they were thought to be applied in areas of active continental margin. However, the fact that the area has presented results of SL, Vf and AF compatible with the performance of recent tectonics, justifies the consideration of these data in the present work.

The results achieved in this work, have as main objective the dissemination of this methodology to other regions of passive continental margin that can open new fields of application and understanding as to the development and evolution of the relief and its relationship with tectonics in areas of continental margin passive. There is no way to refute that the drainage network arrangements and the distinctive morphological and hydrographic features verified in a relatively small area are linked to conspicuous tectonics that cannot be disowned. The performance of the resistance and the lithological arrangement, linked to the characteristics of tectonic adjustment should be used in studies of geomorphological nature in watersheds located in the vicinity of the Atlantic continental margin.

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