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VIKTOR FERREIRA DE OLIVEIRA

NEOTECTÔNICA DA BACIA DO ARARIPE PRÓXIMO A ZONA DE CISALHAMENTO PATOS E NO VALE DO ARARIPE: INSIGHTS A PARTIR DA GEOMORFOMETRIA

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Tese de doutorado apresentada ao Programa de Pós-Graduação em Geologia da Universidade Federal do Ceará, como requisito para a obtenção do Título de Doutor em Geologia. Área de concentração: Geodinâmica e Recursos Minerais.

Orientador: Prof. Dr. Wellington Ferreira da Silva Filho

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BANCA EXAMINADORA

Prof. Dr. Wellington Ferreira da Silva Filho (Orientador)
Universidade Federal do Ceará (UFC)

Prof. Dr. Christiano Magini
Universidade Federal do Ceará (UFC)

Prof. Dr. Sebastián González Chiozza
Universidade Federal do Ceará (UFC)

Prof. Dr. Sérgio Wilians de Oliveira Rodrigues
Universidade Federal de Goiás (UFG)

Dr. Luís Carlos Bastos Freitas
Serviço Geológico do Brasil (SGB/CPRM)

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“Nossa maior fraqueza está em desistir. O caminho mais certo de vencer é tentar mais uma”

Thomas Edison

RESUMO

Este estudo examina a atividade tectônica no segmento norte da Bacia do Araripe, localizada no sul do estado do Ceará, Nordeste do Brasil, próximo à zona de cisalhamento Patos, utilizando índices morfométricos derivados de imagens SRTM. A pesquisa integra diversos parâmetros morfométricos, incluindo os índices de Relação Declividade-Extensão (SL), Fator de Assimetria (AF), Sinuosidade de Frente de Montanha (SMF) e Integral Hipsométrica (HI), para formular uma Categoria de Intensidade Tectônica (CIT), que é posteriormente transformada no Índice de Atividade Tectônica Relativa (IAT), o qual indica o grau de influência da atividade tectônica em uma determinada área. Essa abordagem permite uma avaliação abrangente dos processos tectônicos e da evolução da paisagem. Os resultados indicam que 26,75% da região estudada apresentam um valor alto de IAT, enquanto 3,34% são categorizados como muito altos. A maior parte da área, abrangendo 59,93%, apresenta atividade tectônica moderada. Por meio de uma análise combinada desses índices e de avaliações morfológicas, que destacam o impacto de *horsts* e *grabens* no relevo, o estudo identifica as áreas mais influenciadas pela atividade tectônica na modelagem da paisagem.

Palavras-Chave*:* Bacia do Araripe; índices morfometricos; neotectônica; zona de cisalhamento Patos.

ABSTRACT

This study examines the tectonic activity in the northern segment of the Araripe Basin, located in southern Ceará state, NE Brazil, near the Patos shear zone, using morphometric indexes derived from SRTM imagery. The research integrates various morphometric parameters, including the Stream Length Gradient (SL), Asymmetry Factor (AF), Mountain-front Sinuosity (SMF), and Hypsometric Integral (HI), to develop a Composite Index of Tectonic Activity (CIT), which is further refined into the Relative Tectonic Activity Index (IAT), which indicates the degree of influence of tectonic activity on a given area. This approach facilitates a comprehensive assessment of tectonic processes and landscape evolution. The findings indicate that 26.75% of the studied region demonstrates a high IAT value, while 3.34% is categorized as very high. The majority of the area, encompassing 59.93%, shows moderate tectonic activity. Through a combined analysis of these indexes and morphological analyses, which highlight the impact of *horst*s and *graben*s on the terrain, the study identifies areas most influenced by tectonic activity in shaping the landscape.

Keywords: Araripe Basin; morphometric indexes; neotectonics; Patos shear zone.

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1 INTRODUÇÃO

1.1 Apresentação

Trabalhos em que os dados são obtidos de forma remota, seja por meio de satélites, drones ou outros equipamentos, estão sendo cada vez mais difundidos no mundo das geociências. A aplicação do sensoriamento remoto permite obter informações de caráter regional, e até mesmo fazer determinadas análises localizadas. Portanto, o presente trabalho usa modelos digitais de elevação (MDE) para coletar dados de relevo, gerados a partir de morfometria (Pike, 2000) e extrair informações que possam ser interpretadas à luz da neotectônica local e regional da Zona Transversal da Província Borborema.

Usando dados SRTM (Shuttle Radar Topography Mission), pertencentes a USGS (United States Geological Survey), com resolução espacial de 30m, foi possível aplicar técnicas definidas por Hamdouni *et al.* (2008) e modificadas por Oliveira et. al (2018) para indicar áreas que têm maior chance de ter ocorrido alguma influência neotectônica.

O presente trabalho foi elaborado na forma de artigo, que foi submetido ao *Journal of South American Earth Sciences*, disponível em: https://doi.org/10.1016/j.jsames.2024.105333.

1.2 Objetivo

O principal objetivo deste trabalho foi dar continuidade às pesquisas de Oliveira *et al.* (2018), onde buscou-se analisar a morfologia da área de estudo (Figura 1), ampliada em relação aos estudos prévios, para determinar setores com valores de índices morfométricos que podem indicar maior probabilidade de influência tectônica recente.

Para obter o resultado principal, fez-se necessário atingir objetivos específicos, a saber: gerar mapas de elevação e drenagem; analisar a relação declividade-extensão (SL); analisar o fator de assimetria (AF); analisar a sinuosidade de frente de montanha (SMF); analisar a integral hipsométrica (HI) e compilar as análises prévias para obtenção de um índice de atividade tectônica (IAT).

Com base nisso, o artigo objetivou identificar áreas propícias à atividade neotectônica na parte norte e leste da Bacia do Araripe. Esse artigo gerou dados para um segundo artigo que analisará a morfoestrutural da região a partir de análises de lineamentos e drenagens ali presentes.

1.3 Localização da área de estudo

A área de estudo está localizada no extremo-sul do estado do Ceará, Brasil, a aproximadamente 500 Km de distância da capital Fortaleza e engloba as partes norte e leste da Bacia do Araripe (Figura 1). A Bacia do Araripe possui aproximadamente 9000 Km² de área e 190 Km de extensão leste-oeste (Peulvast & Bétard, 2014),

2 CONTEXTO GEOLÓGICO

2.1 Embasamento Cristalino

O embasamento cristalino localizado na região norte da área de estudo tem idades pré-silurianas. Essas unidades são: ortognaisses do Complexo Granjeiro, Complexo Arábia, Complexo Piancó, Complexo Caicó, Fm. Independência, Grupo Cachoeirinha e Suíte Intrusiva Itaporanga.

As rochas mais antigas são os ortognaisses tonalito-granodioríticos, localmente trondhjemíticos, que apresentam grandes lentes de rochas metamórficas (metacalcários, metacalcissilicáticas e metaultramáficas) e formações ferríferas relacionadas ao Complexo Granjeiro, que datam do paleo-neoarqueano (Pineo *et al.*, 2020).

O Complexo Arábia é composto por ortomigmatitos e ortognaisses de composição granítica a granodiorítica, com níveis anfibolíticos e de formações ferríferas. Também apresenta rochas metassedimentares formadas por xistos granatíferos, quartzitos, metacherts, mármores, rochas calcissilicáticas e formações ferríferas bandadas. As rochas metamórficas e metaultramáficas são representadas por anfibolitos, hornblenditos, tremolititos e talcoxistos (Pineo *et al.*, 2020).

O Complexo Piancó é composto predominantemente por ortognaisses migmatíticos de composição granodiorítica a tonalítica, micaxistos, mármores e rochas calcissilicáticas (Pineo *et al.*, 2020).

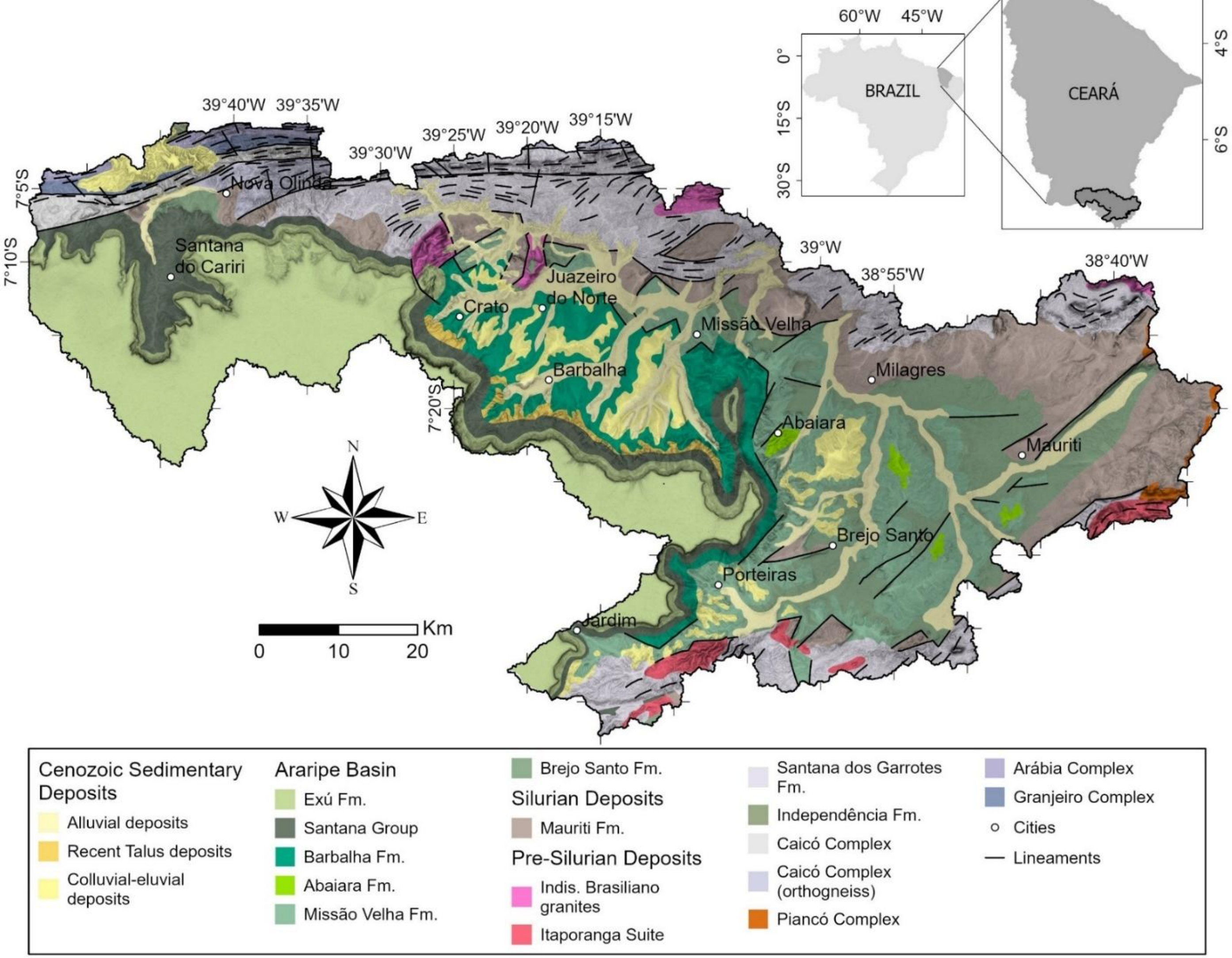
O Complexo Caicó é composto por ortognaisses migmatíticos de composição monzogranítica a granodiorítica, migmatitos e paragnaisses com lentes de anfibolitos e de mármores. A unidade ortognaisse apresenta ortognaisses de composição granítica, granodiorítica e tonalítica, além de migmatitos ortoderivados (Pineo *et al.*, 2020).

A Formação Independência tem predomínio de xistos aluminosos e paragnaisses, por vezes milonitizados e migmatíticos. Ocorrem ainda quartzitos, rochas calcissilicáticas e mármores, anfibolitos e rochas metavulcânicas félsicas (Pineo *et al.*, 2020).

O Grupo Cachoeirinha, de idade criogeniana, tem em sua parte inferior a Formação Santana dos Garrotes (Silva Filho, 1984), uma sequência de metarritmitos e metapsamitos, incluindo metagrauvacas de baixo grau metamórfico. Apresenta biotita xistos de granulação fina, laminados e de cor cinza. Ocorrem níveis de metarenitos granoblásticos finos cinza-claros.

A Suíte Intrusiva Itaporanga, datada do neoproterozóico, é composta de granitos, granodioritos e quartzo-monzonitos porfiríticos com fenocristais leucocráticos de até 5cm de comprimento. Existe uma rara ocorrência de textura granoblástica grossa. Estão presentes, cortando os afloramentos, diques graníticos finos leucocráticos da suíte intrusiva Dona Inês (Pineo *et al.*, 2020).

Figura 1 – Mapa geológico modificado de Pineo *et al.* (2020).



Fonte: Elaborada pelo autor.

2.2 Bacia do Araripe

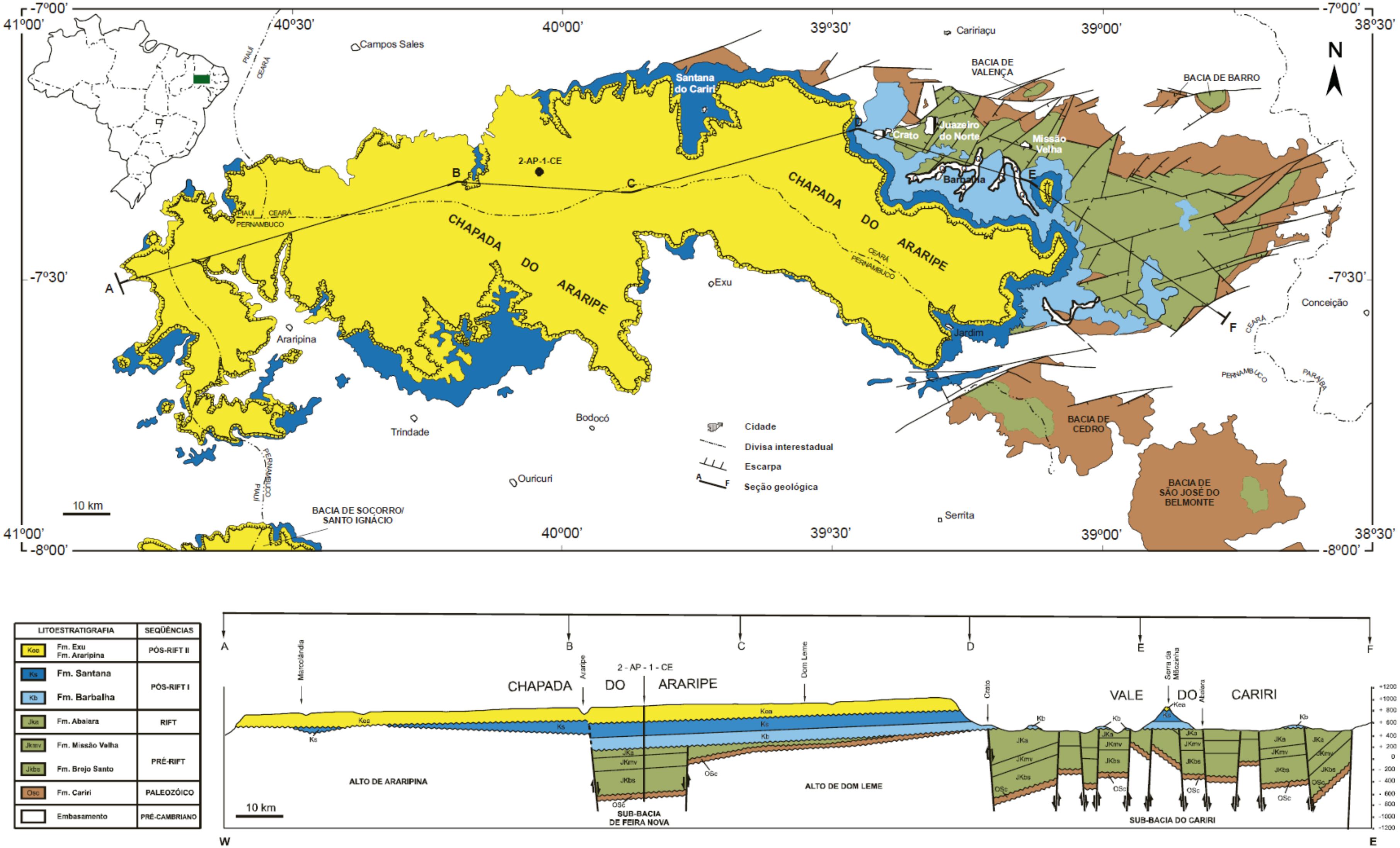
A bacia sedimentar do Araripe (Figura 2) tem preenchimento predominantemente mesozoico e está localizada no sul do estado do Ceará, com partes englobando os estados do Pernambuco e Piauí. Dentre as bacias interiores do nordeste brasileiro, ela é a mais extensa, ocupando uma área de 9000km² (Peulvast & Bétard, 2014). Foi originada na reativação Wealdeniana (Almeida, 1967), quando o paleocontinente Gondwana se fragmentou e formou os riftes mesozóicos do nordeste brasileiro (Ponte & Ponte Filho, 1996).

A bacia é dividida em cinco sequências tectono-sedimentares, (Assine, 2007), limitadas por discordâncias de caráter regional ou por lacunas definidas por meio de bioestratigrafia (Figuras 3 e Figura 4):

- Sequência tectônica Beta - Representada pela Formação Cariri, com idade neo-ordoviciana a siluriana;
- Sequência tectônica pré-rifte - Representada pelas formações Brejo Santo e Missão Velha, com idade neojurássica a eocretácica. Esse pacote encontra-se sobre uma discordância pré-mesozóica.
- Sequência tectônica rifte – Composta pela Formação Abaiara, de idade eocretácea (neocomiana). Tem um contato inferior marcado pelo hiato definido por bioestratigrafia. O topo desta formação é truncado por uma superfície erosional, conhecida como discordância pré-aptiana.
- Sequência tectônica pós-rifte I e II – É o último ciclo sedimentar, o qual foi iniciado depois do período de erosão e não deposição. É representado pelas Formações Barbalha, Santana, Araripina e Exu, com idades de deposição variando do Aptiano até o Cenomaniano.

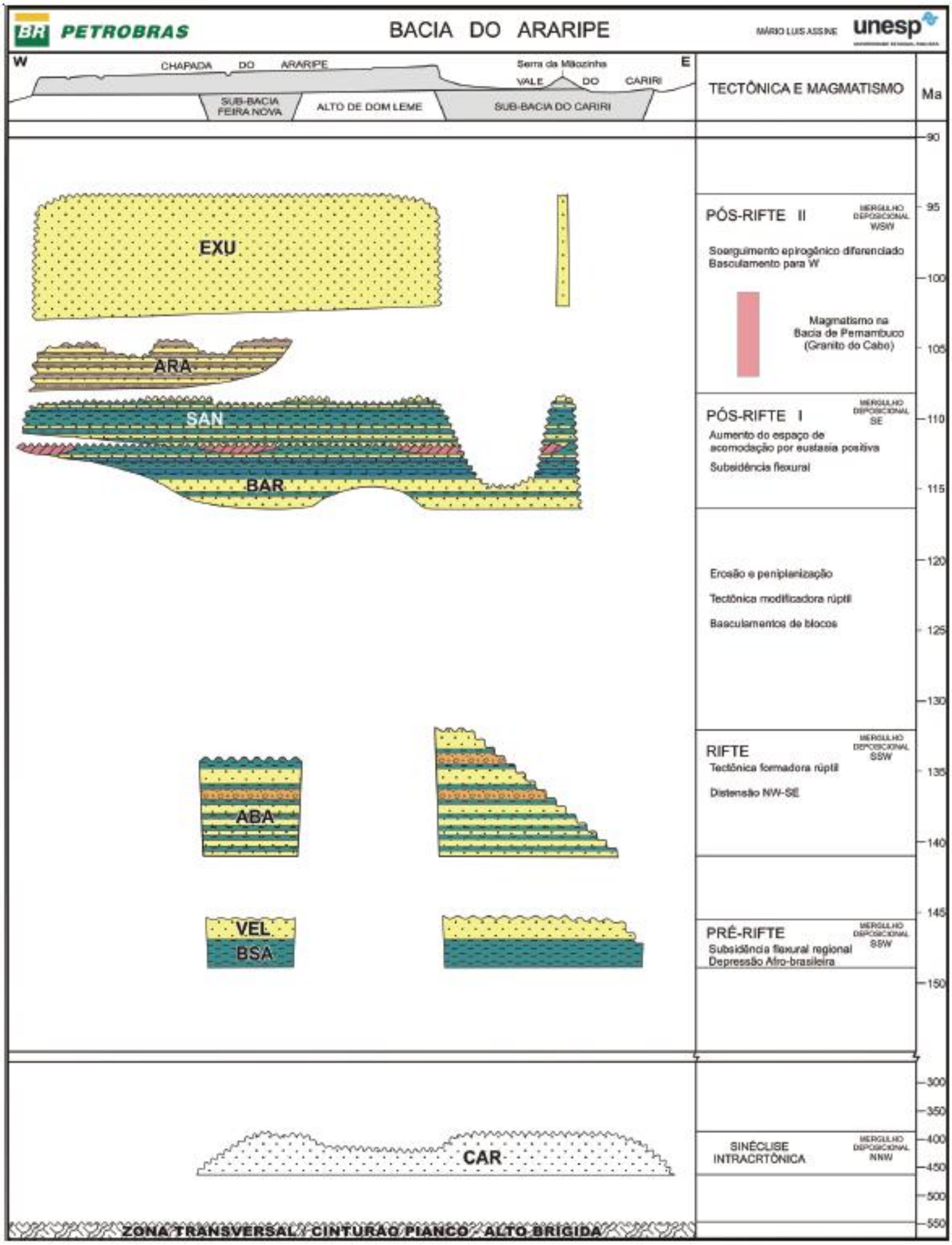
A forma em que as camadas estão dispostas reflete diretamente a formação da bacia. Na parte inferior tem-se uma zona de rifte encravada no embasamento e na parte superior uma cobertura tabular, sub-horizontal que encobre em discordância as porções da sequência rifte. A feição geomorfológica de maior expressão é a Chapada do Araripe, que forma uma extensa "mesa" constituída por rochas sedimentares da Formação Exu (Assine, 1990).

Figura 2 - Mapa geológico da Bacia do Araripe



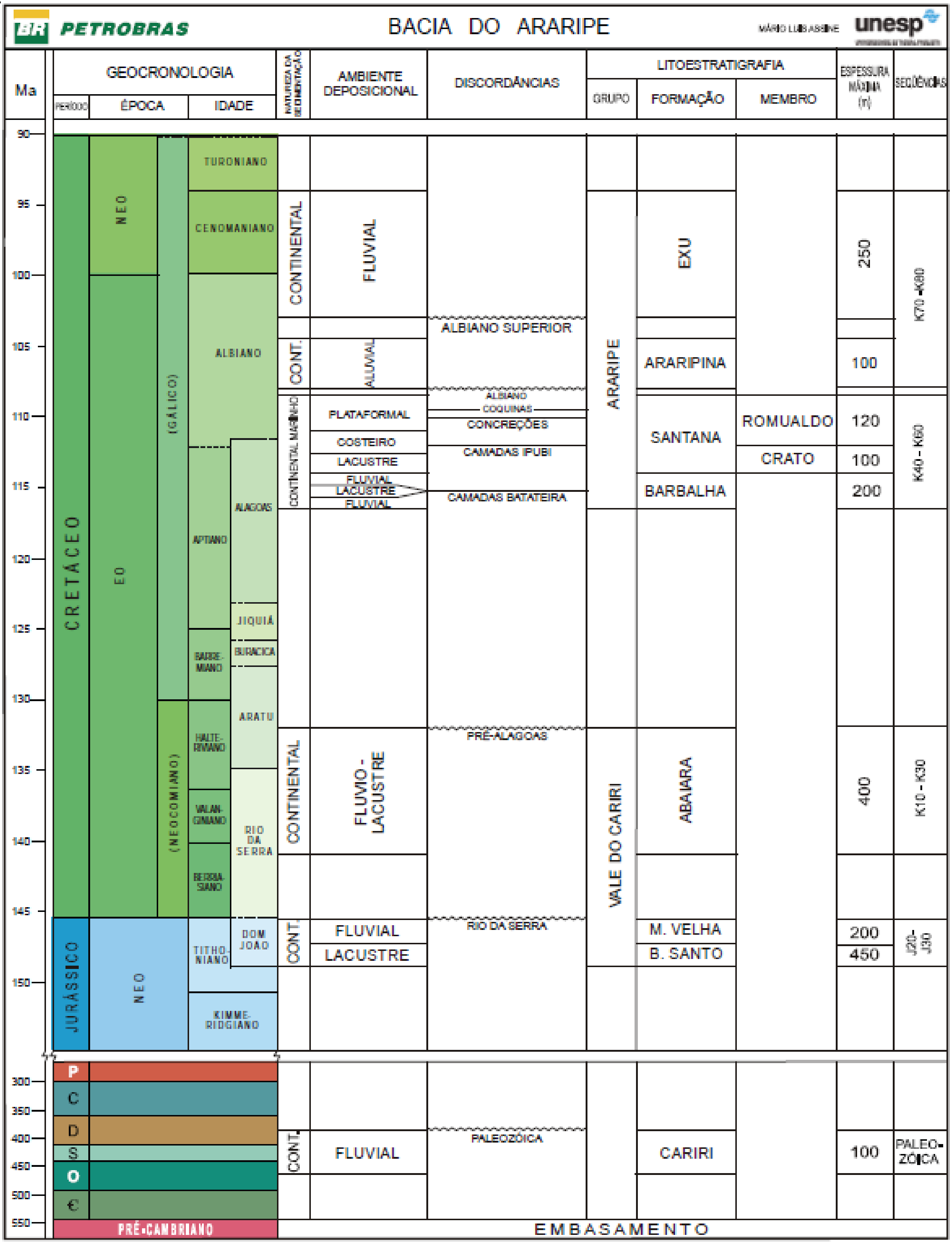
Fonte: Assine (2007).

Figura 3 – Carta cronoestratigráfica da Bacia do Araripe



Fonte: Assine (2007)

Figura 4 – Síntese litoestratigráfica da Bacia do Araripe



Fonte: Assine (2007)

3 NEOTECTONICS OF ARARIPE BASIN NEAR PATOS SHEAR ZONE AND ARARIPE VALLEY: INSIGHTS FROM GEOMORPHOMETRY

AUTHORS

Viktor Ferreira de Oliveira [a] – viktorferreira@gmail.com

Wellington Ferreira da Silva Filho [a] – welfer@ufc.br

[a] Departamento de Geologia, Universidade Federal do Ceará

ABSTRACT

This study examines the tectonic activity in the northern segment of the Araripe Basin, located in southern Ceará state, NE Brazil, near the Patos shear zone, using morphometric indexes derived from SRTM imagery. The research integrates various morphometric parameters, including the Stream Length Gradient (SL), Asymmetry Factor (AF), Mountain-front Sinuosity (SMF), and Hypsometric Integral (HI), to develop a Composite Index of Tectonic Activity (CIT), which is further refined into the Relative Tectonic Activity Index (IAT), which indicates the degree of influence of tectonic activity on a given area. This approach facilitates a comprehensive assessment of tectonic processes and landscape evolution. The findings indicate that 26.75% of the studied region demonstrates a high IAT value, while 3.34% is categorized as very high. The majority of the area, encompassing 59.93%, shows medium tectonic activity. Through a combined analysis of these indexes and morphological assessments, which highlight the impact of *horst*s and *graben*s on the terrain, the study identifies areas most influenced by tectonic activity in shaping the landscape.

KEYWORDS

Araripe Basin; morphometric indexes; neotectonics; Patos shear zone.

INTRODUCTION

The application of remote sensing in regional tectonic studies is being increasingly utilized worldwide to assess sedimentary basins (Oliveira *et al.*, 2018; Mukul *et al.*, 2016; El Hamdouni *et al.*, 2008; Mahmood & Gloaguen, 2011).

The Araripe Basin, located in the southern part of the state of Ceará, northeastern Brazil (Fig. 1), is recognized as one of the most significant paleontological sites globally and supports an important regional economy driven by mining and tourism. This study aims to analyze the northern segment of the Araripe Basin, in proximity to the Patos shear zone (PSZ), to identify potential areas of neotectonic activity by using morphometric indices derived from SRTM images.

Four indices were applied in this analysis: stream length-gradient (SL), asymmetry factor (AF), mountain-front sinuosity (MFS), and hypsometric integral (HI). These indices were combined to generate the final relative tectonic activity index (IAT).

GEOLOGICAL AND GEOMORPHOLOGICAL CONTEX

The Araripe Basin, spanning approximately 9000 km², stretches about 190 km from east to west (Peulvast & Bétard, 2014 and Claudino Sales *et al.*, 2024) (Fig. 1). To the north, its basement exhibits outcrops characterized by Precambrian/Cambrian rocks. Prominent among these are the Santana dos Garrotes Formation, which includes rocks of a low metamorphic grade; granites of Serra do Deserto Formation; tonalite-granodiorite orthogneiss of the Granjeiro Complex; and a co-ocurrence of gneisses, calcisilicatic rocks, feldspathic mica-schist, and quartzites from the Farias Brito Formation. Cenozoic sedimentary deposits are also noteworthy in this region (Pineo *et al.*, 2020).

The Araripe Basin is divided into five distinct tectonic sequences (Assine, 2007). The Paleozoic Sequence, represented by the Cariri Formation, stands out as the oldest tectonic unit in the region. Composed of Paleozoic sandstones, this sequence is distinct from the Mesozoic sedimentary fill of the basin. Based on lithological correlations with other siliciclastic units, the Cariri Formation is inferred to have a Silurian age. This formation provides insights into the geological evolution of the Araripe Basin, shedding light on the tectonic events and sedimentary processes that shaped the region during the Paleozoic era.

The pre-rift Supersequence, dating to the Late Jurassic, marks a significant phase in the basin's geological development. This supersequence includes formations such as the Brejo Santo and Missão Velha Formations, each with distinct lithological characteristics. The Brejo Santo Formation is characterized by reddish mudstones, while the Missão Velha Formation comprises upper quartz to subarkosic sandstones containing silicified wood (Barreto Jr. *et al.*, 2021). The contact between the Paleozoic sequence and the pre-rift Supersequence is defined by a major angular unconformity, indicating a period of tectonic activity and sedimentary hiatus.

The rift Supersequence, beginning in the Neocomian period, signals the start of the rift stage. It includes the Abaiara Formation, characterized by silty shales and red siltstones, with significant lateral and vertical facies variations, clearly distinguishing it from pre-rift strata. The basal contact with the Missão Velha Formation is discordant due to the absence of ostracods from the *Theriosynoecum varietuberatum varietuberatum* Zone (Coimbra *et al.*, 2002).

The post-rift phase, extending from the Aptian to the Cenomanian, is the terminal sequence and includes the Barbalha Formation and the Santana Group (Crato, Ipubi, and Romualdo Formations), which Assine *et al.* (2014) divided into post-rift I, along with the Araripina and Exú Formations classified as post-rift II.

The Barbalha Formation, consisting of siliciclastic deposits, reflects fluvial sedimentation during the mid-Cretaceous period and is composed of fine to medium-grained sandstones interbedded with reddish shales and thin conglomerate layers (Brito & Silva Filho, 2021). The formation exhibits retrogradational stacking patterns, suggesting a transition to lacustrine conditions and the development of an extensive lacustrine system with anoxic environments.

The Santana Group includes the Crato, Ipubi, and Romualdo Formations. The Crato Formation is predominantly composed of laminated limestones and siliciclastic facies, indicative of lacustrine and coastal deposition. This unit represents a highstand system tract with alternating beds of carbonate and fine-grained rocks, transitioning into dark/greenish-gray shales and laminated limestones typical of transgressive systems. The Ipubi Formation is noted for its evaporites, specifically gypsum and anhydrite, indicative of extreme arid conditions. These evaporitic facies suggest a period of reduced water availability and arid climatic conditions within the basin. The Romualdo Formation features coastal sandstones at its base, transitioning to conglomerates and gravelly sandstones towards the basin margins. This unit displays a transgressive stacking pattern, with coastal onlap from southeast to northwest, signaling a shift towards marine environments. Thin shell beds and bioclastic limestones overlie fossiliferous marine shales, with regressive sandstones marking a return to continental conditions in tidally influenced highstand coastal systems.

The Araripina Formation, initially referred to as the Arajara Formation by Ponte and Appi (1990), had its designation reconsidered due to the absence of a well-defined type locality and the lack of stratigraphic correlation between exposures in Ceará (Arajara City) and those in Pernambuco (Araripina City). Assine (2007) formalized the term Araripina Formation, recognizing it as a distinct, mappable unit with its best exposures occurring in the western portion of the Araripe Basin, particularly around the escarpments near the city of Araripina in Pernambuco (Fambrini *et al.*, 2020). Primarily composed of Albian fluvial facies, the formation reflects continuous fluvial sedimentation during the later stages of the Cretaceous period, indicating a persistent continental influence within the basin. It is characterized by sandstones, mudstones, and conglomerates, which suggest deposition in fluvial environments with occasional coarse-grained sediments, marking a phase of stable sedimentation and environmental progression (Assine *et al.*, 2014). Although the Araripina Formation is present in the Araripe Basin, it does not occur in the study area.

The Exú Formation, dominated by Albian-Cenomanian fluvial facies, represents sedimentation in fluvial settings during the mid-Cretaceous period and signifies a shift back to continental conditions following earlier marine phases. It is characterized by sandstones, siltstones, and conglomerates, reflecting a mix of coarse and fine-grained sediment deposition (Assine *et al.*, 2014).

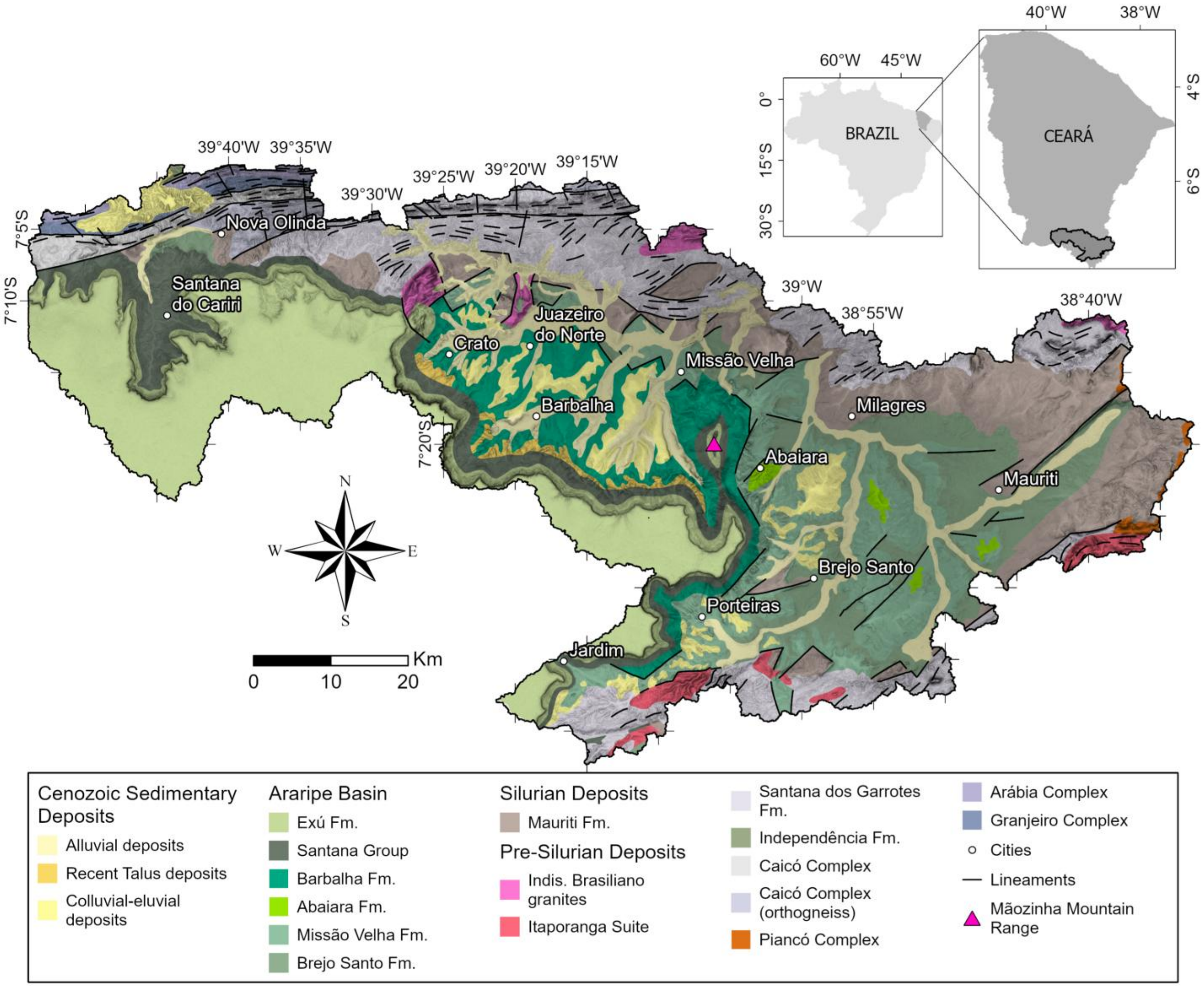
In terms of geomorphology, the study area includes the significant Crajubar region (Crato-Juazeiro-Barbalha), noted for its diverse geomorphological features shaped by natural processes. Situated at the edge of the plateau (Fig. 1 and Fig. 2), the region displays cuesta-like scarps overlooking the Cariri depression, illustrating the effects of tectonic forces, erosion, and sedimentation over time. The presence of humid massifs rising from the semi-arid plains of northeastern Brazil contributes to the region's complexity, showcasing the interplay between climate and geology. These features—including escarpments, depressions, valleys, and hills—highlight the intricate geomorphic evolution of the Crajubar area, emphasizing the combined influence of environmental factors in shaping the terrain (Peulvast *et al.*, 2011).

The Araripe Plateau adds to this geomorphological diversity through its distinct topographic and sedimentary characteristics. With an average altitude of approximately 900 meters, the plateau's summit, underlain by the Exu Formation sandstones, is marked by its flat relief and the absence of surface runoff, a result of the porosity and horizontal disposition of the rocks. Surrounding depressions, however, exhibit regressive erosive processes and evidence of fluvial incisions and gravitational mass movements, reflecting the dynamic interplay between uplift and erosion (Claudino-Sales *et al.*, 2024).

The slight eastward tilt of sedimentary layers in the plateau facilitates the emergence of springs and small watercourses along its periphery. This is especially prominent on the northern escarpments, where humid microclimates sustain perennial vegetation. These features underscore the plateau's role in water distribution, contributing significantly to the hydrological balance of adjacent regions, including the Salgado River Basin (Claudino-Sales *et al.*, 2024).

The Mãozinha Mountain Range (Fig. 2) stands out in the region as an important geomorphological divide. It extends approximately 9 km in the N-W direction and 6 km in the E-W direction, with a maximum elevation of around 915 m. It is situated between the cities of Missão Velha and Abaiara. According to Bétard *et al.* (2017), the Mãozinha Mountain Range is classified as an outlier, an area of younger rock surrounded by older rocks. Such formations typically result from the erosion of surrounding rocks, severing the younger rock's original continuity with a nearby larger mass of similar younger rocks. The drainage patterns in the Mãozinha Mountain Range include a sharp ridge with a radial arrangement and downslope areas with sub-radial and sub-annular geometries. Additionally, the existence of this mountain range as a residual hill appears to be associated with a linear NNW-SSE feature that originates from the plateau's summit, shifting to a N-S orientation, thereby isolating the distinct elevation from the surrounding slopes.

Fig. 1 - Geological map over Digital Elevation Model with location reference. Modified from Pineo et. al (2020).



MATERIALS AND METHODS

This study utilized SRTM-30m images sourced from the USGS Earth Explorer. These images met specific quality criteria: (a) vertical accuracy of 16 meters (Rabus *et al.*, 2003), (b) sparse and low-density vegetation cover, which enhances the quality of the DEM (Andrades Filho & Rossetti, 2015), and (c) mappable features at a minimum scale of 1:100,000, following standards set by Andrades Filho & Rossetti (2015) and Oliveira & Paradella (2008). Adherence to these criteria ensures the suitability of the images for various geospatial applications, particularly for the semi-arid region of northeastern Brazil.

Morphometric indexes were employed to detect anomalies in drainage networks, mountain fronts, and basin surfaces. Four specific indexes were used to indicate the level of tectonic activity, arising from local elevation changes, subsidence, or block tilting in sub-basins. The chosen indexes measure properties of mountain fronts and drainage systems: Stream Length-Gradient (SL), Asymmetry Factor (AF), Mountain-front Sinuosity (SMF), and Hypsometric Integral (HI). These indexes were amalgamated into a Tectonic Index Class (CIT) to derive the Relative Tectonic Activity Index (IAT). This methodology follows the approach proposed by El Hamdouni *et al.* (2008) and refined by Andrades Filho & Rossetti (2015) and Oliveira *et al.* (2018).

The Stream Length-Gradient index was introduced by Hack (1973) following studies on rock resistance to fluvial erosion in the Appalachian Mountains, southeastern United States. This index reflects the equilibrium between a drainage bed's erosion capacity and its sediment transport load, commonly referred to as stream power. It is highly sensitive to variations in channel gradient (Keller & Pinter, 1996) and depends on factors such as eustasy, large tributary confluences, litho-structural substrate heterogeneities, and neotectonic vertical movements (Acklas Jr. *et al.*, 2003). High SL values signify tectonic activity, while low values suggest stable zones or drainages influenced by transcurrent shear zones (Keller & Pinter, 2002). The index is calculated as $SL = (\Delta h/\Delta l)l$, where Δh and Δl represent height and length variations, respectively, and l is the distance from the drainage's starting point to the middle of the segment being measured.

The outcome is categorized into three categories based on Andrades Filho & Rossetti (2015) and Oliveira *et al.* (2018):

- SL < 2 (non-anomalous, Category 1)
- 2 ≤ SL < 10 (anomalous, Category 2)
- 10 ≤ SL (anomalous, Category 3)

The Asymmetry Factor (AF) is an index for determining the tilt of a basin perpendicular to its main river, as described by Keller & Pinter (1996). It's computed using the formula AF = 100(Ar/At), where Ar represents the area right of the main downstream drainage, and At denotes the basin's total area. A symmetrical basin yields an AF value of 50. Values exceeding 50 indicate a rightward tilt, while lower values indicate a leftward tilt. For simplification, the absolute difference from 50 (|AF-50|) is considered. The corresponding values for the Tectonic Intensity Classes (CIT) are: CIT=3 for 0 < |AF-50| ≤ 7; CIT=2 for 7 < |AF-50| ≤ 15; and CIT=1 for |AF-50| > 15 (Oliveira *et al.*, 2018).

Mountain-front sinuosity reflects the balance between erosive and tectonic processes shaping mountain fronts. High sinuosity indicates erosion-dominated fronts, while tectonically influenced fronts, often aligned with faults, appear more linear (Bull & McFadden, 1977; Keller & Pinter, 1996). Bull & McFadden (1977) proposed the formula Smf = Lmf/Ls, where Lmf is the mountain-front length, measured along a slope line between 20° and 30° (Oliveira *et al.*, 2018) and Ls is the straight-line distance for the same segment. Values of 1 to 1.1 indicate tectonic influence (CIT=1), 1.1 to 1.5 suggest moderate activity (CIT=2), and values > 1.5 indicate low tectonic activity (CIT=3).

The Hypsometric Integral (HI) represents the elevation distribution of a basin, visualized as a cumulative frequency curve of altitudes (Strahler, 1952). This curve provides insights into the proportion of the basin that remains uneroded. The HI is calculated using multiple elevation data points, with a minimum of 50 for accuracy. It is determined by $HI = (h_{avg} - h_{min}) / (h_{max} - h_{min})$, where h represents minimum, average, and maximum heights. The curve's shape correlates with HI values:

- HI values ≤ 0.4 – These indicate concave curves, which are associated with significant erosion and minimal recent tectonic activity (CIT = 3) (Keller & Pinter, 2002).

- HI values between 0.4 and 0.5 – These values suggest curves transitioning from concave to convex, implying moderate tectonic influence (CIT = 2).
- HI values > 0.5 – These are indicative of recent tectonic activity due to relatively recent uplift events that expose new surfaces for erosion. This results in convex curves (CIT = 1) (El Hamdouni *et al.*, 2008).

The assessment of regions with varying degrees of tectonic activity influence can also be performed through a quantitative combination of these individual morphometric indices. The Relative Tectonic Activity Index (IAT) is derived from the average cumulative value of the Tectonic Intensity Classes (CIT) across all four indexes. The formula for this is $Sn = \frac{\sum_{i=0}^{n} \ cit}{n}$. Table 1 details the correlation between Sn value and IAT, providing insight into the scale of relative tectonic activity across the study area (Oliveira *et al.*, 2018).

Table 1 - Correlation of IAT classes with tectonic activity.

IAT	Sn Range	Tectonic Activity
1	1 ≤ Sn < 1,5	Very High
2	1,5 ≤ Sn < 2	High
3	2 ≤ Sn < 2,5	Medium
4	2,5 ≤ Sn	Low

Fig. 2 - Hydrographic map with main rivers and simplified geology using Digital Elevation Model.

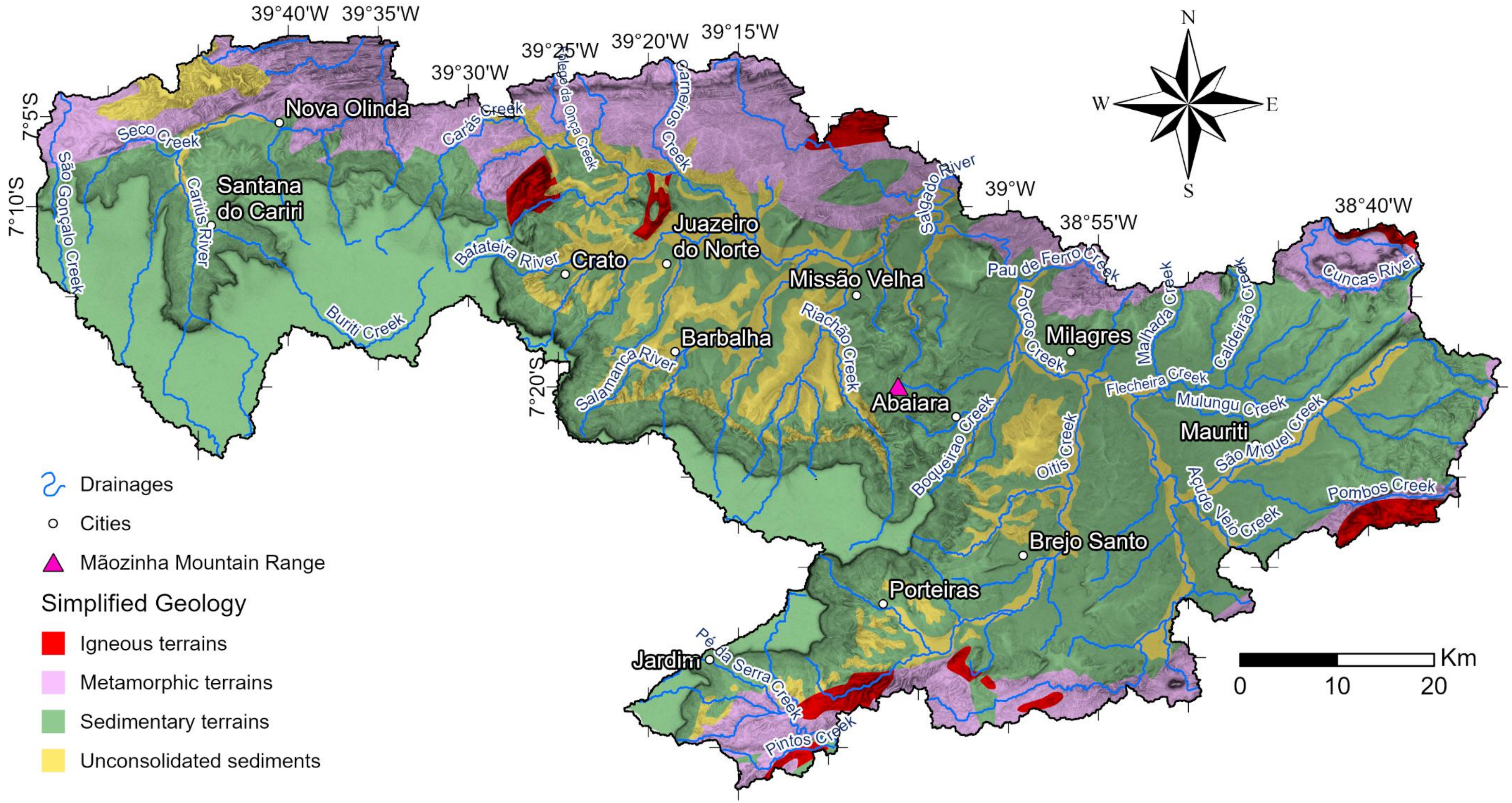
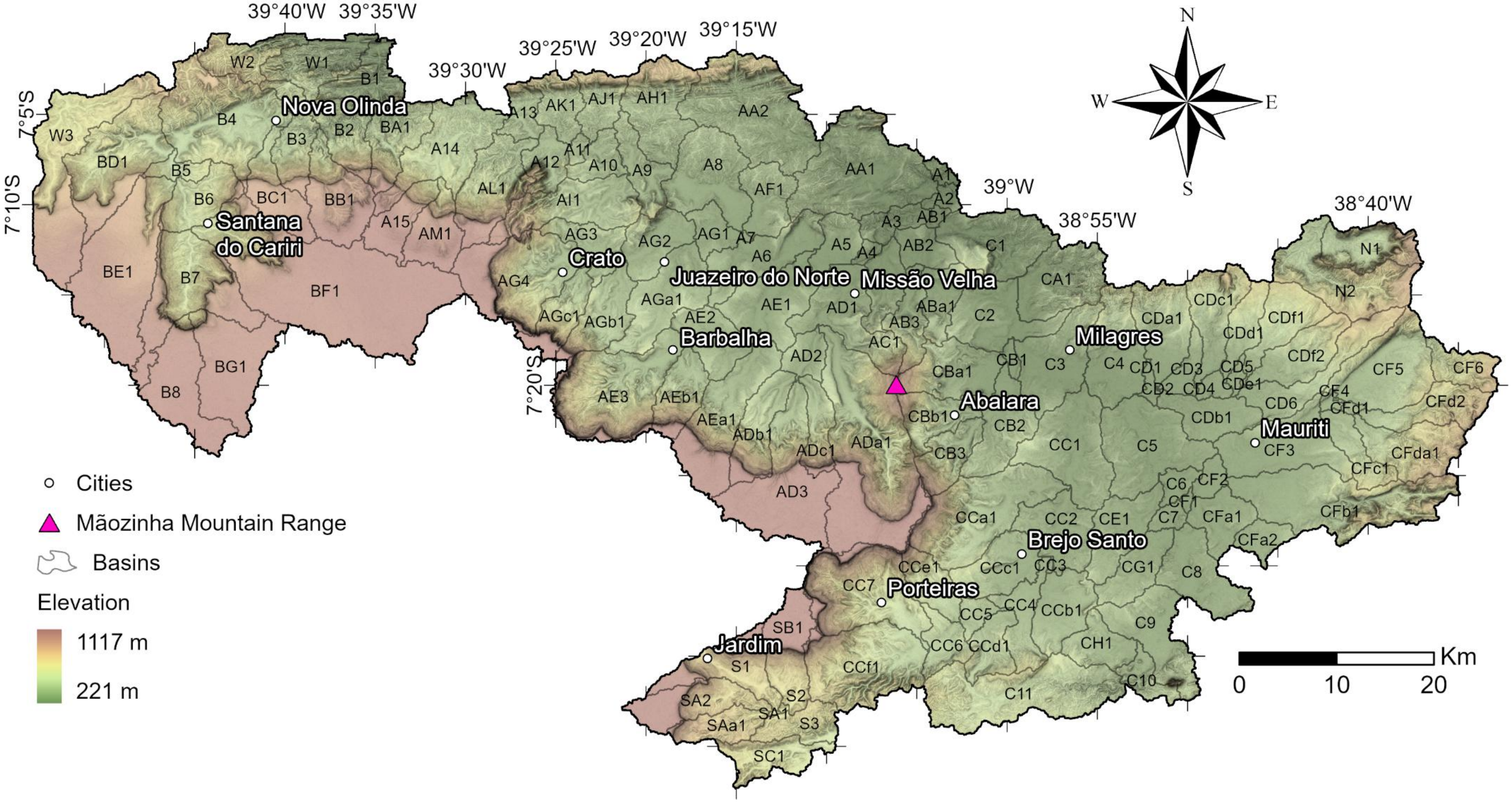


Fig. 3 - Elevation map showing the division of sub-basins.



RESULTS

Morphometric Indexes

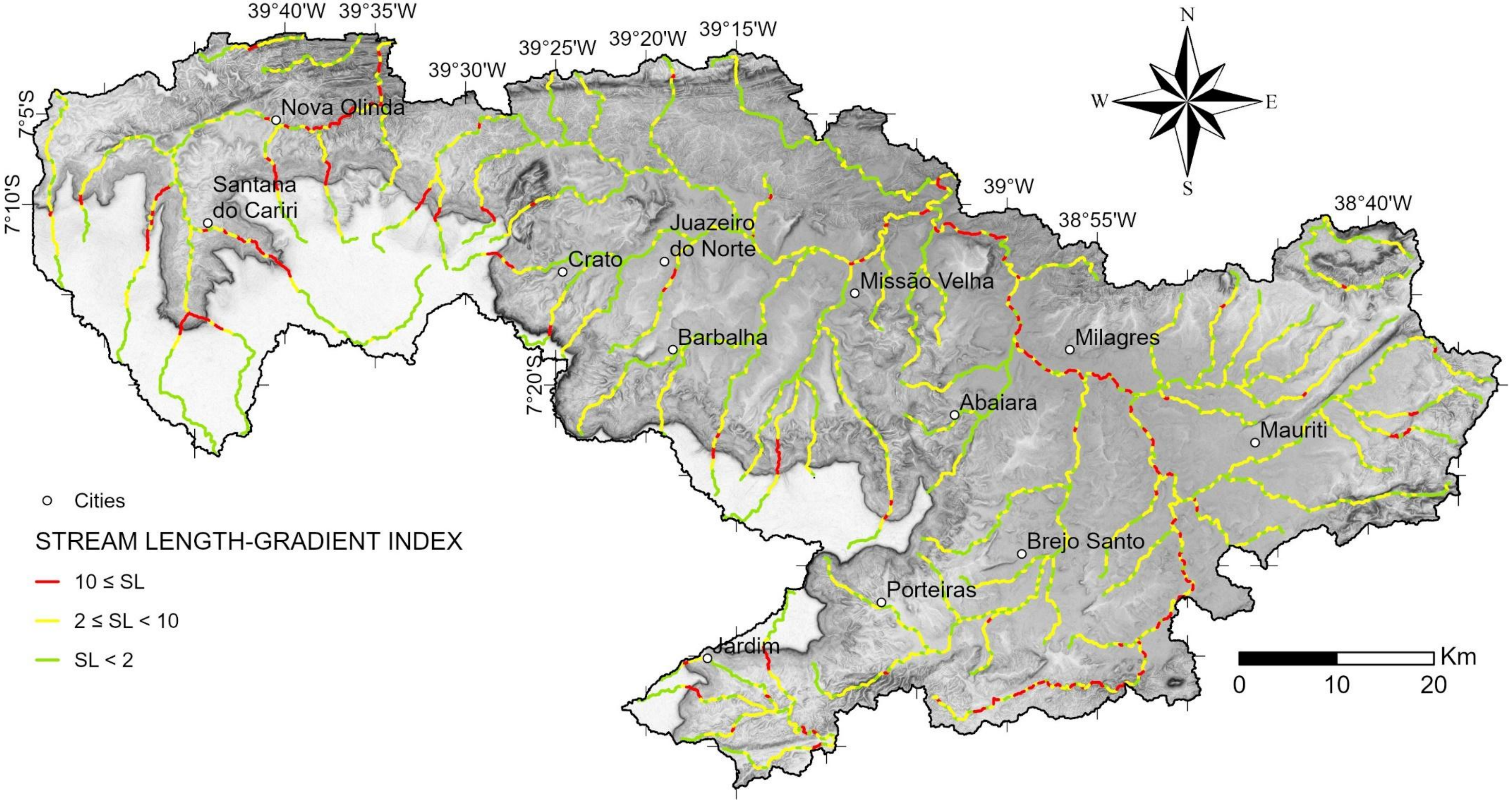
For this study, the area was divided into 134 sub-basins based on the higher order of drainages as defined by Horton (1945). These sub-basins are distributed across three main hydrographic basins: the Cariús River, Batateira River, and Porcos Creek (Fig. 2 and Fig. 3). The simplified geological framework highlights the varying resistance of the terrain to erosion and flooding. Drainages smaller than 600 meters in length were excluded from the analysis due to their limited regional significance within the context of the working scale.

Stream Length-Gradient Index (SL)

For the Stream Length-Gradient Index (SL), a Tectonic Index Class (CIT) of 3 corresponds to non-anomalous drainage segments. A CIT of 2 is assigned to segments showing anomalies up to 50%, while segments with anomalies exceeding 50% are classified as CIT 1 (Oliveira *et al.*, 2018). Applying the SL index to all sub-basins, 2,659 segments spanning a total of 1,573.7 km were analyzed. Of this, 845.95 km (53.75%) were identified as anomalous, and 727.78 km (46.25%) were classified as non-anomalous (Class 3). Among the anomalous segments, 712.11 km (45.25%) were in Class 2, and 133.84 km (8.5%) in Class 1 (Fig. 4).

SL index anomalies aligned with the direction of deposition are observable in the alluvial deposits. In the eastern part, near Brejo Santo, numerous anomalies cross these deposits orthogonally. Additionally, anomalies are prominent around the igneous bodies located to the east and southeast.

Fig. 4 - Distribution of SL Index values by categories: (1) SL < 2; (2) 2 ≤ SL < 10; and (3) 10 ≤ SL.



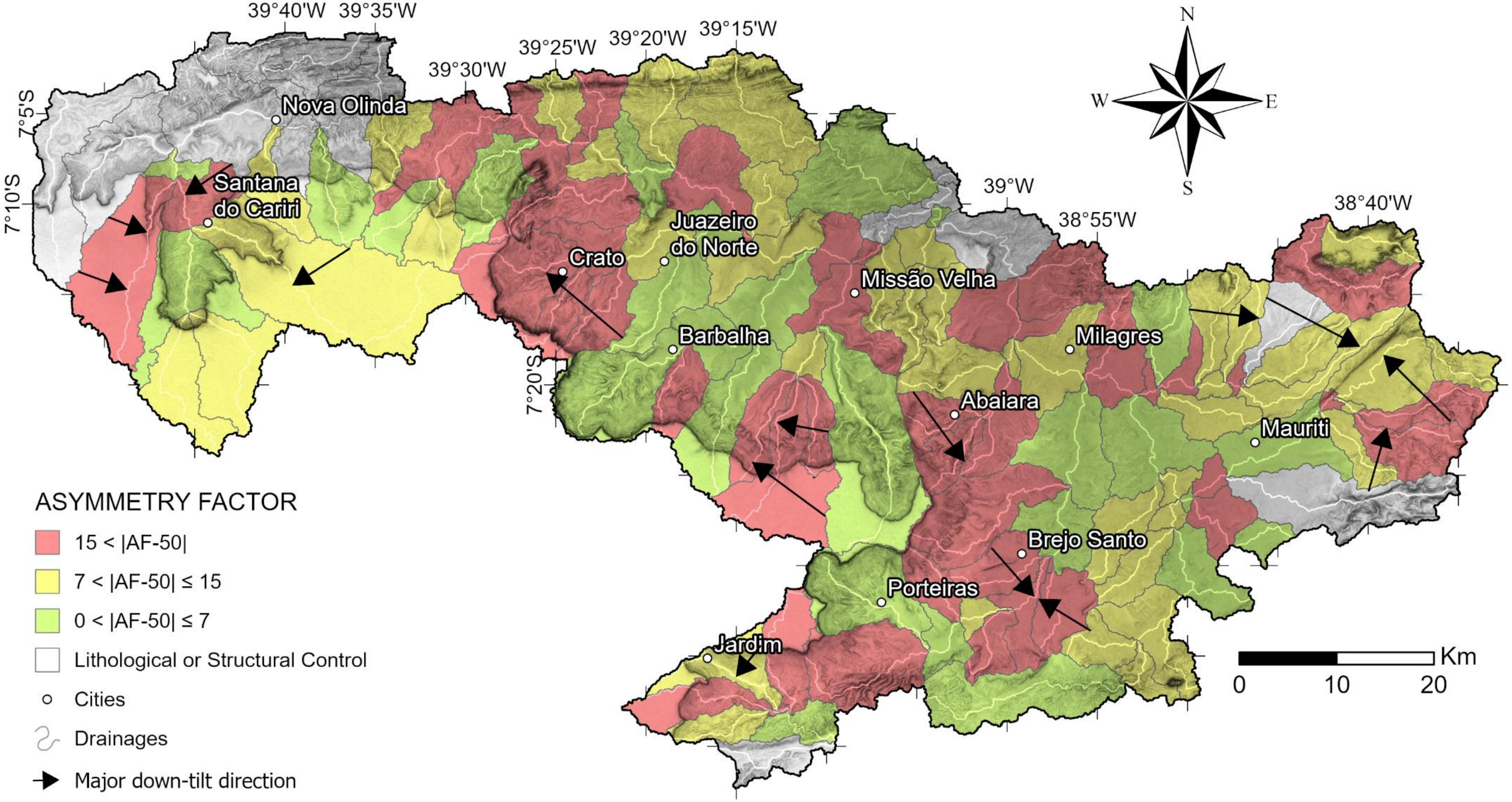
Asymmetry Factor (AF)

The sub-basin classification for the Asymmetry Factor (AF) was as follows: 27 sub-basins displayed low asymmetry (values between 0 and 7), 42 sub-basins showed medium asymmetry (values between 7 and 15), and 50 sub-basins exhibited high asymmetry with values exceeding 15.

Within the study area, fluvial basins may be influenced by structural controls, lithologic controls, or a combination of both—all contributing factors impacting terrain morphology. Sub-basins A1, A2, A3, C1, CDf1, CFb1, and SC1 are influenced by structural controls, where foliations and bandings guide water flow patterns and modify valley shapes. Lithologic control is evident in sub-basins B1, B2, B3, B4, BD1, W1, and W2, where drainage paths adjust based on lithotype strength or adhere to contacts between different lithologies. Sub-basin W3 shows a combination of both controls. Due to these non-neotectonic factors, the application of the AF index is unsuitable in these cases.

Structural and lithological controls, predominantly present in the northwest, relate directly to the PSZ and the basement of the Araripe Basin. Notably, the central regions, around Crato City in the west and between Abaiara and Brejo Santo in the east, have sub-basins with elevated AF values. The broader area shows a diverse distribution of the AF index. A discernible N-S and NE-SW elongation trend characterizes sub-basins mostly far from the basement. In the easternmost areas, sub-basins exhibit a westward tilt, with drainages moving counter to the embracing regional trend (Fig. 5).

Fig. 5 – Map illustrating Asymmetry Factor values across the sub-basins. Drainages demarcate the divisions between the eastern and western segments of each sub-basin.

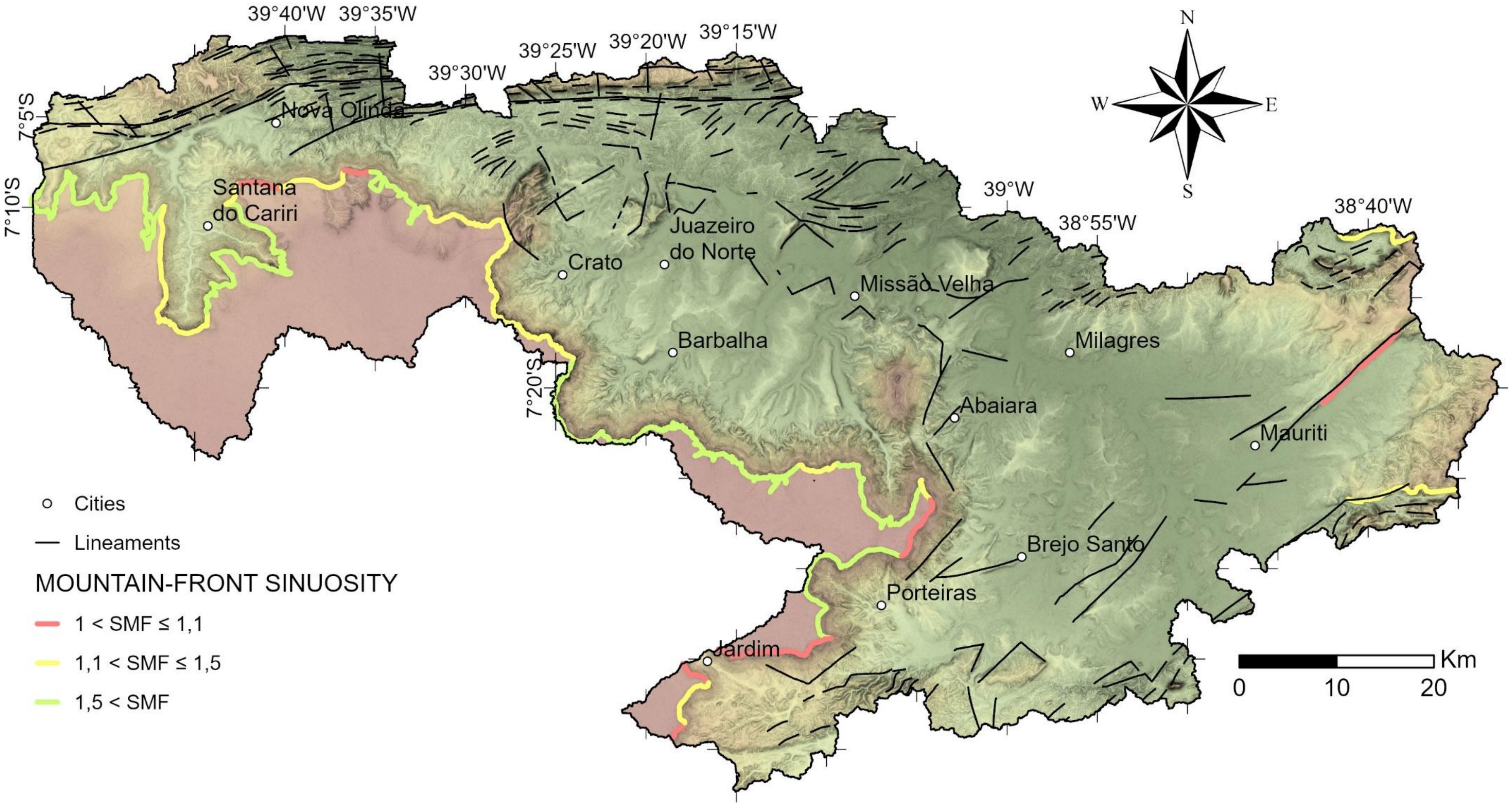


Mountain-Front Sinuosity (SMF)

The analysis of Mountain-Front Sinuosity (SMF) was concentrated southwards, towards the northern fringe of the Araripe Plateau. The mountain front was divided into 45 segments, corresponding to 42 unique sub-basins (31.3% of the total sub-basins). The starting and ending points of these segments align with the boundaries of their respective sub-basins. For sub-basins with two mountain fronts, the final SMF value was calculated as the average of both segments.

Sub-basins ADc1, AG4, AGb1, AGc1, AI1, AL1, AM1, B3, B6, B8, BB1, BG1, CB3, CFb1, N1, and SA2 displayed medium tectonic activity and were evenly distributed across the region. High tectonic activity was concentrated primarily in the southeastern part of the Araripe Plateau and along the eastern edge of the Vale de Santana do Cariri, with sub-basins B2, B4, CCa1, CCe1, CCf1, CF4, CF5, S1, SAa1, and SB1 showing high tectonic indexes.

Fig. 6 - Segments of mountain-front lengths alongside their corresponding Smf values.

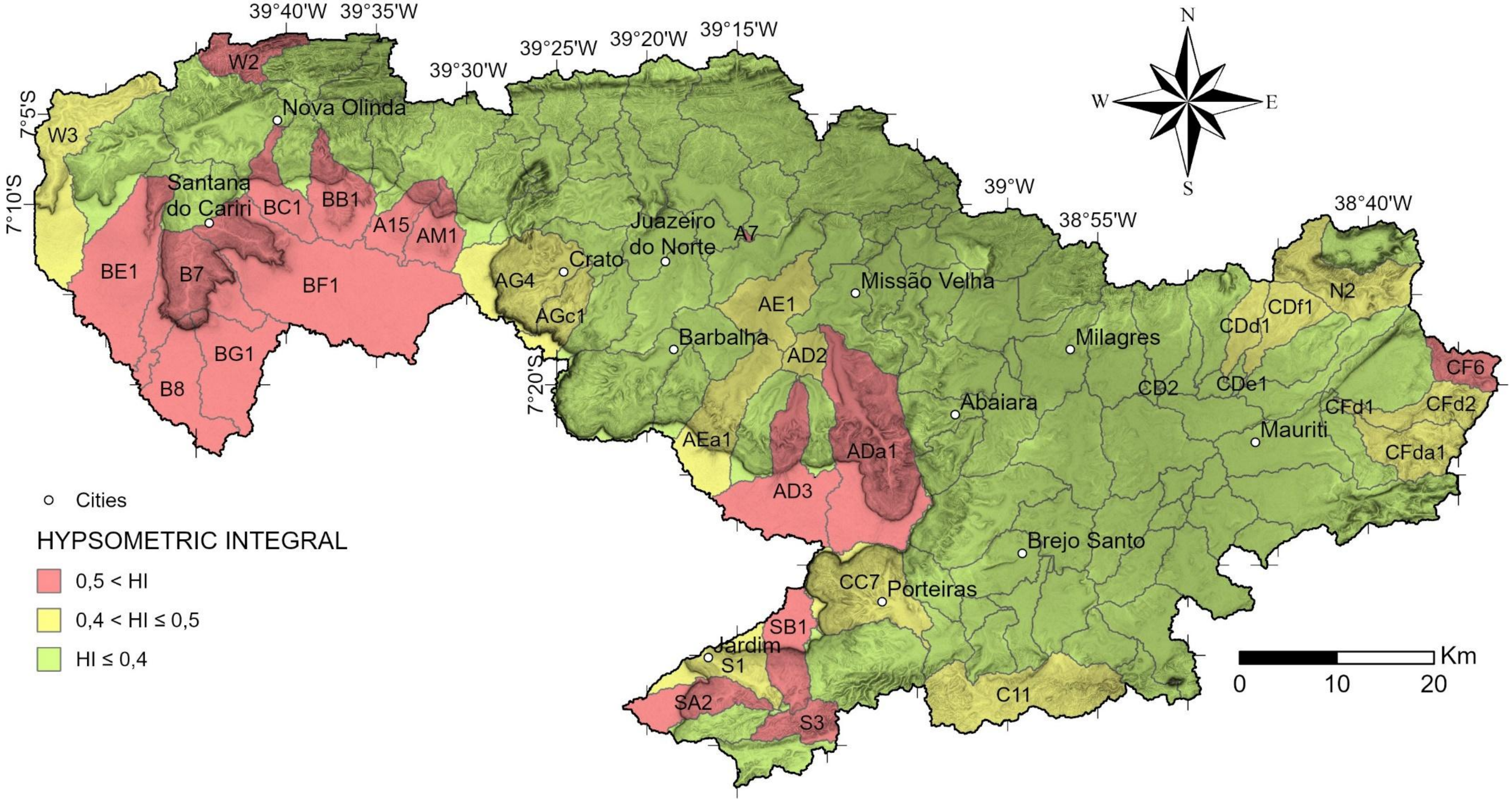


Hypsometric Integral (HI)

In analyzing the Hypsometric Integral (HI), 17 sub-basins display high HI values, indicating recent terrain surfaces prone to increased denudation with minimal erosion. These sub-basins are primarily located to the east of the Araripe Plateau and around Vale de Santana do Cariri. Additionally, 17 sub-basins show medium HI values, while 100 sub-basins present low values (Fig. 7).

The plotted curves consistently aligned with their respective numerical HI values, confirming the accuracy of the results. Notably, sub-basins A7, CF6, and S3 exhibited values nearing the medium activity threshold, explaining their concave-to-convex curve representations.

Fig. 7 - Distribution of Hypsometric Integral values across individual sub-basins.



Relative Tectonic Activity Index (IAT)

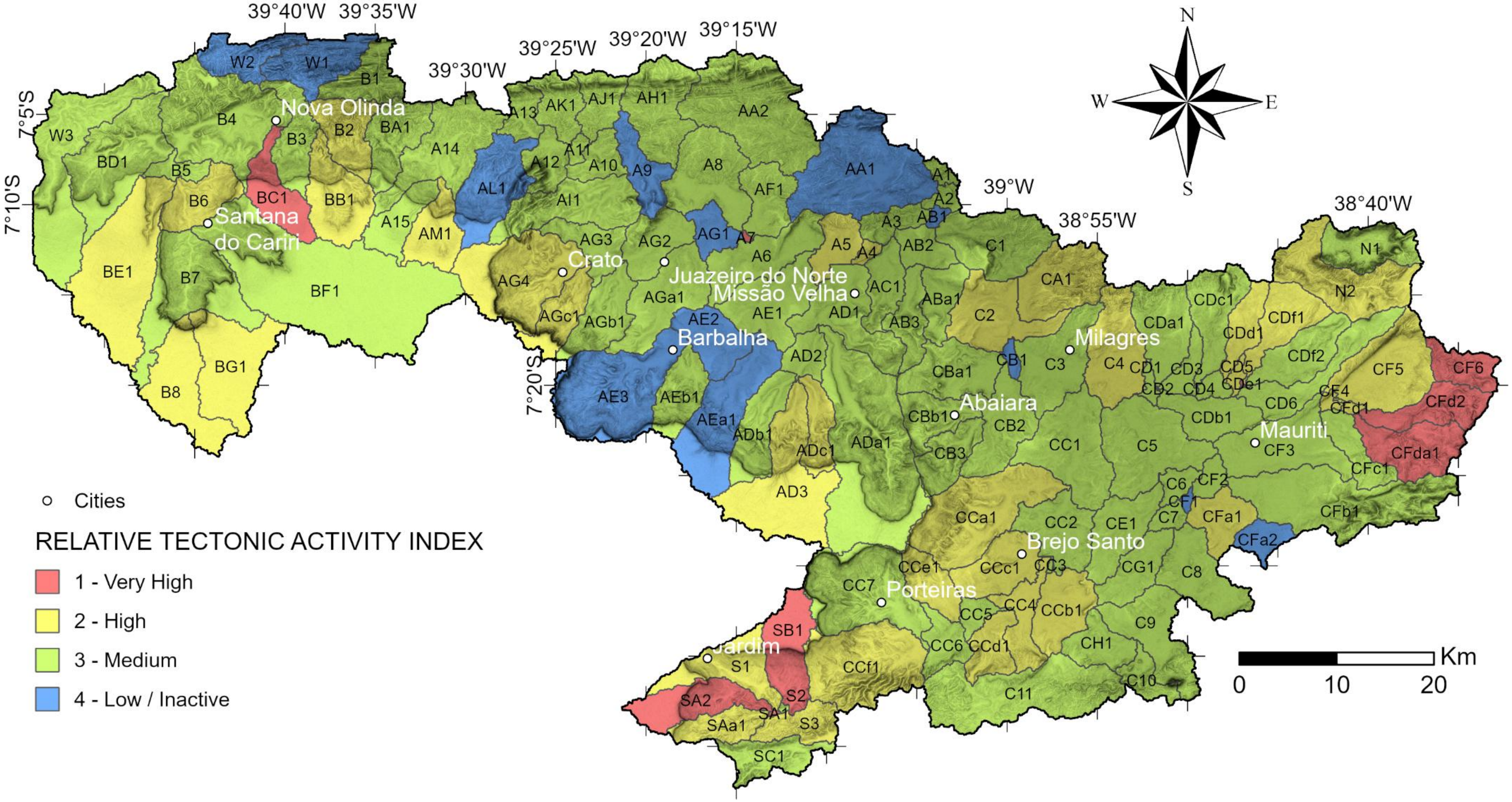
The tectonic intensity classes (CIT) were determined using four indexes: SL, AF, HI, and SMF across all sub-basins. The Relative Tectonic Activity Index (IAT) was subsequently calculated.

The study area, encompassing 134 sub-basins over 5,638.96 km², exhibits a varied range of tectonic activities:

- Low Tectonic Activity: 14 sub-basins, covering 563.25 km² and representing 9.99% of the total area.
- Medium Tectonic Activity: The most common category, including 79 sub-basins that span 3,379.39 km² or 59.93% of the study area.
- High Tectonic Activity: Found in 39 sub-basins, covering 1,508.18 km² and constituting 26.75% of the area.
- Very High Tectonic Activity: The most intense tectonic activity, observed in 7 sub-basins that collectively cover 188.15 km², accounting for 3.34% of the total area.

The spatial distribution of tectonic activity levels varies considerably. The easternmost portion of the region, for example, features three sub-basins with very high tectonic activity, likely influenced by the metamorphic and igneous lithologies of the basement. Additionally, the vicinity of Santana do Cariri Vale includes multiple sub-basins with high tectonic activity, one of which is marked by very high values (Fig. 8).

Fig. 8 - Spatial distribution of relative tectonic activity index (IAT) across the study area.



DISCUSSION

Overall, the drainage systems in the study area follow patterns influenced by geological structures, particularly near the Patos Shear Zone (PSZ). In the central region, a significant structural high and the Mãozinha Mountain Range, which runs approximately north-south, act as a regional divide between the Batateira River and Porcos Creek domains. This division contributes to the predominantly radial or sub-radial drainage pattern observed in smaller local systems within the Mãozinha Mountain Range. In the eastern part of the study area, the drainage patterns exhibit unique behavior compared to the rest of the region. Instead of flowing primarily northeast (NE), many drainages trend towards the southwest (SW) and northwest (NW). This indicates a tributary geometry towards the singular outflow of the region into the Salgado River, which has its local axis oriented in a northeast-southwest (NE-SW) direction, coinciding with the Mãozinha Mountain Range Horst (Rosa *et al.*, 2023). This reverse flow pattern indicates the presence of a series of elevated terrains in an arc shape along the margins of the Cariri Valley, east of the area, which could be the result of tectonics inherited from the Cretaceous period, a sum of transtensive phases (Richetti *et al.*, 2023) in the uplift process of the Araripe Basin (Fig. 9).

To the west, the boundary between the Cariús River and Batateira River domains is defined by a small structural high associated with the Dom Leme Horst. The Cariús River domain exhibits a distinct drainage pattern compared to other areas. Sediments in the Santana do Cariri Valley are partially deposited as colluvium on the plateau's slopes and partially flow into the Cariús River, forming alluvial deposits or depositing in a possible depression between the Araporanaga valley and the basin edge. The Batateira River domain is characterized by large-scale mass movements (Peulvast *et al.*, 2011) with drainage patterns potentially influenced by Cenozoic reactivation of structures from the Crato-Juazeiro *graben* (Rosa *et al.*, 2023).

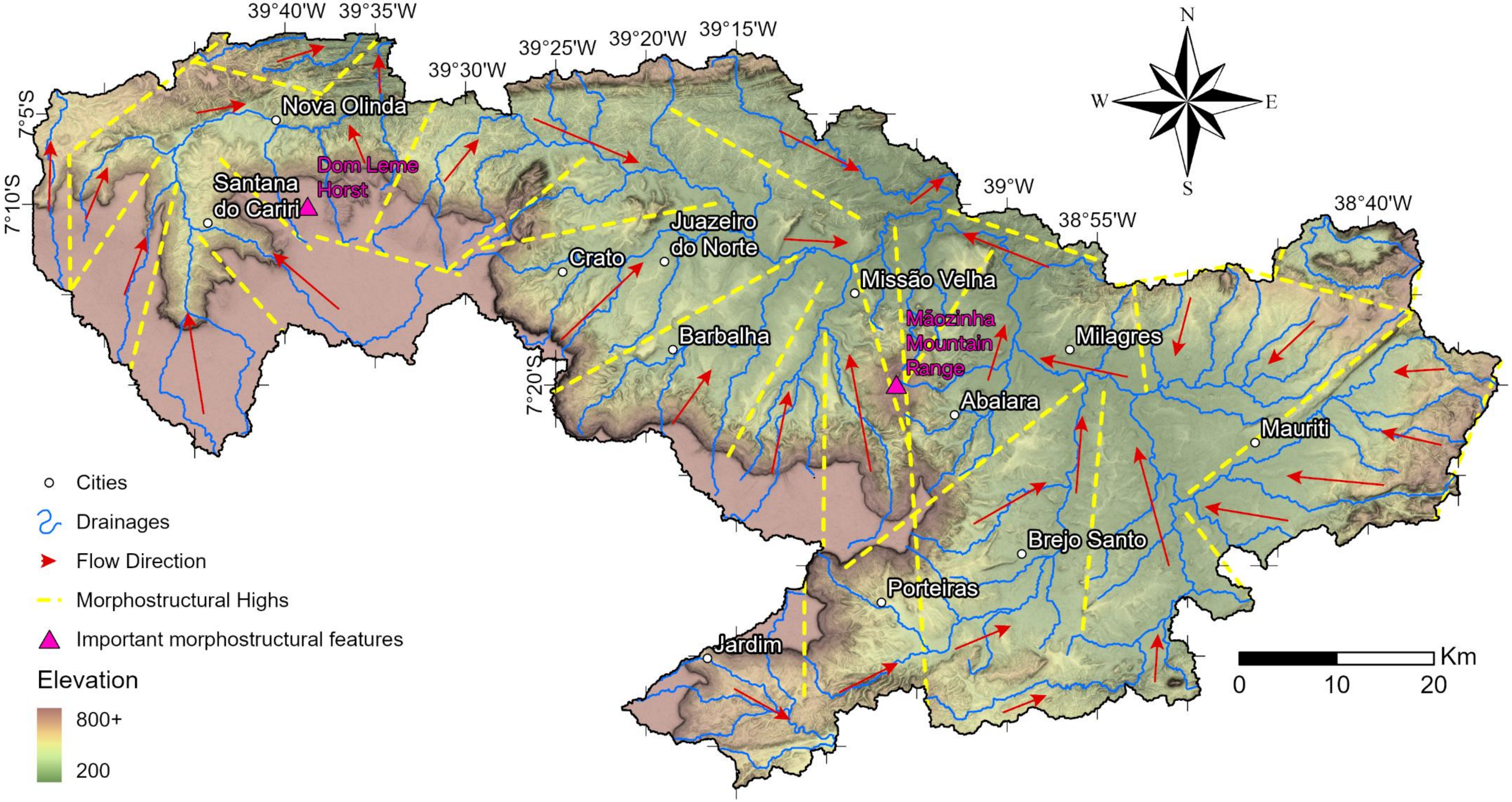
Within the Batateira River domain, which contains many recent deposits (Pineo *et al.*, 2020), numerous *horst*s and *graben*s formed during the Cretaceous period significantly shape the current landscape. This suggests a possible opening of the Araripe Basin, where NE-SW normal faults from the Cretaceous were reactivated by the ENE-WSW thrust, with a dextral transtensive component (Richetti *et al.*, 2023), along with a normal component. This region lies between the Cariús River and Porcos Creek domains, which exhibit more similar structural contexts. This may indicate that the basin is still evolving and, therefore, showing recent activity. The only region where the drainage from the Batateira River and Porcos Creek domains escapes from the hydrographic confinement is through the Salgado River (the confluence of the drainage from these two hydrographic basins), reinforcing the idea that the entire edge of the Cariri Valley is elevated due to possible reverse faults accommodating most of the Cenozoic compression efforts (Richetti *et al.*, 2023).

SL anomalies are widespread throughout the region, with higher concentrations in specific areas. The north-northwest section shows irregularities likely due to the alternation of harder and softer lithologies associated with the PSZ and its morphostructural influence. Another anomaly cluster is found in the southwest near Santana do Cariri, where sedimentary terrains generally have low SL values, except where well-cemented sandstones of the Exú Formation occur.

High SL values in the upper reaches of Porcos Creek (Fig. 4) may be related to drainage over a heterogeneous basement (Pineo *et al.*, 2020). In the creek's central section, located in the Cariri Valley, high SL values persist despite relatively uniform sedimentary characteristics. In the region of the city of Milagres, the drainages flowing through the plains of the Cariri Valley to the northwest, crossing NE-SW lineaments orthogonally (Fig. 1), may be the reason for the high SL values. The outflow from the region is the confluence of these drainages with the Batateira River to form the Salgado River that may coincide with a fault zone, marked by high SL values.

At the Araripe Plateau's edge, high SL values are noted at the contact between the Exú Formation sandstones and the upper pelitic rocks of the Santana Group (Romualdo Formation) (Oliveira *et al.*, 2018). This contact zone, historically referred to as the "Arajara Formation" by Ponte and Appi (1990) but later discarded, comprises more friable sandstones than the Exú. Median SL values in the "Crajubar" escarpments suggest active erosion rather than tectonic influence (Peulvast *et al.*, 2011), while higher SL values in the Santana do Cariri Valley—the antiform hinge zone at the plateau's summit—point to possible tectonic activity (Fig. 9).

Fig. 9 - Elevation map with upper limit at 800m elevation, showing drainage networks and arrows indicating flow direction in the eastern region of the area.



AF values across the region vary, with high values distributed unevenly. In the "Crajubar" region within the Batateira River domain, sub-basin drainages are arranged orthogonally to Precambrian basement structures (Pineo *et al.*, 2020; Camacho & Sousa, 2017), suggesting that these structures are not the main directing factor for any tilting perpendicular to the drainages, or that these drainages are controlled by another set of surface structures.

In areas near Santana do Cariri, Crato, Jardim, and between Abaiara and Brejo Santo, such tilting is likely to occur due to the uplift of the plateau (Fig. 6). This process has impacted the proximal edge of the plateau, resulting in a more pronounced alteration of the relief.

Along the Brejo Santo-Mauriti axis, the asymmetries outline a synform with a NE-SW axis (Fig. 10), possibly inherited from the dextral transtensional phase during the Cretaceous, as evidenced by Rosa *et al.* (2023). In this context, regional stress reactivated the structures, though to a lesser extent, resulting in the uplift of the fold's flanks and hinge. The antiform near Mauriti, also with a NE-SW axis, underwent similar influences during its formation. Compartmentalization by *horst*-dividers appears to offer a more coherent explanation for the distributions of morphometric features.

Mountain fronts predominantly surround the plateau, with three additional fronts in the eastern area linked to the PSZ. It is worth noting that although the Mãozinha Mountain Range is approximately straight along its crest, its foothills do not meet the minimum slope value (20°) required to characterize mountain fronts, according to the method used (Oliveira *et al.*, 2018). We can consider this range as an anomalous mesa within the general context of the plateau morphology, related to the Mãozinha Mountain Range Horst (Camacho & Sousa, 2017).

The fronts near Jardim, at the plateau's eastern edge and near the Santana do Cariri Valley, display straight escarpments that suggest a possible influence of fault control (Fig. 6). In the eastern and southeastern sectors, parallel faults to the straight fronts are found, which may indicate a tectonic influence in these areas.

High HI values in the Santana do Cariri valley, within the Cariús River domain, as well as in SL, may be related to the hinge of the antiform at the top of the plateau (Fig. 9). In the south, in the Jardim valley, high values are related to both the flanks of the antiform and the southern basement. In the center, these high indices are directly related to the Mãozinha Mountain Range *horst*. At the eastern (Mauriti region) and western (W sub-basins) edges, we observe arcs denoting a positive HI due to uplift. It can be stated, then, that the HI index is effectively marking the dividers of the domains, where, along with the basin edge, past structures of the rift phase affect this separation. Regions with low HI values correspond to areas of significant deposition, encompassing much of the "Crajubar" lowlands and the Batateira River and Porcos Creek hydrographic basins.

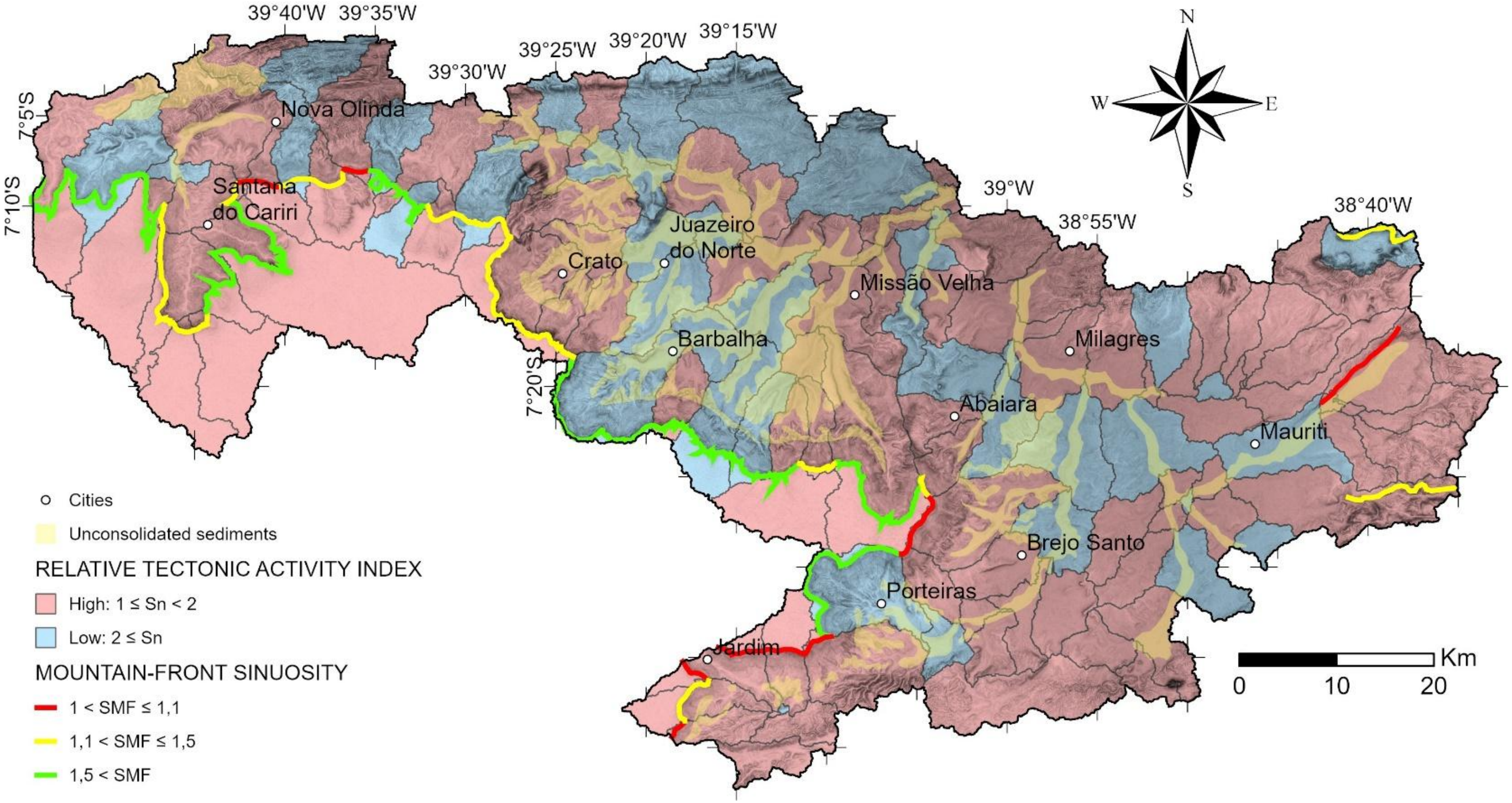
High or very high IAT values confirm what the other indices presented individually, where they are high in the regions near Jardim, in the Santana do Cariri Valley, at the easternmost end, where the uplift of the Cariri Valley edge was theorized, around Crato, and around Brejo Santo, with only 'High' values occurring in the latter two (Fig. 10). These regions of high IAT values indicate prospects for neotectonic structures.

Just like the findings presented by Oliveira *et al.* (2018), this study reinforces the model proposed by Marques *et al.* (2014), suggesting that the basin inversion originated from regional horizontal compression acting to the west due to the formation of the Andes and to the east during the opening of the Atlantic, as complemented by Richetti *et al.* (2023), who added the observation that oblique efforts may have occurred during the basin inversion, thus complementing the initial idea of Marques *et al.* (2014).

In the analysis of the Relative Tectonic Activity Index (IAT), grouping values considered very high, high, and upper medium ($2 < Sn < 2.25$) as higher IATs, and the rest as lower, a direct correlation between unconsolidated sediment bodies and regions where IATs are lower becomes evident (Fig. 10). This suggests that terrains less affected by recent tectonic activity have undergone a longer period of erosion, whereas more tectonically active areas have experienced uplift or have remained relatively preserved. Notably, these terrains are found in the most pronounced sinuosities of the Araripe Plateau edge, where SMF values are low to medium, indicating reduced geological activity.

Considering these factors collectively, it can be inferred that the regions with indentations along the edge of the Araripe Plateau are experiencing more intense erosion. Specifically, in the Crato-Juazeiro do Norte-Barbalha region, this erosion has resulted in the formation of various deposits associated with the Batateira River and its tributaries, shaping the local geological structure. In the Santana do Cariri valley, it is plausible that this eroded material has been deposited as colluvium, which is commonly found on the Mb. Romualdo formation, or has been transported to another basin, as significant alluvial deposits are not apparent. Conversely, deposits from the south likely originate from the indentations near the city of Porteiras, transported and deposited by the Porcos Creek (Fig. 10).

Fig. 10 - Spatial distribution of relative tectonic activity index (IAT) divided in two groups (High and Low) compared with SMF and unconsolidated sediments across the study area.



CONCLUSION

The results obtained from the integration of geological and geomorphological data, coupled with the analysis of morphometric indexes, represent a significant advancement in understanding the evolution of the Araripe Basin.

In this study, the watershed boundaries of the region's main hydrographic basins, the Mãozinha Mountain Range and the Dom Leme Horst, were defined. This division allowed the area to be segmented into three major domains, two of which converge into the same drainage system.

The area was divided into 134 sub-basins, which facilitated the calculation of four morphotectonic indices (SL, AT, SMF, and HI). These indexes highlighted specific features of the sub-basins and were consolidated into the IAT, which identified the areas most likely influenced by tectonic activity in shaping the current relief. Overall, the study area exhibited few sub-basins with low IAT, indicating significant tectonic influence on the region's relief.

This work aimed to provide a regional characterization that supports more localized future studies in areas with higher IAT. Such field-based studies could validate the results obtained through remote methods.

Additionally, this study presents new data on the northern and eastern portions of the Cariri region, including the Araripe Basin—one of the most significant fossiliferous basins in the world. These findings greatly contribute to scientific knowledge in an area that still requires detailed investigation for comprehensive understanding.

High or very high IAT values confirm what the other indices presented individually, where they are high in the regions near Jardim, in the Santana do Cariri Valley, at the easternmost end, where the uplift of the Cariri Valley edge was theorized, and around Crato and Brejo Santo, where only 'High' values were observed (Fig. 8). These regions of high IAT values indicate prospects for neotectonic structures.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Viktor Ferreira de Oliveira: Writing – original draft. **Wellington Ferreira da Silva Filho:** Writing – review & editing.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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DATA AVAILABILITY

Data will be made available on request.

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4 CONCLUSÃO

O trabalho teve como objetivo identificar possíveis áreas afetadas por eventos tectônicos na borda norte da Bacia do Araripe, utilizando sensoriamento remoto e técnicas morfométricas. A abordagem remota permitiu uma análise ampla, eficiente e detalhada de uma extensa área.

Foram analisados quatro índices morfométricos: relação declividade-extensão (SL), fator de assimetria (AF), sinuosidade de frente de montanha (SMF) e integral hipsométrica (HI). Esses índices foram consolidados em um único parâmetro, o índice de atividade tectônica (IAT), utilizado para quantificar o grau de atividade tectônica em áreas específicas.

A relação declividade-extensão apresentou anomalias em aproximadamente 16% dos trechos analisados, totalizando 79 dos 492 avaliados. O fator de assimetria revelou que seis bacias sofreram influência de controles tectônicos, enquanto outras seis não apresentaram anomalias. No caso da sinuosidade de frente de montanha, os resultados indicaram, em geral, um grau moderado de tectonismo. Já os valores do HI mostraram maior homogeneidade entre as bacias, com 8 apresentando CIT=1, 4 com CIT=2 e 9 com CIT=3.

A consolidação dos resultados no índice de atividade tectônica identificou as bacias B11, B34, B311, B312 e B313 como áreas de alta atividade tectônica. No entanto, a classificação da bacia B34 como de alta atividade pode ser questionada devido à eficiência do método em terrenos antigos. Anomalias observadas próximas a terrenos cenozoicos sugerem que contatos litológicos podem estar representados de forma imprecisa no mapa, uma vez que essas coberturas não acompanham consistentemente os terrenos mais elevados da região.

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APÊNDICE A – ILUSTRAÇOES E TABELAS DO ARTIGO

LISTA DE ILUSTRAÇÕES

LISTA DE TABELAS