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Research Article

Drainage rearrangement in semi-arid intermountain depressions: a case study in South America

Rearranjos de drenagem em depressões intermontanas semiáridas: um caso de estudo na América do Sul

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Abstract: River captures are drainage rearrangements commonly reported in divides of high topographic gradient, triggered by headward erosion. Captures also occur in divides of low topographic gradient through differential fluvial incision between rivers, however, in a smaller proportion of reports, mainly in dry regions. Thus, this research contributes to the theme by investigating possible river captures in the semi-arid equatorial margin of South America related to the Jaguaribe River, which flows over intermountain depressions. This study used morphological and sedimentary evidence obtained in field expeditions and by application of morphometrics (local relief, paleotopographic modelling and χ variable). Among the results, the following stand out: depressions drained by radial tributaries upstream of water gaps; opposing headwaters with relative extension that drain low-relief divides, damming fluvial-lacustrine sediments and transfers signatures of upstream areas. These data suggest drainage rearrangements and a possible endorheic phase during the study area evolution. Continuous incision of the Jaguaribe River conditioned river captures by rupture of paleodivides supported by structural ridges (shear zones). In this context, the drainage rearrangements were effective for the configuration of the Jaguaribe River, even in a region of low topographic gradient and water flow instability.

Keywords: River capture; Semi-arid; Brazil; Drainage network.

Resumo: Capturas fluviais são rearranjos de drenagem comumente reportados em divisores hidrográficos de elevada amplitude topográfica, deflagrados pela erosão remontante. Capturas também correm em divisores de baixa amplitude topográfica mediante incisão fluvial diferencial entre rios, contudo, em menor proporção de reportes, sobretudo em regiões secas. Assim, esta pesquisa contribui com o tema investigando possíveis capturas fluviais na margem equatorial semiárida da América do Sul relacionadas ao rio Jaguaribe, que escoa sobre depressões intermontanas. Esse estudo utilizou evidências morfológicas e sedimentares obtidas em expedições de campo e pela aplicação de morfométricas (amplitude topográfica, modelagem paleotopográfica e a variável χ). Dentre os resultados destaca-se: depressões drenadas por tributários radiais a montante de vales transversais; cabeceiras opostas com relativo prolongamento que drenam baixos divisores, represamento de sedimentos flúvio-lacustres e assinaturas de transferências de áreas de contribuição. Esses dados sugerem rearranjos de drenagem e possível fase endorreica durante a evolução da área de estudo. A contínua incisão do rio Jaguaribe condicionou capturas fluviais por rompimento de paleodivisores suportados cristas estruturais (zonas de cisalhamento). Nesse contexto, os rearranjos de drenagem foram determinantes para a configuração do rio Jaguaribe, mesmo em região de baixo gradiente topográfico e de instabilidade de fluxo hídrico.

Palavras-chave: Captura fluvial; Semiárido; Brasil, Rede de Drenagem.

1. Introduction

Geomorphological evolution in non-glacial erosion landscapes is related to the incision of bedrock channels (HANCOCK; ANDERSON; WHIPPLE, 1998; KIRBY; WHIPPLE, 2012). The erosive capacity of beds is significantly affected by external factors to river systems, such as climate fluctuations, rock erodibility, tectonic and eustasy (WHIPPLE; TUCKER, 1999; WHIPPLE; DIBIASE; CROSBY, 2013). Contrasts in the incision competence between channels make river divides susceptible to progressive migration and promote topological/geometric changes in drainage networks (WILLET et al., 2014). In this context, river systems establish a dynamic of expansions and contractions in which rivers with incised gradients and immediate topographic adjustment to their base levels (local and regional) incorporate rivers with low incision gradients that flow over levels that are out of adjustment in relation to their base levels (WILLET et al., 2014).

These river reorganizations are called drainage rearrangements, characterized by transfers of areas and drainage lines, total or partial, between adjacent rivers (BISHOP, 1995). Drainage rearrangements are classified by Bishop (1995) into top-down and bottom-up processes. Top-down processes refer to drainage transfers in which a river is “pushed” or diverted to another adjacent river by tectonic (lateral migration) or by bed channel aggradation (overflow and avulsion) (BISHOP, 1995). Bottom-up processes are due the active interception and incorporation of drainage areas by river capture and decapitation (BISHOP, 1995).

River captures or river piracy are the most common types of drainage rearrangements and generally occur in divides with large differences in local relief between their hillslopes (DOUGLASS; SCHMEECKLE, 2007). In a river capture, the pirate headwater, which drains the hillslope most adjusted to the base level, expands towards the headwater less erosive (pirated) which flows over the hillslope of less adjustment in relation to its base level (SCHERLER; SCHWANGHART, 2020). Therefore, high-relief divides coincident with great escarpments at the edges of sedimentary tablelands, folded belts and crystalline massifs, are more prone to the occurrence of river capture, both on active margins (CLARK et al., 2004; YANG; WILLET; GOREL, 2015; GARCÍA-DELGADO; VELANDIA, 2020); as well as on passive margins (STOKES et al., 2008; PRINCE; SPOTILA; HENIKA, 2010; SALGADO et al. 2016, HAREL et al., 2019).

Although less common, river captures also occur in low-relief divides, such as in depressions and plains, between rivers that flow over the same surface levels (SMALL, 1972; MATHER, 2000; SALGADO; MARENT; PAIXÃO, 2021). In these cases, river capture generally occurs due to an anomalous base level fall (local or regional) of one of the rivers, establishing an erosional regression towards the headwaters of adjacent rivers (MATHER, 2000). This change of the base level can be due to differential bed erosion; local tectonics and eustatic regressions (TWIDALE, 2004).

However, studies regarding drainage rearrangements in low-relief divides are rare, especially in regions with arid and semi-arid climates. The rarity of sedimentary deposits preserved in these environments, given the aggressive denudation (TOOTH, 2000), is one of the factors that contributes to this rarity. Another factor is intermittent to ephemeral water flows, which impose accentuated structural control on limited river systems (GOUDIE, 2013) and can mask evidence of drainage rearrangements such as river elbows and changes in their water flow (ZAPROWSKI; EVENSON; EPSTEIN, 2002). On the other hand, the structural fabric of these environments also denotes an important role in epigenic weathering processes (TWIDALE, 2004; MAIA; NASCIMENTO, 2018), such as percolation, which in turn, is identified as important aids to the drainage rearrangements (PEDERSON, 2001). Joints, faults, and others lithological discontinuities (e.g., bedding, bands, and lineation) provide preferred planes of weakness for subsurface weathering, facilitating the erosive advance in hydrographic divides (TWIDALE, 2004; MANJORO, 2015).

In this context, our research aims to contribute to the debate on drainage rearrangements, investing the possibility of these processes occurring in divides with low-relief topography under the influence of dry and hot climates. The study area is the Jaguaribe River, located in the semi-arid area of the South American equatorial margin. This region, located in a predominantly depressed topography, had its current hydrographic configuration interpreted as a legacy of a set of fluvial superimpositions on compartments of Cretaceous rift systems aborted during the opening of the Equatorial Atlantic Ocean (PEULVAST; BÉTARD, 2015).

Superimposition characterizes a morphogenetic process of transverse drainages – rivers that cross topographic/structural barriers such as tablelands, plateaus, cuestas, massifs, mountain ranges and structural ridges from canyons and gorges, generally discordant with the orientation of these landforms (STOKES; MATHER, 2003). In superimposition, the transverse river is older than its barrier (DOUGLASS; SCHMEECKLE, 2007), and the superimposition is carried out through the incision of a riverbed over friable or highly erodible lithologies (covermass) until reaching low erodible lithologies, crossing them through the formation of transversal valleys (DOUGLASS et al., 2009). Evidence of this process is: preservation of low erodibility covers in the landscape and the existence of river deposits at the top of the transverse valleys that prove the pre-existence of the river that cut the structures (TWIDALE, 2004; DOUGLASS; SCHMEECKLE, 2007).

According to this model, a large part of the current hydrographic configuration of the Jaguaribe River (middle-upper course) was interpreted as a legacy of superimpositions on Precambrian shear zones (SZ) reactivated during the Cretaceous (MAIA; BEZERRA, 2012, 2014; PEULVAST; BÉTARD, 2015). However, this hypothesis of generalized superimposition is questionable as some regional morphological and geological evidence – which will be further discussed later in this article – suggests the occurrence of river rearrangements during the evolution of this river basin (CAVALCENTE, 2006; ARIMA 2007; MAIA; BEZERRA, 2012).

Therefore, this work studies the evolution of the drainage network of the Jaguaribe River with a focus on drainage rearrangements. Our hypothesis assumes that part of the tributaries of the Jaguaribe River, especially the upper-middle course rivers, underwent transfers of areas and drainage lines with adjacent rivers. To this end, this research was based on the investigation of morphological and sedimentary evidence obtained from remote sensing products and field works.

2. Study Area

The Jaguaribe River is an exorheic drainage network with ~75,000 km², located in the northern portion of the Brazilian Semi-arid region (Figure 1). The channels are predominantly intermittent, with flows associated with the short rainy season (January to May) with average annual precipitation of ~600 mm (CAVALCANTE; CUNHA, 2012). Geologically, the Jaguaribe River is located in the Northern Borborema Province, a geotectonic domain almalgamated during the Brasilian/Pan-African Orogeny (BRITO NEVES; SANTOS; VAN SCHMUSS, 2000). This Neoproterozoic orogenesis promoted: intense deformation of metamorphic rocks and supracrustal covers; magmatic intrusions; and structuring sets of ductile and ductile-brittle ZC in NE-SW, E-W and N-S trends (OLIVEIRA; MEDEIROS, 2018). In the Neocomian, Northern Borborema Province underwent extensive and transtensional stress related to the Northeast Brazilian Rift System, developed during the Cretaceous (MATOS, 1992). These tectonic events reactivated Precambrian structures and conditioned sets of half grabens (today covered by the Mesozoic Basins) until culminating in the opening of the Equatorial Atlantic Ocean (MATOS, 1999). The Jaguaribe River flows in depressed areas corresponding to the main continental extension axis of the Northern Borborema Province, the Cariri-Potiguar Rift (MATOS, 1992), which extends from the deposition areas between Araripe and Potiguar Basins in a NE-SW trend. Other interior basins correlated to this aborted rift system are recorded on the same deformation axis, as Iguatu, Lima Campos, Malhada Vermelha and Icó, which share siliciclastic formations (predominantly sandstone) of correlated ages and deposition cycles (MATOS, 1999).

At the end of the Cretaceous, the beginning of the South American Plate drift phase imposed a new regional compressive stress in the Northern Borborema Province (BEZERRA et al., 2011). Such compression was accompanied by process of regional uplift, new reactivations of Precambrian structures and Oligocene-Miocene alkaline magmatism – Macau, 45 to 6 Ma (MIZUSAKI et al., 2002; CAVALCANTE, 2006; MORAIS NETO et al., 2009; RAMOS et al., 2021) – which conditioned tectonic inversion of basins and intensified the basement exhumation during the Cenozoic (PEULVAST et al., 2008). The geological record of this phase comprises the Paleogene covers (Barreiras Formation) and subsequent Neogene-Quaternary depositions, especially the Moura Formation, the Faceira Formation and colluvium-eluvial deposits (PEULVAST; CLAUDINO-SALES, 2004; MAIA; BEZERRA, 2019). Paleoclimatic data indicate that denudation and deposition of these Cenozoic covers took place in a predominantly arid climate with peaks of humidity that occurred from the Pleistocene to the Middle Holocene (DE OLIVEIRA et al., 1999; BEHLING et al., 2000; JENNERJAHN et al., 2004).

The Moura Formation is composed of sedimentary packages with thickness of ~50 m, overlapping hillslopes of the Orós ZC (SILVA, 2018). The basal layer thickness has ~8 m, composed of polymictic conglomerates in a sandy matrix weakly cemented by silty-sandy material (ARIMA, 2007).

Above the basal layer, massive silt-clay deposits are found overlain by coarse-textured sand (SILVA, 2018). The Faceira Formation are terraces positioned ~50 m above the bed of the Jaguaribe Valley, composed of basal sandstones overlying conglomerates (interspersed with gravelly levels) and sands of fine to medium textures (MAIA, 2005).

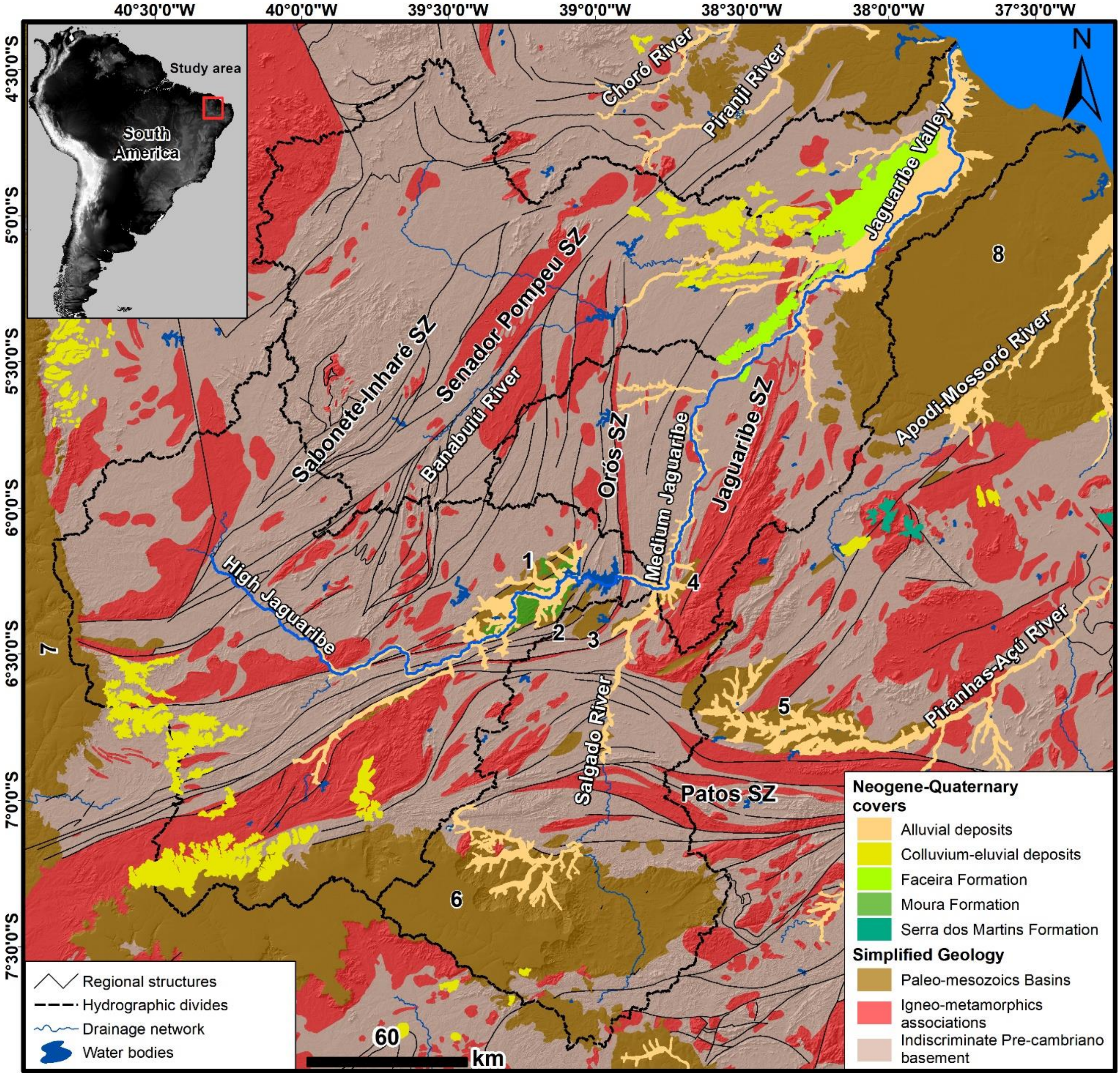

Figure 1. Location and simplified geology of the Jaguaribe River. Location in relation to South America from MDE SRTM 1 arcsecond (30 m). Basins: 1 – Iguatu, 2 – Lima Campos, 3 – Malhada Vermelha, 4 – Icó, 5 – Rio do Peixe, 6 – Araripe, 7 – Parnaíba and 8 – Potiguar. Adapted from Cavalcante et al. (2003).

The colluvium-eluvial deposits mostly originate from debris flows and have compositions that comprise intercalations of fine and coarse sand, with sub-rounded-angular pebbles (PALHETA, 2013; CAVALCANTI; VALE FILHO, 2014). In some sectors of the High Jaguaribe, these sediments are partially lateritized and can reach thickness of 4 m (CAVALCANTI; VALE FILHO, 2014). In some sectors are found conglomeratic facies and even flat-parallel or cross-stratifications structures, indicating a possible alluvial origin of their basal layer (VERISSIMO et al., 2014).

Geomorphologically, the surfaces drained by the Jaguaribe River comprise landforms of a semicircular erosion amphitheater with relatively continuous escarpment that reaches 1200 m a.s.l. called Jaguaribe-Piranhas Amphitheater (PEULVAST; CLAUDINO-SALES, 2004). This escarpment is composed of the eastern border of the

Parnaíba Basin (Ibiapaba Plateau), the northern border of the Araripe Basin (Araripe Plateau) and the hillslopes of the Borborema Massiff (Borborema Plateau) (Figure 2).

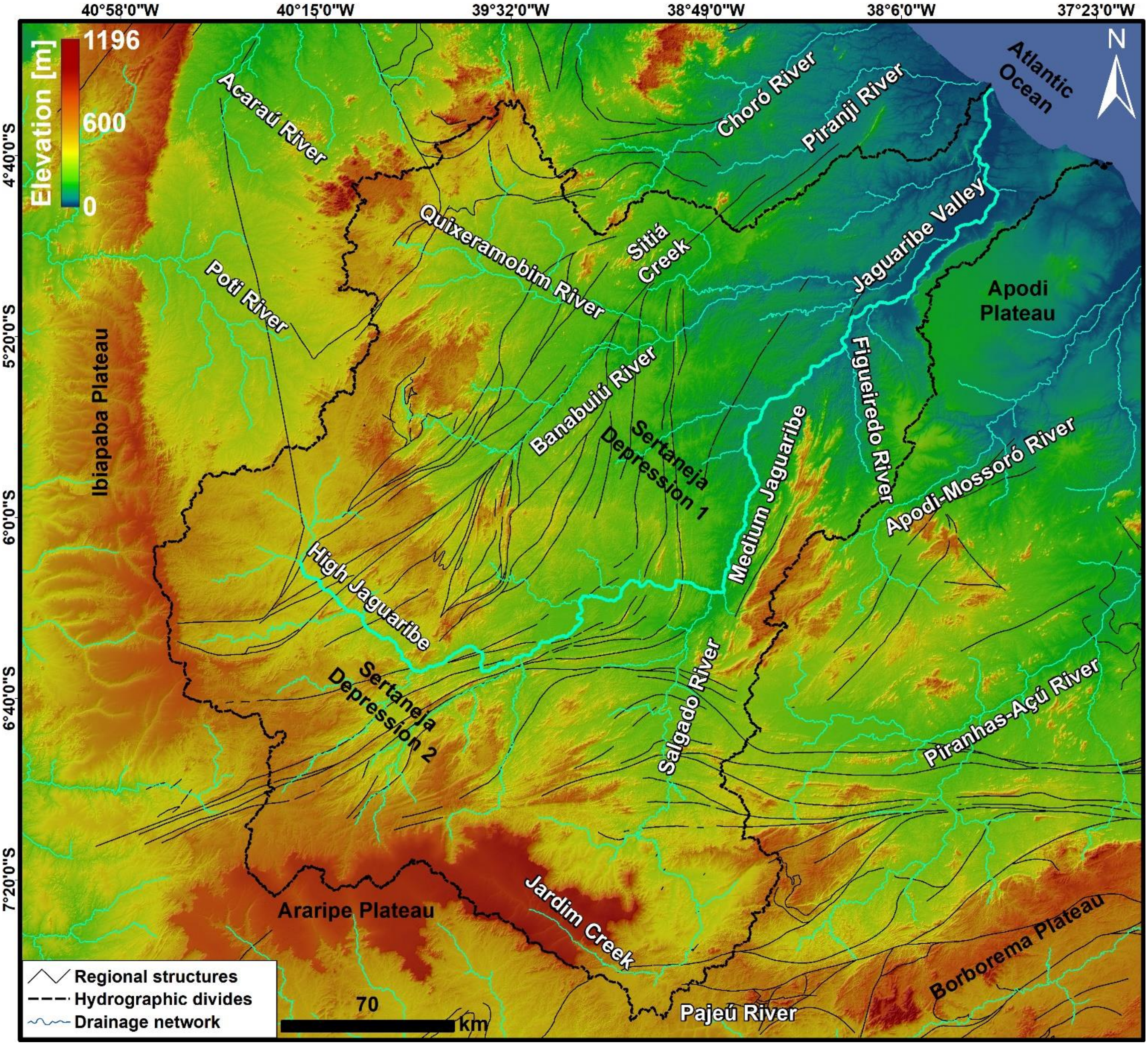

Figure 2. Hypsometry and main geomorphological compartments of the Jaguaribe River in relation to the Jaguaribe-Piranhas Amphitheater. Elevation and drainage data derived from MDE AW3D30 (30 m). Highlighting the different levels of the Sertaneja Depression mentioned in the text (100 < Level 1 < 250 m and 250 > Level 2 > 400 m).

Generally speaking, inner amphitheater surfaces are depressed and have elevations ranging from 50 to 400 m (Figure 3, A), interspersed by residual landforms like massifs, inselbergs, and structural ridges (SZ) which reach 900 m in elevation. In some areas, these surfaces are overlaid by low-relief tablelands locally described as “tabuleiros”, composed of sediments from the Barreiras and Faceira Formations in the coastal zone. Inland, tabuleiros are capped by sediments from the Moura Formation and colluvium-eluvial deposits (Figure 3, B).

The Jaguaribe River has a main SW-NE trend, following the regional gradient fall and draining the intermountain depressed surfaces in different dissection levels (Figure 2): the first level surface comprises depressions that extend to the Jaguaribe Valley at the massifs and structural ridges, with elevations between 100 and 250 m a.s.l. (Sertaneja Depression 1); and the second level surface comprises terrains dissected in low-relief hills that border sedimentary plateaus at the South and Southwest of the study area, with elevation that do not exceed 400 m a.s.l. (Sertaneja Depression 2).

The interpretation of superimposition related to the High and Medium courses of the Jaguaribe River is based on the arrangement of Cretaceous covers over the half grabens in the Cariri-Potiguar Rift axis (Figure 1, Araripe, Iguatu, Lima Campos, Malhada Vermelha, Icó, Rio do Peixe and Potiguar Basins).

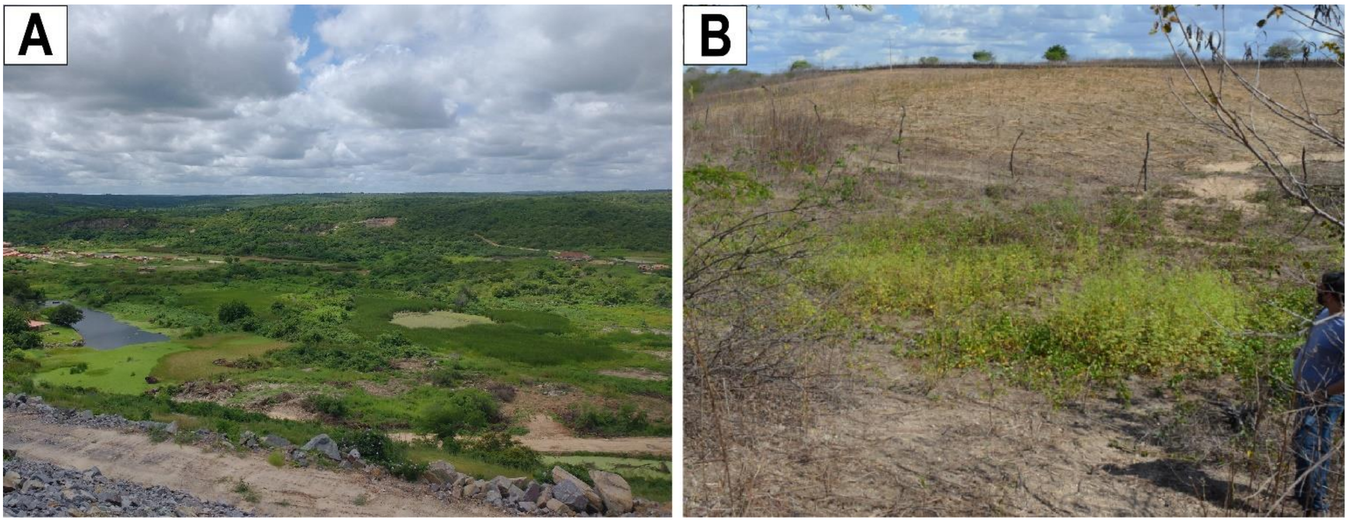

Figure 3. Detail of geomorphological aspects of the study area. A- Banabuiú Valley (tributaries) that dissects intermountain surfaces of the Medium Jaguaribe course. B- Colluvium-eluvial deposit in the form of tabuleiros overlapping the divide between the Sitiá Creek and the headwaters of the Piranji River.

These covers suggest the existence of ancient surfaces that facilitate river incision over basement rocks (PEULVAST et al., 2008; PEULVAST; BÉTARD, 2015). In this conception, factors such as the subsidence of coastal marginal basins, eustatic variations and regional uplift resulting from the Cenozoic regional compressive phase, favored the incision of river systems (PEULVAST; BÉTARD, 2015). The process of differential erosion exposed most resistant rock compartments and pre-existing channels were superimposed on structures, carving a wide set of transverse valley segments: gorges of short spatial extent, locally called "boqueirões" (MAIA; BEZERRA, 2014; PEULVAST; BÉTARD, 2015). The position of the terraces of the Faceira Formation highlights the maximum base level fall of the Jaguaribe trunk stream (MAIA, 2005). In turn, the inland tabuleiros (Moura Formation and colluvium-eluvial deposits) would be erosional records of the drainage network incision on the study area surfaces.

3. Material and Methods

Morphological and geological evidence of drainage rearrangements were discussed based on data extractions from the Digital Elevation Model (DEM) Advanced Land Observation Satellite (ALOS) model AW3D30 (spatial resolution of 30 m), such as drainage network, hydrographic divides, and other morphometric parameters (local relief, DAI, χ profiles and paleotopographic models); and field work.

Morphological evidence of drainage rearrangements (BISHOP, 1995; HILGENDORF et al., 2020) were visually identified from drainage network extracted from DEM in TopoToolBox (MATLAB scripts) (SCHWANGHART; SCHERLER, 2014) obtained by D8 flow direction algorithm (TARBOTON, 1997) with a pixel threshold above 1 km². This morphological evidence corresponds to elbows of capture (BISHOP, 1995); rivers with asymmetrical margins (SUMMERFIELD, 1991; OLLIER; PAIN, 2000); and convergent drainage patterns (TWIDALE, 2004; TWIDALE; BOURNE, 2010). The boqueirões were visually demarcated in gorges identified from drainage network overlaid to hillshaded DEM's (light angle of 45° and azimuths of 45°, 90°, 135°, 180°, 235°, 270°, 315° and 360°).

The study area local relief was quantified to investigate favorable conditions to drainage rearrangements by changes in local base levels. Furthermore, we search lowered morphologies in divides that could be river paleovalleys called low-relief divides. Local relief was calculated by the difference between maximum and minimum elevations extracted from AW3D30 MDE in moving windows of pre-determined dimensions. Tests were carried out to define the dimensions of the moving windows (2 x 2, 1 x 1, 0.5 x 0.5 km). Due to the general lowered topography of the study area, the moving window that presented the best level of distinction between regional surfaces was 0.5 x 0.5 km. This procedure was carried out in TopoToolBox using the Local Topography algorithm.

Divides were quantified using the Divide Asymmetry Index (*DAI*) in TopoToolBox (SCHERLER; SCHWANGHART, 2020). This index is obtained by measuring hillslopes relief (*HR*) between a point at the top of the divide and another at the river thalweg. The *DAI* is given by the *HR* difference in the divide (*ΔHR*), normalized by the sum of the *HR* differences in the divide (*ΣHR*), according to Eq. (1):

$$DAI = |\Delta HR/\Sigma HR| \tag{1}$$

DAI has values in range 0 < 1, with values close to 0 comprising relatively symmetrical segments and values close to 1 comprising asymmetric divides. Scherler and Schwanghart (2020) consider that *DAI* > 0,5 indicate asymmetric segments and suggest favorable conditions for divide mobility. The processing of this index was also carried out in TopoToolBox, and the *HR* calculation was made according to the threshold established for the drainage network extraction (> 1 km²).

Possible signatures of drainage rearrangements between the Jaguaribe River, and other adjacent rivers were analyzed by χ profiles extractions. Perron and Royden (2013) propose an integral calculation of the normalized channel slope index (k_{sn}), known as χ gradient or χ variable. In this method, the horizontal coordinates of the river profiles (x) are transformed into χ coordinates based on a reference scaling drainage area (A_0) (PERRON; ROYDEN, 2013). Assuming steady-state conditions (balance between uplift and erodibility rates in time and space) the river gradient is given according to Eq. (2):

$$\chi = \int_{xb}^{x} \left(\frac{A_0}{A(x)}\right)^{\theta_{ref}} dx' \tag{2}$$

where xb represents the outlet of a position of interest x, A represents the upstream contribution area and θ_{ref} corresponds to a ratio given between local hydrological parameters (m/n) generally assigned to pre-established values based on other regions of the Earth (reference concavity index).

Then χ profiles were paired to analyze possible drainage areas exchange signatures. In χ gradients (z versus χ), river profiles with linear forms indicate channel stability, and curvilinear forms indicate transient state (WILLET et al., 2014). The comparison of transient signatures in χ profiles of adjacent rivers is used to determine drainage rearrangements, as they can characterize the effects of changes in contribution areas and on the river incision (WILLET et al., 2014; YANG; WILLET; GOREL, 2015). In circumstances of steady-state (E=U), upstream areas transfers mark the following transient signatures (WILLET et al., 2014; WHIPPLE et al., 2017): (i) captor rivers show a decrease in χ, an increase in k_{sn} and concave-up forms; and (ii) captured rivers shows an increase in χ, a decrease in k_{sn} and convex-up forms (Figure 4).

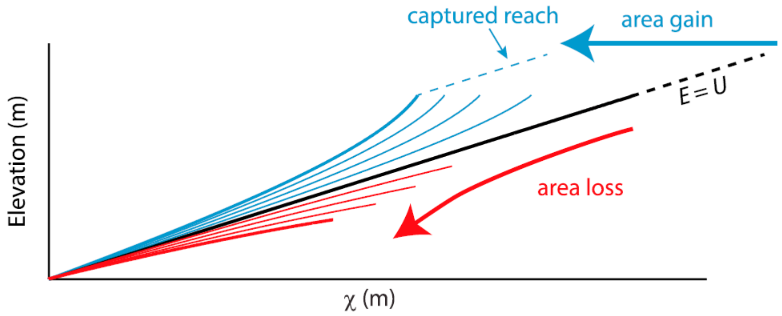

Figure 4. Transfer signature of contribution areas between rivers. Area loss- convex-up red lines. Area gain- concave-up blue lines. The black line indicates steady-state with erodibility (E) and uplift (U) rates on equilibrium. Adapted from Whipple et al. (2017).

The χ profiles were extracted from channels that flows on lithologies with similar erodibility according to the classification proposed by Goudie (2006), from a xb of 100 m. Most of the lithologies drained by these channels comprise crystalline basement rocks such as granites, gneisses (ortho-paraderivatives) and migmatites, classified as strong rocks (GOUDIE, 2006). Only the paired profiles between the Salgado and Pajeú rivers (see Figure 7, G) crossed sedimentary rocks such as sandstones, classified as moderately strong (GOUDIE, 2006). Furthermore, values of 1 m^2 were used for A_0 and 0,45 for θ_{ref} – a value widely used for comparing rivers with different sizes/dimensions in non-glacial erosion landscapes on the Earth (WOBUS et al., 2006).

Paleotopography models were produced according to the Seppômen method (MOTOKI et al., 2008) aiming to reconstruct the paleovalleys morphology of the study area. This method has been used to analyze drainage network evolution on tropical passive margins (COUTO et al., 2012; MARQUES NETO; MOREIRA; DA SILVA, 2019, FREITAS et al., 2022). Seppômen method is limited to modeling river incision scenarios in a DEM, considering only the valley downcutting mechanism, unlike other physical-mathematical modeling methods that consider more complex parameters and interrelationships for riverbed erosion simulation (e.g., stream power). Seppômen method is processed by extraction of maximum elevation points in a grid of moving windows with pre-determined dimensions (MOTOKI et al., 2008). These points are used to produce a topographic model by interpolating maximum elevation values (nearest neighbor) in which valleys tend to be filled in simulated surfaces that interconnect their hillslopes. The size of moving windows influences the valleys fill process because grids with wider windows denotes fewer maximum elevation points to be extracted and more generalization of interpolated surfaces (COUTO et al., 2012). In this context, Seppômen method allows inferring which is evolution mechanism of a drainage network according to valley filled simulations: (i) rivers that maintain their courses while their valleys are filled indicate a superimposition mechanism; and (ii) rivers that have undergone changes in their courses with the filling of their valleys indicate drainage rearrangements. In the study area, these models were generated from windows size tests in the ArcGIS software, with dimensions ranging from 1x1 km to 20x20 km. Models that provided best results have grids with windows dimensions of 1x1 km, 2x2 km, 3x3 km, 4x4 km and 5x5 km. The smaller models indicate the most recent incision scenarios. After that, extractions of the drainage network and hydrographic divides were carried out for each of the five models using the D8 flow direction algorithm (TARBOTON, 1997) at a pixel threshold above 1 km^2.

Furthermore, paleotopographic models were also used for an age estimate to the time that the Jaguaribe River reaches or approaches its current configuration (drainage lines and divides). This estimate was based on eroded material calculation proposed by Freitas et al. (2022), through the difference, pixel by pixel, between DEM AW3D30 and the Seppômen model. The eroded volume was divided by the drainage area (km^2) in order to obtain an average denudation per depth (m^3/m^2). In turn, the average denudation was divided by an average of the denudation rates measured from cosmogenic isotopes (^{10}Be) for the Sertaneja Depression – ~7.7 m/Ma (MORAIS NETO et al., 2012). The result indicated the number of years necessary to Jaguaribe surfaces reach their current topography. It is worth highlighting that the Borborema Province does not yet have effective sample quantities of cosmogenic isotopes (^{10}Be) for producing an absolute regional denudation rate. Most of the data used in denudation rate presented here is reported to limited samples in depressions and escarpments close to the Borborema and Araripe Plateaus (MORAIS NETO et al., 2012). This condition imposes that the estimates obtained through the Seppômen method may be underestimated or overestimated, attributing a complementary character to these estimates in relation to other evidence (morphological and sedimentary).

Subsequently, the morphological and geological evidence was checked in field work that focused on observing river divides areas and boqueirões. The main sedimentary records sought were river terraces in low-relief divides and fluvial-lacustrine deposits dammed along the drainage network. The river terraces in low-relief divides constitutes evidence of river capture, as they prove that the current hydrographic divides were river valleys in the past (BISHOP, 1995; ZAPROWSKI; EVENSON; EPSTEIN, 2002). The fluvial-lacustrine records were important to verify the occurrence of rearrangements due to overflow mechanism and possible endorheism periods (DOUGLASS et al., 2009; HILGENDORF et al., 2020).

4. Results

The regional local relief does not exceed 635 m, while it only reaches 100 m in steeper areas, such as hillslopes of the structural ridges, massifs, and sedimentary plateaus (Figure 5). The predominance of low local relief values is consistent with the level of regional landscape dissection, with the lowest values (< 20 m) occurring in tablelands in structural depressions, uplifted plateaus and in Jaguaribe Valley. The largest local relief (> 300 m) are found in divides supported by crystalline massifs; and in structural ridges controlled by SZ to the S-SE of the Jaguaribe River. The distribution of local relief values also indicates a general trend of increasing values from the Jaguaribe Valley towards the divides on basement rocks.

The morphology shown by local relief map indicates that the Jaguaribe River has a series of intermountain depressed surfaces (20–40 m) delimited by structural ridges (ZC) with low variations in local relief values (Figure 5). These depressions are slightly stepped from E to W and from S to N, towards the trunk stream of the Jaguaribe River. On the other hand, depressions in the Banabuiú, Apodi-Mossoró and Salgado rivers are higher than of the Middle Jaguaribe River (Figure 5). It can also be seen that in the High Jaguaribe River and the Sitiá Creek, the depressed surfaces have sectors with a low-relief divides (local relief that does not exceed 30 m) forming lowered lands that become more steeper towards the adjacent rivers: Poti and Piranji (Figure 5). The same occurs in depressions drained by the Jardim Creek and the Apodi-Mossoró River, with low-relief divides on their limits with the Pajeú and Figueiredo rivers. During the fieldwork it was possible identified that these divide segments have smooth hillslopes without any apparent morphological differences in both sides of the divides.

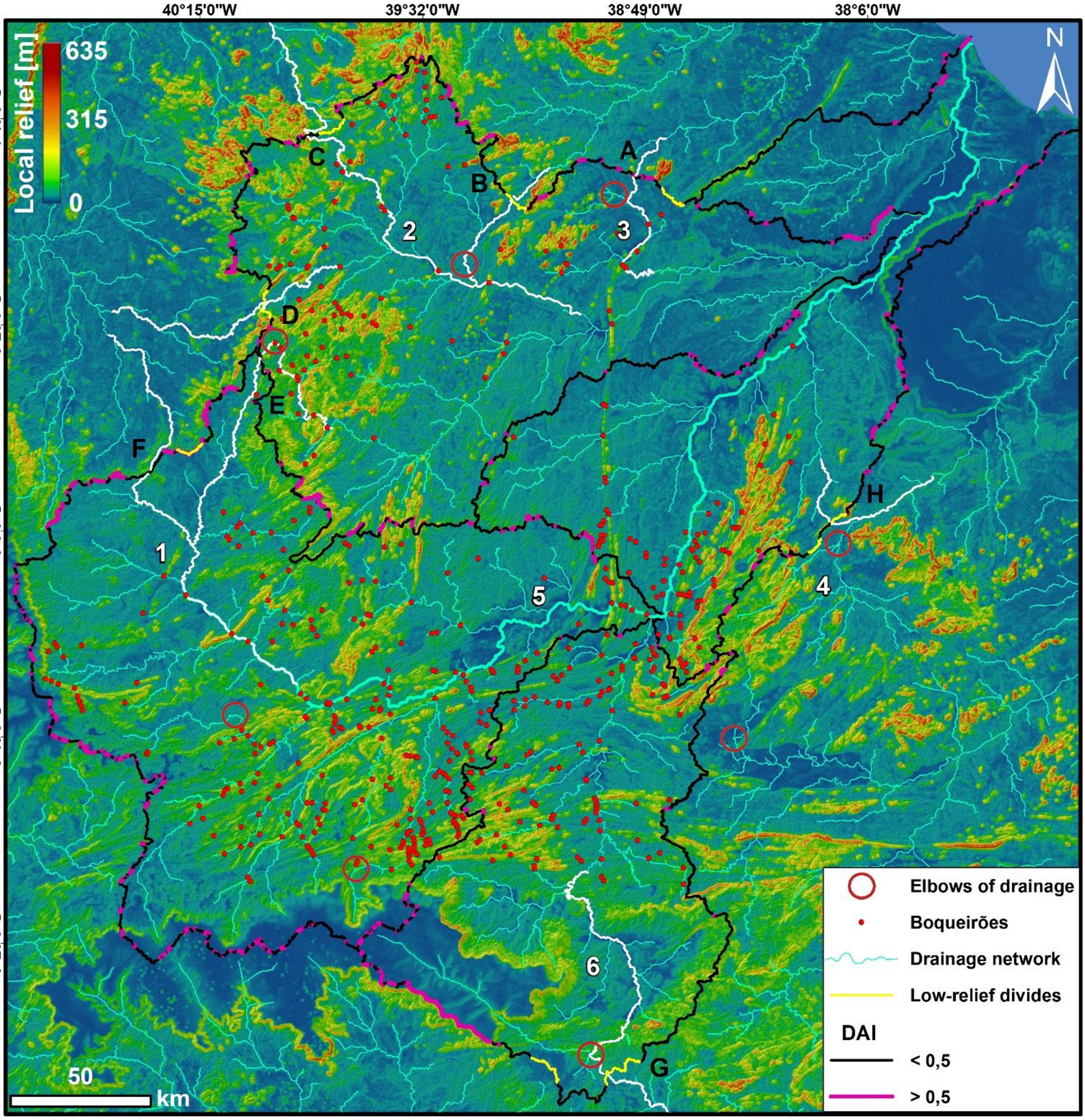

Figure 5. Local relief, *DAI*, and Morphological Evidence. Intermountain depressions: 1 – Alto Jaguaribe, 2 – Quixeramobim, 3 – Sitiá, 4 – Apodi-Mossoró, 5 – Iguatu Basin and 6 – Jardim. Elevation and drainage data derived from MDE AW3D30 (30 m). Highlights include the elbows of drainage/capture that show sudden changes in flow orientation (inflections) towards the downstream, characterizing "hook" patterns. The black letters (location of the divides) and the white channels (rivers opposite the divide) mark the location of the paired χ profiles in Figure 7.

The *DAI* was calculated for 3935 segments of the Jaguaribe River. Symmetrical segments (DAI < 0,5) are predominant (Figure 5) and around 727 segments show asymmetrical morphologies (18.4% of DAI > 0,5). These are mostly concentrated on the western margin of the Jaguaribe River. Asymmetrical segments have predominant small *ΔHR* between their sides (0.5 < DAI < 0.7) and only 33.7% of the segments exhibit high *ΔHR* (DAI > 0.7). Around 63.7% of the segments with high *ΔHR* are on the divides with the Parnaíba (including the Poti River) and São Francisco (except for the Pajeú) rivers (Figure 5). Generally speaking, divides sides with lower *HR* values are drained by the Jaguaribe River or by its tributaries. The asymmetrical subdivides with high *DAI* values are drained by the Banabuiú River. In this context, *DAI* indicates a predominance of stable divides in the study area, with small mobility trends towards the Jaguaribe River. Furthermore, the Banabuiú River tends to mobility in relation to other inner tributaries of the Jaguaribe River.

The drainage patterns are slightly radial to convergent, with tributaries showing a marked structural control in depressed surfaces drained by the trunk stream of the Jaguaribe River (High Jaguaribe and Iguatu Basin), by the Quixeramobim River (Banabuiú River) and by the Apodi-Mossoró River (Figure 5). The drainage convergent patterns of the High Jaguaribe and the Quixeramobim River expand upstream (SW) of the rivers that drain the Atlantic side to the NW (Piranji, Choró, Acaraú and Apodi-Mossoró). Both drainage networks converge towards the SZ (Sabonete-Inharé, Senador Pompeu and Orós), crossing them from boqueirões controlled by fractures with E-W and NW-SE trends (Figure 5). Furthermore, some headwaters on these depressions also draining low-relief divides like in Quixeramobim/Choró Divide, Sitiá/Piranji Divide, Jardim/Pajeú Divide and Apodi-Mossoró/Figueiredo Divide. In addition, some of the depressions also have channel inflections in a "hook" pattern like elbows of capture, as in the case of the Sitiá and Jardim Creeks (Figure 5). The latter, which rises above Araripe Plateau flows in a NW-SE trend and curves in a S-N trend until the adjacent depression where it converges with the Salgado River. Similar behavior is observed in Apodi-Mossoró River that flow in a SE-NW trend and then curves approximately in a SW-NE trend in their middle course. In a smaller dimensional scale, are also observed in the "hook" patterns between Jaguaribe and Poti headwaters (Figure 5).

Around 66.7% of the total boqueirões in the study area are concentrated in Sertaneja Depression 2. Multiple boqueirões generally cross the same SZ with morphologies in valleys with wide bottoms and smooth hillslopes; or narrow-bottomed valleys with steep hillslopes (Figure 6, A and B).

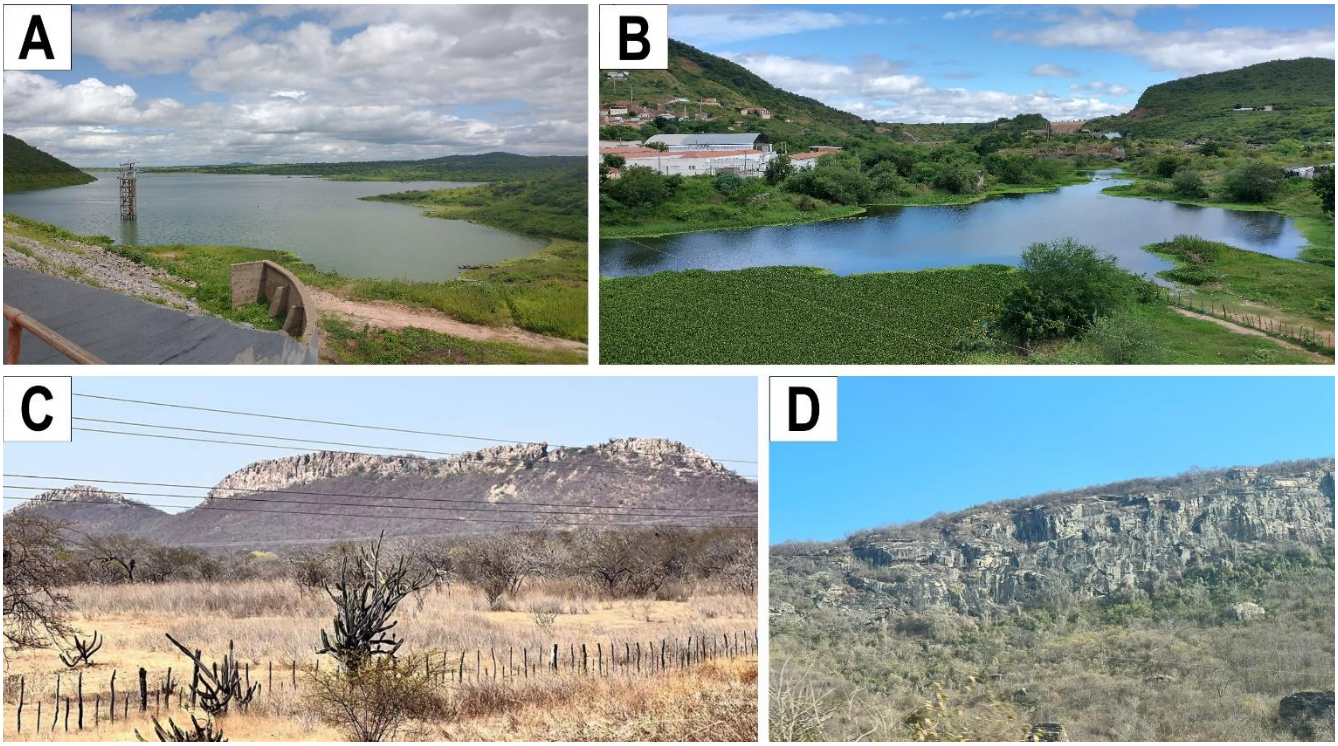

Figure 6. Boqueirões identified along the Jaguaribe River. A- Boqueirão in an extended valley above the Senador Pompeu ZC, drained by the Banabuiú River. B- Boqueirão in a narrow valley above the ZC Orós, drained by the middle course of the Jaguaribe River. C- Fractured ridges along the ZC of the study area. D- Fracture systems (vertical and horizontal) in ZC, sometimes associated with the detachment of rounded and angular rock blocks.

"V" shaped openings controlled by faults and joints are common on structural ridges supported by SZ (Figure 6, C). Along these ridges, orthogonal sets of fractures were also identified in outcrops that underwent chemical weathering associated with the detachment of in situ blocks according to the arrangement of vertical and horizontal fractures (Figure 6, D).

The paired χ profiles show segments with a tendency for area gains (concave-up forms and decreasing χ values in captor channels). These segments are located on divides of the Jaguaribe River with the Piranji, Apodi-

Mossoró, Poti and Banabuiú rivers (the last two in relation to the High Jaguaribe). In other words, the profiles with a tendency to gain area are in places where "hook" patterns (channels inflections) were identified (Figure 7, A, D, E, F and H). In the other divides, the profiles sampled present balance between the paired channels (Figure 7, B, C and G). This context indicates areas gains favorable to the Jaguaribe River in divides with the Piranji, Poti (in relation to the Banabuiú) and Pajeú rivers. On the other hand, the Jaguaribe River tends to small areas losses in the divides with the Banabuiú (in relation to the High Jaguaribe), Poti and Apodi-Mossoró rivers.

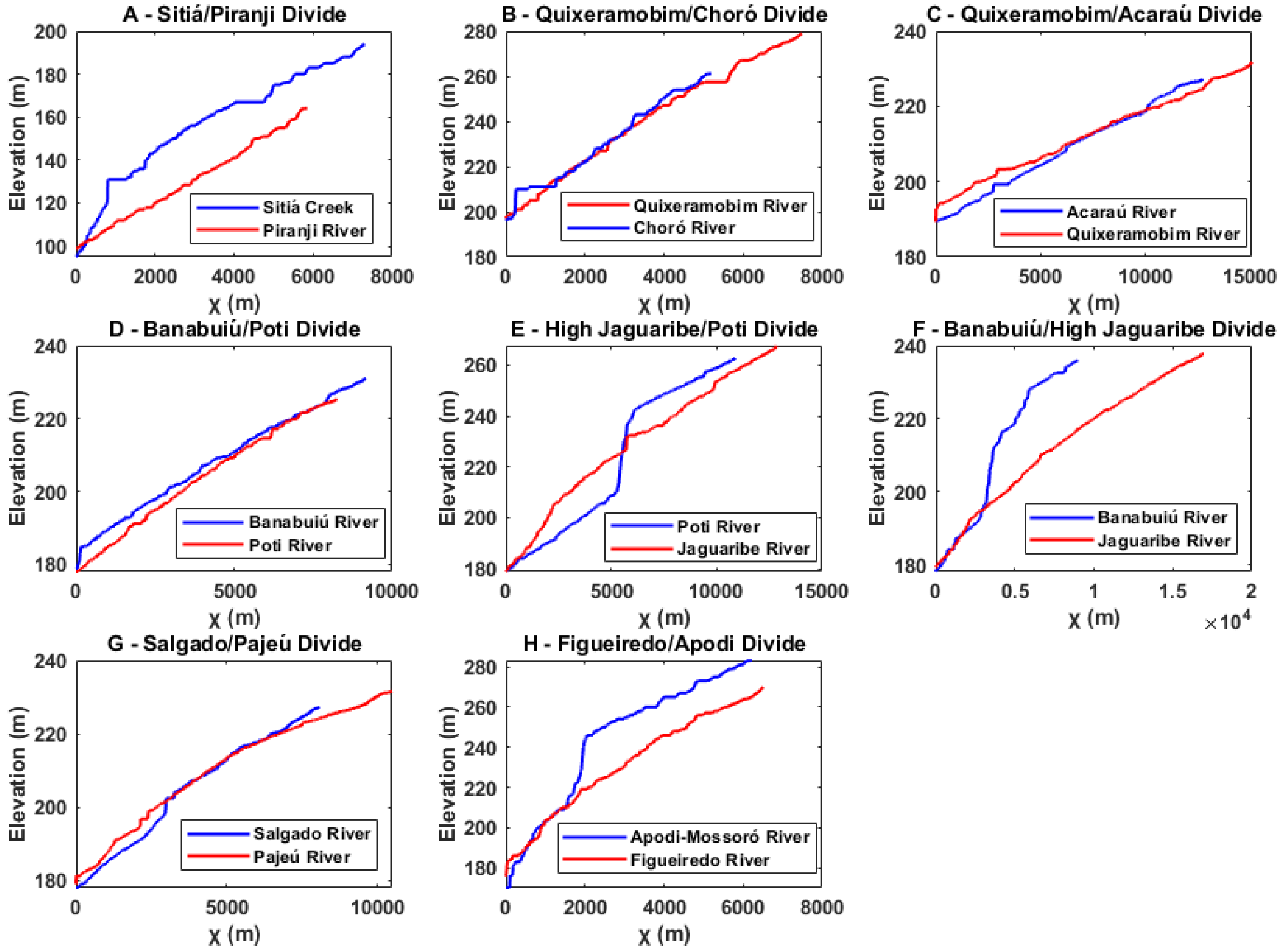

Figure 7. Paired χ profiles of the Jaguaribe River and other adjacent rivers. The location of the profiled rivers is available in Figure 5. Parameters used: $A0 = 1\ m^2$; $\theta ref = 0.45$ and xb = 100 (A), 180 (C, D, E, F, G and H) and 200 (B).

Paleotopographic models show a gradual widening of the intermountain depressions following the retreat of hillslopes and escarpments (Figure 8). The sector that presented the largest river incision was the Jaguaribe Valley (Faceira Formation, Figure 1). As the valleys were filled, changes were seen in the configuration of divides and in the contribution upstream areas in the 5 x 5 km and 4 x 4 km models compared to the DEM AW3D30 (Figure 8, A, B and F). In the part of the depressions currently drained by the High Jaguaribe, the Sitiá Creek and the Jardim Creek are disconnected from the trunk stream of the Jaguaribe River. The 5 x 5 km and 4 x 4 km models also indicate more extensive headwaters for the Figueiredo River, in areas that are nowadays drained by the Apodi-Mossoró River (Figure 8, A and B).

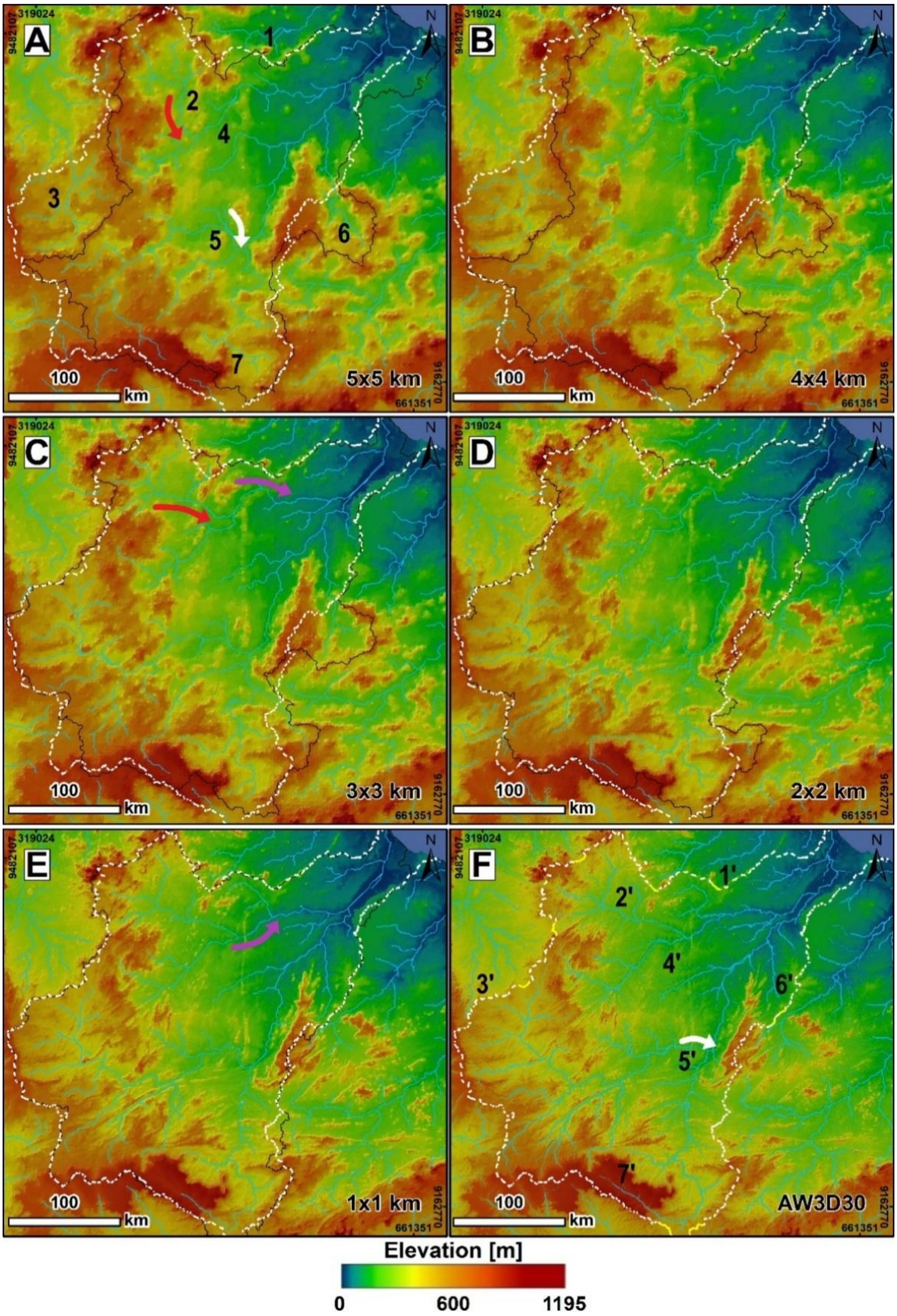

Figure 8. Paleotopography of the Jaguaribe River and adjacent rivers. A- Model 5 x 5 km. B- Model 4 x 4 km. C- Model 3 x 3 km. D- Model 2 x 2 km. E- Model 1 x 1 km. F- MDE AW3D30. The numbers in black indicate changes in the drainage areas after drainage rearrangements: 1-1'- Piranji, 2-2'- Quixeramobim, 3-3'- Poti, 4-4'- Banabuiú, 5-5'- Middle Jaguaribe, 6-6'- Figueiredo and 7-7'- Salgado. The filling of the valleys is established from F to A, with a scenario where superimposition is not predominant mechanism. Arrows indicate internal flow changes: Red- connections modification between the Quixeramobim and Banabuiú rivers; Purple- connections modification between the Banabuiú and Jaguaribe rivers; and White- connection modification in the Middle Jaguaribe. The black lines indicate the paleodivides of each model. The dashed white lines show the current divide configuration of the Jaguaribe River to compare the drainage network in each model. The yellow lines on DEM AW3D30 shows the position of low-relief divides.

Furthermore, it is also possible to notice changes in some of the current confluence segments in the Jaguaribe tributaries, with emphasis on changes in Quixeramobim, Banabuiú, and Middle Jaguaribe rivers confluences in a NW-SE trend (Figure 8, white and red arrows). From Model 3 x 3 km to DEM AW3D30, the drainage incision advance is responsible for the rearrangement that makes the Jaguaribe River reach its nowadays configuration (Figure 8, C, D, E and F). In general, the rivers that flowing in depressions disconnected from the Jaguaribe River (High Jaguaribe, Sitiá Creek and Jardim Creek) are being connected to the trunk stream of Jaguaribe River in these models. Area's losses, on a larger scale, are also caused by the disconnection of the Figueiredo and Quixeramobim paleoheadwaters in response to erosive advance of the Apodi-Mossoró, Acaraú and Choró rivers. Internally, the continuous retraction of the structural ridges favors river interceptions and new connections between tributaries that draining steeped depressed surfaces. This morphogenesis shows that part of the boqueirões in the study area did not evolve by superimpositions. On the contrary, some boqueirões evolved by drainage rearrangements.

Considering the 1 x 1 km Model (Figure 8, E) as the moment when the Jaguaribe drainage network reaches its nowadays configuration, we can estimate that ~2025 km^3 were eroded up to the dissection level identified in the DEM AW3D30. This means ~27,6 m depth per km^2 (m/km^2). According to the average denudation rates of the Sertaneja Depression – ~7.7 m/Ma – the current drainage network would have needed 3.6 Ma to erode the entire volume of material calculated between the Model 1 x 1 km and the DEM AW3D30. Therefore, the nowadays drainage network has started in the Pliocene, while some internal changes to the Jaguaribe River would be even younger, for example, the possible rearrangement in the Middle Jaguaribe on the Moura Formation records (Figure 7 and Figure 9, red arrows).

In field work, no terraces or others sedimentary records were found preserved over divides or in inner plateau areas. However, massive banks from the Moura Formation were identified with evidence of natural topographic damming associated with Orós SZ, that controls the Iguatu Basin half graben (Figure 9).

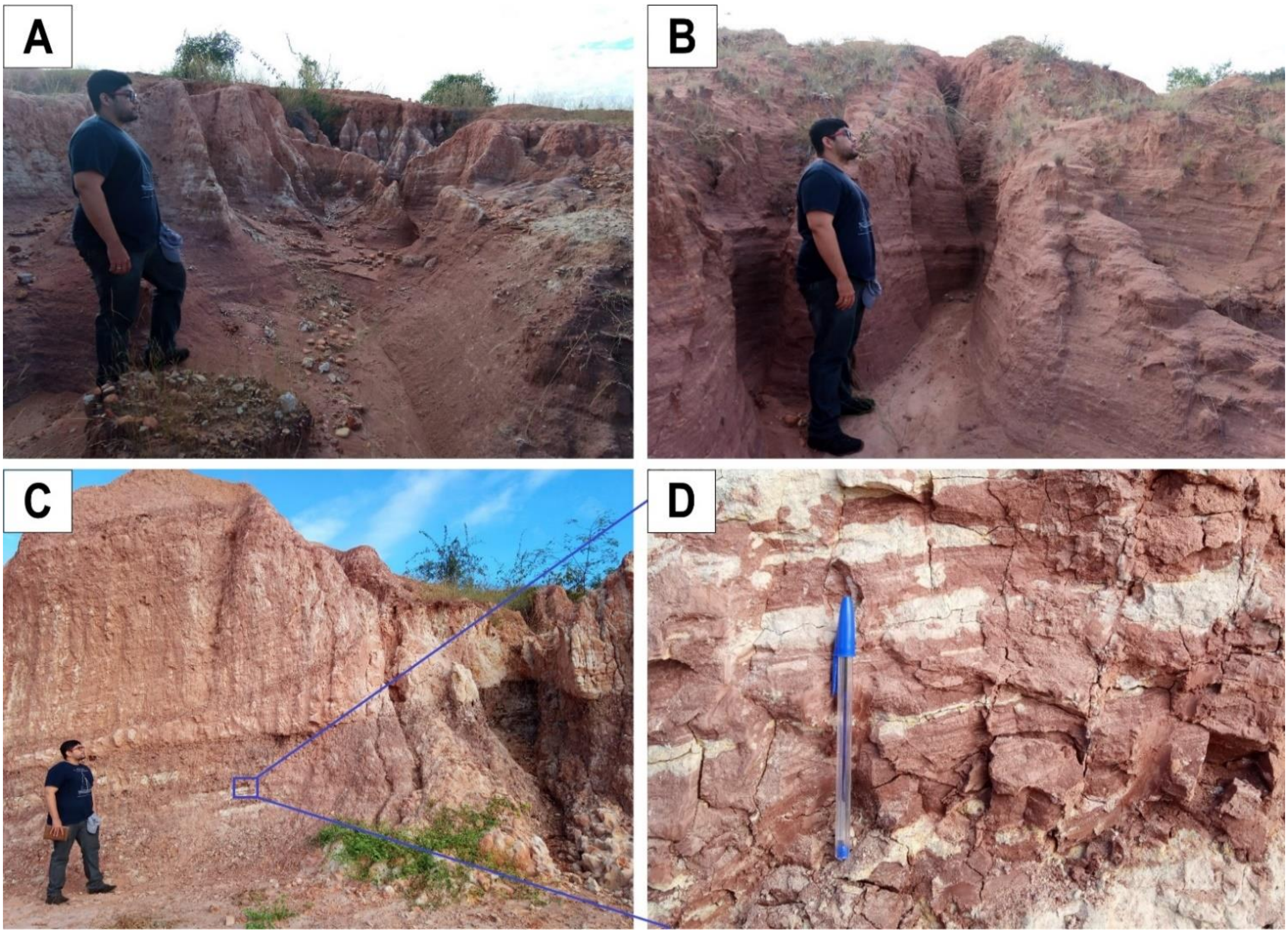

Figure 9. Moura Formation in Middle Jaguaribe River. A- Sandy strata without evidence of flow. B- Silty-clay strata without evidence of flow. C- Intercalations of silt and clay on a detailed scale. D- Detail of the silt-clay intercalations.

In general, these deposits do not have stratification and their composition varies toward the top from medium to fine sands (Figure 9, A and B) to silt-clay intercalations (Figure 9, C and D) in addition to the localized occurrence of thin conglomeratic strata in a coarse sand matrix. This suggest that these massive banks were deposited in lacustrine area or in a fluvial low transport capacity environment. Furthermore, the area of occurrence of the Moura Formation is restricted to the Iguatu Basin and is not identified in the adjacent sedimentary basins (Lima Campos, Malhada Vermelha and Icó). This indicates a cessation of flow between these basins (a dam), which were connected throughout Cretaceous deposition in the region.

5. Discussion

The results indicate that Cretaceous morphotectonics was very important for the regional topographic configuration of the steeped depressed surfaces, in accordance with the axis of the Cariri-Potiguar Rift. However, some Cretaceous geological and lithostructural aspects, used as arguments in favor of the superimposition mechanism in the region are questionable.

The absence of Cenomanian to Neogene (~50 Ma) sedimentary records, associated with the thickening of bioclastic strata in the coastal basins (Ceará and Potiguar), indicates that until the Oligocene, Northern Borborema Province had already experienced intense exhumation of inner amphitheater depressions (PEULVAST; CLAUDINO -SALES, 2004). The Oligocene marks the beginning of the last phase of SZ reactivations with records available in the study area, which lasted until the Miocene (CAVALCANTE, 2006; MORAIS NETO et al., 2009). A possible consequence of these reactivations would be the structural ridges (SZ) uplift, consistent with the morphotectonic regional events in the study area (PEULVAST et al., 2008). Thus, this region which underwent intense denudation of the Cretaceous covers until the Oligocene, possibly no longer had favorable conditions for the superimposition mechanism to take effect (absence of covermass) during the last pulse of regional structural reactivation (Mioceno). The presence of “V” shaped openings on the structural ridges suggests possible areas of incision that were abandoned due to the continuous regional uplift. Furthermore, the depositional advance of Neogene-Quaternary covers over the amphitheater inner lands also reinforces this interpretation because at the top of boqueirões (as in the case of High Jaguaribe), there are colluvium-eluvial deposits that do not have or rarely keep fluvial structures that demonstrate existence of a paleochannels. Therefore, it is understood that superimposition was an effective mechanism for regional evolution, but that from the Neogene onwards, this mechanism became secondary or at least ineffective in the evolution of some tributaries of the Jaguaribe River. Conversely, the scenario from the Miocene onwards appears to be favorable for the fluvial evolution of these same tributaries through drainage rearrangement processes.

The Oligocene-Miocene reactivations of the SZ’s (Jaguaribe and Portoalegre) contributed to the tectonic inversion of the Potiguar Basin (LOPES et al., 2018). Linked to this, the coast underwent reactivation of main graben faults at the mouths of the Jaguaribe and Apodi-Mossoró rivers in response to the regional compressive phase (OLIVEIRA et al., 2018; BEZERRA et al., 2020). This tectonic inversion is consistent with a base level fall context of these rivers, marked by bed incision in their valleys (MAIA; BEZERRA, 2012). This differential base level fall in relation to the rivers that drain the study area NW coast, possibly favored the headward erosion necessary to headwaters expansion of the Jaguaribe River over headwaters of the Piranji, Choró, Acaraú and Poti rivers. This erosive regression would have been responsible for the rupture of divides (possibly coincident with the structural ridges), formation of new boqueirões and drainage areas transfers.

Evidence of epigenic weathering in SZ’s also suggests that these drainage rearrangements took advantage of lithostructural weak zones. The fractured areas possibly mediated the subsurface wear of the substrates with the advance of a vertical weathering front along the fractures, while the advance of the headwards erosion over the hillslopes was responsible for captures made by the Jaguaribe and Apodi-Mossoró rivers (in relation to the Figueiredo). Similar models were proposed by Cavalcante (2006) and Peulvast et al. (2006) for the Banabuiú River morphogenesis.

The absence of river deposits or pebbles preserved in divides makes it difficult to identify the drainage areas transferred in this process. However, the set of following morphologies reinforces the hypothesis of drainage rearrangements: (i) disproportionality of areas drained by the Jaguaribe River and the rivers that drain the NW coast, (ii) slight steeped depressions of the Jaguaribe River, (iii) occurrence of low-relief divides drained by opposing headwaters with relative trend of flow continuity, (iv) slightly radial or convergent drainage patterns to boqueirões and (v) drainage "hook" patterns like elbows of captures. Thus, these evidence shows that the drainage rearrangements would be responsible for the incorporation of ~9295 km² (12.6%) of the drained areas on the western margin of the Jaguaribe River (High Jaguaribe, Jardim Creek and tributaries of the Banabuiú River) and the retraction of ~3838 km² (5.2%) of its eastern margin (Figueiredo River headwaters area losses). Stratigraphic data from coastal marginal basins supplied by the Acaraú, Choró and Piranji rivers indicate loss of sedimentary recharge, with moderate and discontinuous post-Miocene sedimentary influxes (PEULVAST et al., 2008). This fact is consistent with the hypothesis of drainage rearrangements and changes in the upstream contribution areas of these rivers.

Analysis of the paired χ profiles and *DAI* data indicates a context of drainage rearrangements that altered the equilibrium between the investigated headwaters, but which in general is not more active, since the steady state is predominant in the analyzed divides. Areas transfers signatures preserved in paired χ profiles may indicate recent exchanges or slow readjustment capacity of river systems (return to equilibrium) due to low erosive efficiency and/or the size of the transferred areas (BEESON; MCCOY; KEEN- ZEBERT, 2017). These circumstances are observed in the study area in relation to predominantly intermittent to ephemeral rivers.

The paleotopographic reconstruction reinforces the hypothesis of river captures due to the base level fall of the mouth of the Jaguaribe River. The continuous simulation of filling the valleys reveals that some of the boqueirões in the study area were broken and their upstream drainages reorganized (High Jaguaribe, Quixeramobim River, Jardim River), while the other boqueirões deepened their valleys by incising the structures. Furthermore, paleotopographic models indicate that the Jaguaribe River current configuration of the drainage areas was only reached in the Pliocene, result that disagrees with the hypothesis of ancient tributaries superimposed on SZ's since the Cretaceous.

In parallel, the Cenozoic tectonic context and other data from this research also suggest the possibility of a regional endorheic phase pre or syn drainage rearrangements. After the last phase of structural reactivation, in the Miocene, the drainages that flowed over the intermountain depressions may have suffered isolation from their confluents, attributing a new aggradational phase to these surfaces through the last regional SZ uplift. In this context, rivers that progressed their incision over regional structures lost erosive capacity with the reactivation of these SZ and were disconnected, while their upstream contribution areas were limited by topographic barriers (structural ridges). This process would form endorheic drainage networks in the study area. Thus, the ancient paleoheadwaters of the Piranji, Choró, Acaraú, Poti and Figueiredo rivers may have been isolated from their main channels during this phase.

The existence of damming signs in the Moura Formation, restricted to the Iguatu Basin, may represent the last trace of this possible phase of endorheic aggradation in the Jaguaribe River (Figure 10). The damming model is proposed by Arima (2007), indicating that the massive silt-clay banks of the Moura Formation are associated with natural damming resulting from structural reactivations (reverse faults) of the Orós SZ.

As indicated in the paleotopographic models and the estimate of eroded material, this reconnection must have only been effective in the Quaternary. This estimate is consistent with the current preservation of the Moura Formation in the study area. This estimate is also consistent with an important global paleoclimatic transition period, running from the Pliocene to the Pleistocene (BRIDGLAND; WESTAWAY, 2008). This climate transition caused an increase in a global river incision in Plio-Pleistocene glacial-interglacial transitions, responsible for river captures and integration of endorheic basins across the Earth (STOKES et al., 2017; CUNHA et al., 2019; FREITAS et al., 2022).

Correlating Arima's model (2007) with thermochronological data (CAVALCANTE, 2006; MORAIS NETO et al., 2009), in the Miocene, after structure's reactivation, the Middle Jaguaribe bed may have been filled (deposition of the Moura Formation) and its start the possible endorheic phase in the High Jaguaribe. The subsequent rearrangement would be responsible for the incision on the Moura Formation and the dissection of the current inner tabuleiros.

Finally, the presence and arrangement of the Moura Formation also suggest the possibility of drainage rearrangements by overflow mechanism. Characterized as a river diversion process in Bishop's (1995) classification, overflow results from a riverbed aggradation (HILGENDORF et al., 2020). The sediments are dammed generating an increase in the water level bed which, in a flood episode, exceeds the topographic barrier and overflow into an adjacent river. (STOKES; MATHER, 2003). The constancy of flood episodes generates erosive wear of the topographic barrier to the point that the channels, over time, are connected, promoting a drainage rearrangement (DOUGLASS et al., 2009).

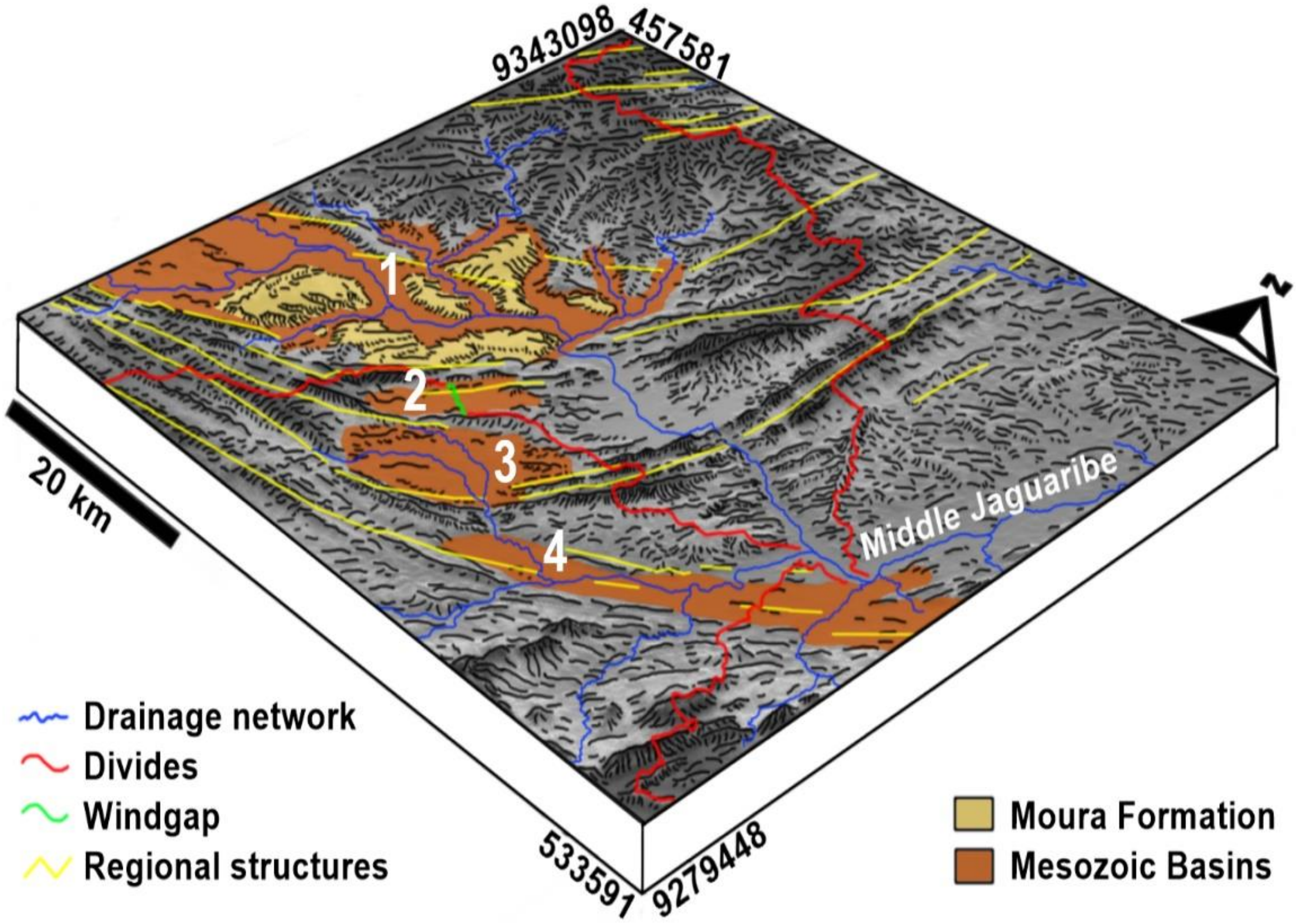

Figure 10. Structural barriers for the Moura Formation in the Middle Jaguaribe. Cretaceous Basins: 1- Iguatu, 2- Malhada Vermelha, 3- Lima Campos and 4- Icó. Note that the Moura Formation only denotes records in the Iguatu Basin, and that Lima Campos and Malhada Vermelha Basins no longer have a connection with the Iguatu Basin

In this context, the Moura Formation, and its massive banks with signs of damming support this possibility. Furthermore, the morphological aspects described above can also be used to design this mechanism in other tributaries of the Jaguaribe River. However, the absence of sedimentary damming records in the other depressions makes the applicability of the model difficult to a regional scale. Specifically for the depression of the Iguatu Basin, the convergent pattern of drainage, the records of the Moura Formation at the base of Orós SZ ridges, the evidence of structural reactivation (ARIMA, 2007) and the presence of fracture systems are important evidence for the overflow be debated.

6. Conclusions

Based on the evidence presented, it is concluded that the Jaguaribe River, on the semi-arid South American passive margin, underwent drainage rearrangement processes during its evolution. Superimpositions occur widespread in the study area, reflecting accentuated control of the rifting context and ancient regional Cretaceous depositional surfaces. However, despite this legacy, the data presented in this research reinforce that the current hydrographic configuration of some tributaries is more recent and comes from Neogene-Quaternary River capture. Cenozoic structural reactivations were essential for the development of these drainage rearrangements, while they subordinated tributaries expansion on the western margin and the headwaters retractions on the eastern margin of the Jaguaribe River. Therefore, even in depressed semi-arid surfaces, with headwaters that flow over low-topographic divides, drainage rearrangements can contribute substantially to the landscape evolution.

This research shows that processes such as base level fall and epigenic weathering can condition the development of river captures in flattened topography. The anomalous lowering of the base level on the Jaguaribe River mouth is a potentially important mechanism for the evolution of their drainage network and should be considered in the evolution of other rivers in the Northern Borborema Province. Furthermore, it sets up a path of investigation to understand the morphogenesis of other locations in similar environmental contexts in Brazil. Analysis of morphological evidence and geomorphometric data can provide effective clues for determining these types of drainage rearrangements. It is worth highlighting that the study area of this research is a fertile field for continued investigation of the topic based on: (1) analysis of the erosion rates of the rivers involved in the rearrangements; (2) determination of the age of the Moura Formation deposits and their possible relationship with a local endorheic phase; (3) importance of lithostructural conditions in epigenic processes; and (4) analysis of possible drainage rearrangements due to overflow.

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