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Research Article

Planation surfaces and divide mobility in the Chapada do Araripe (NE Brazil)

Superfícies de aplainamento e mobilidade de divisores hidrográficos na Chapada do Araripe (NE Brasil)

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Abstract: This study investigates planation surfaces and the dynamics of river divides in Northeast Brazil, with a focus on the Chapada do Araripe region. The research integrates morphometric metrics and regional geological interpretation to understand the processes that shape the evolution of the relief through the migration of divides and the interposition of planation surfaces. Geomorphometric metrics based on a digital elevation model (including TPI, Ksn, χ index, and Gilbert metrics) were applied, and three main surface levels were identified: S1 (>710 m), S2 (485–710 m), and S3 (<485 m), which reflect distinct stages of pediplanation since the Cretaceous. The analysis reveals that the preservation of these surfaces is strongly conditioned by structural, lithological, and climatic factors. Additionally, the results indicate variations in the stability of the river divides among the Parnaíba, Jaguaribe, and São Francisco basins, with a tendency toward migration on the Jaguaribe-São Francisco and São Francisco-Parnaíba divides, associated with fluvial reorganization processes. This work proposes an evolutionary model for the region's landscape, highlighting the interactions among tectonic heritage, differential erosion, and climate change over geological time.

Keywords: Planation surfaces; landscape evolution; geomorphometry; divide stability.

Resumo: Este estudo investiga as superfícies de aplainamento e a dinâmica dos divisores hidrográficos no Nordeste do Brasil, com foco na região da Chapada do Araripe. A pesquisa integra métricas morfométricas e interpretação geológica regional para compreender os processos que moldam a evolução do relevo por meio da migração de divisores e interposição de superfícies de aplainamento. Foram aplicadas métricas geomorfométricas com base em modelo digital de elevação (incluindo IPT, Ksn, índice χ e métricas de Gilbert) e identificados três níveis principais de superfície: S1 (>710 m), S2 (485–710 m) e S3 (<485 m), que refletem estágios distintos de pediplanação desde o Cretáceo. A análise revela que a preservação dessas superfícies está fortemente condicionada por fatores estruturais, litológicos e climáticos. Adicionalmente, os resultados indicam variações na estabilidade dos divisores hidrográficos entre as bacias do Parnaíba, Jaguaribe e São Francisco, com tendência de migração nas faces Jaguaribe-São Francisco e São Francisco-Parnaíba, associada a processos de reorganização fluvial. O trabalho propõe um modelo evolutivo para a paisagem da região, ressaltando a interação entre herança tectônica, erosão diferencial e as mudanças climáticas ao longo do tempo geológico.

Palavras-chave: Superfícies de aplainamento; evolução de paisagens; geomorfometria; estabilidade de divisores.

1. Introduction

Northeastern Brazil offers a compelling setting for studying landscape evolution, combining remarkable morphostructural diversity shaped by the interplay between an intensely deformed Precambrian basement and overlying sedimentary covers. Cenozoic climatic oscillations further accentuated this complexity, imprinting a distinctive geomorphic signature on the region (Peulvast; Bétard, 2015; Maia; Bezerra; Sales, 2010). The widespread preservation of planation surfaces of varying ages makes the Northeast a valuable archive of geomorphological history, integrating long-term processes — such as pediplain cycles — with ongoing ones, including drainage network reorganization and divide migration.

The Borborema Province, one of the region's principal structural domains, displays stepped surface levels reflecting successive pediplain cycles driven by uplift and erosion (Maia; Bezerra; Sales, 2010). These surfaces extend over sedimentary basins such as the Araripe Basin, where the post-rift stratigraphic record of Atlantic opening bears the strong imprint of reactivated Neoproterozoic shear zones (Castro; Castelo Branco, 1999; Peulvast; Bétard, 2015). Oliveira et al. (2025) recently quantified denudation rates around this plateau using cosmogenic nuclides (^{10}Be and ^{26}Al), obtaining low values (6–19 m/Myr) consistent with a stable cratonic setting, and demonstrated that differential erosion — rather than active tectonics — is the primary driver of regional relief inversion. This chronological framework establishes preserved planation surfaces both as records of long-term erosional history and as markers of the disequilibrium conditions driving current divide dynamics.

Drainage divide migration in response to topographic disequilibrium is well documented along elevated continental margins. In southeastern Brazil, along the Serra Geral escarpment, contrasts in χ values and underfitted valleys indicate progressive capture of interior drainages by coastal tributaries (Sordi et al., 2018; Dal Pai et al., 2023; Crelier et al., 2025; Haag et al., 2025), with denudation rates up to eight times higher along the escarpment reinforcing coastal basin expansion. Similarly, the South American transcontinental divide — separating the Paraná from Atlantic basins — shows a systematic southward migration trend linked to lithostructural contrasts and base-level feedbacks (Crelier et al., 2025).

In northeastern Brazil, evidence of fluvial reorganization is also emerging. Rodrigues et al. (2024) propose that the Poti River canyon, at the elevated rim of the Parnaíba Sedimentary Basin, formed through subsurface stream capture in siliciclastic rocks, transferring approximately 10,540 km² from the paleo-Acaraú catchment. Bastos et al. (2024) further suggest that more intense denudation in the basin's western sector may be driving additional captures. Despite these advances, integrated quantitative approaches combining morphometric metrics, geomorphic surfaces, and drainage dynamics remain scarce.

We propose the following hypothesis: the current configuration of drainage divides around the Chapada do Araripe reflects both long-term structural and lithological inheritances — recorded in stepped planation surfaces — and active erosional disequilibrium promoting differential divide migration between basins with contrasting base levels and erosive capacities. To test this, we applied morphometric indices (χ index, Ksn, and Gilbert metrics) integrated with planation surface mapping and longitudinal profile analysis. Specifically, the study aims to: (i) identify and characterize altimetric levels of preserved erosional surfaces; (ii) assess structural and lithological controls on their preservation; and (iii) evaluate the stability and reorganization potential of the main regional drainage divides. Together, these analyses support a landscape evolution model linking long-term inheritances to present-day dynamics in the northeastern semi-arid region.

2. Study Area

The study area encompasses the Chapada do Araripe and its surroundings, bounded by three major Brazilian hydrographic basins: the Jaguaribe Basin to the north, the São Francisco Basin to the south, and the Parnaíba Basin to the west (Figure 1).

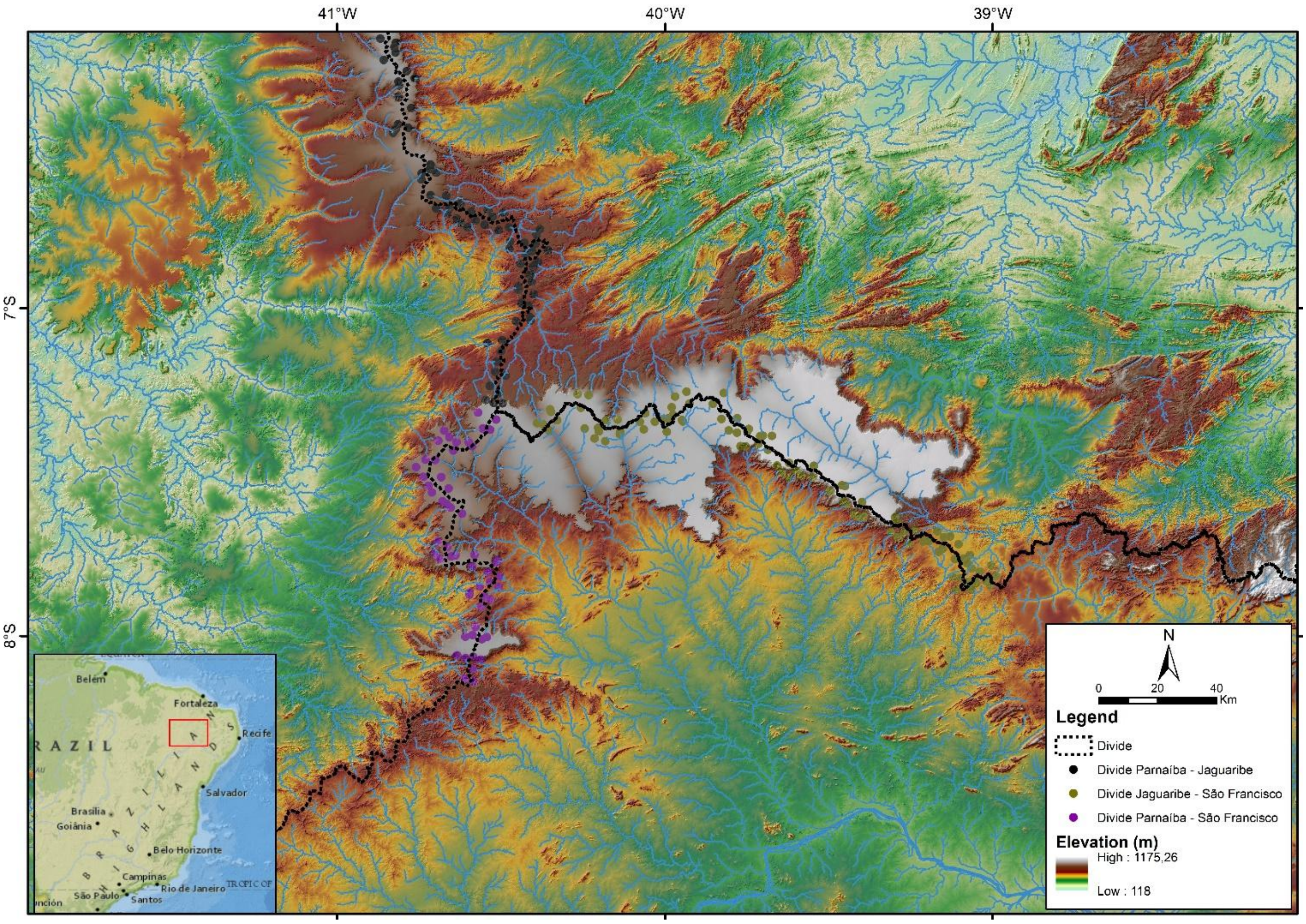

Figure 1. Location map of the study area.

2.1. Geological and geomorphological setting

Most of the study area is within the Borborema structural province (Almeida et al., 1977), except for its western portion, which belongs to the Parnaíba province. The Borborema Province comprises a set of massifs and fold systems structured during the Brasiliano orogeny in the late Neoproterozoic (Oliveira, 2008). The region is characterized by Precambrian terrains overlain by Mesozoic sedimentary basins (Assine, 1992). Its lithological framework is dominated by gneisses and migmatites forming the basement, semi-continuous belts of supracrustal rocks, and Brasiliano intrusions, all crosscut by transcurrent shear zones (Neves, 2003).

The basement is intensely deformed and dissected by Neoproterozoic shear zones. During the Early Cretaceous, reactivation of these structures during Mesozoic intracontinental rifting controlled the internal architecture of the intracratonic sedimentary basins (Castro; Castelo Branco, 1999).

Among the sedimentary basins of the Cariri Valley rift — including the Barro, Betânia, Cedro, Fátima, Padre Marcos, São José do Belmonte, and Socorro basins, located between the Patos and Pernambuco shear zones — the Araripe Basin is the most extensive, covering approximately 8,000 km² (Ponte; Ponte Filho, 1996). Castro and Castelo Branco (1999) interpret this basin cluster as remnants of a formerly larger Mesozoic basin that underwent intense erosional dissection.

The elongated west–east shape of the Araripe Basin reflects reactivation of weakness zones associated with the Patos lineament. NE-SW-trending structures within the basin are concordant with the extensional deformation axis and tectonic subsidence responsible for the Cariri–Potiguar Trend basins and are linked to Proterozoic zones of weakness (Matos, 1987; Castro; Castelo Branco, 1999). The Dom Leme Horst separates the Feitoria (west) and Cariri (east) sub-basins.

The Araripe Basin preserves the most complete stratigraphic record of Cretaceous rifting in the interior Northeast, encompassing fluvial, lacustrine, and coastal depositional systems (Assine, 1992; 2007) (Figure 2). The Paleozoic Cariri Formation consists of immature sandstones from braided fluvial systems with NNW-directed paleodrainage, correlative to the Serra Grande Group of the Parnaíba Basin. The pre-rift Brejo Santo and Missão Velha formations (Upper Jurassic) record lacustrine and braided fluvial environments, respectively, with SSW paleodrainage toward the eastern margin basins. The Aptian–Albian Santana Formation is subdivided into three members: Crato (lacustrine limestones with a rich fossil fauna), Ipubi (evaporites deposited in an arid coastal setting), and Romualdo (marine-influenced shales with concretions and coquinas). The uppermost Exu Formation, deposited between the Albian and Cenomanian in unconformity with underlying units, comprises upward-fining fluvial sandstones from braided systems. Its westward paleocurrent pattern reflects epeirogenic uplift and the restructuring of continental paleodrainage from the Albian onward (Assine, 2007).

Neogene duricrusts occur as remnants of a formerly continuous lateritic cap, now fragmented, supporting tabular landforms at 680–720 m in the NW sector of the Araripe Basin and in the SW portion of the Quincuncá Massif. Their fragmentation is attributed to progressive climatic aridification beginning in the Miocene (~13 Ma), which promoted mechanical stripping of the weathering mantle, leaving only isolated remnants in the municipalities of Campos Sales and Araripe (Cordeiro; Bastos; Maia, 2018).

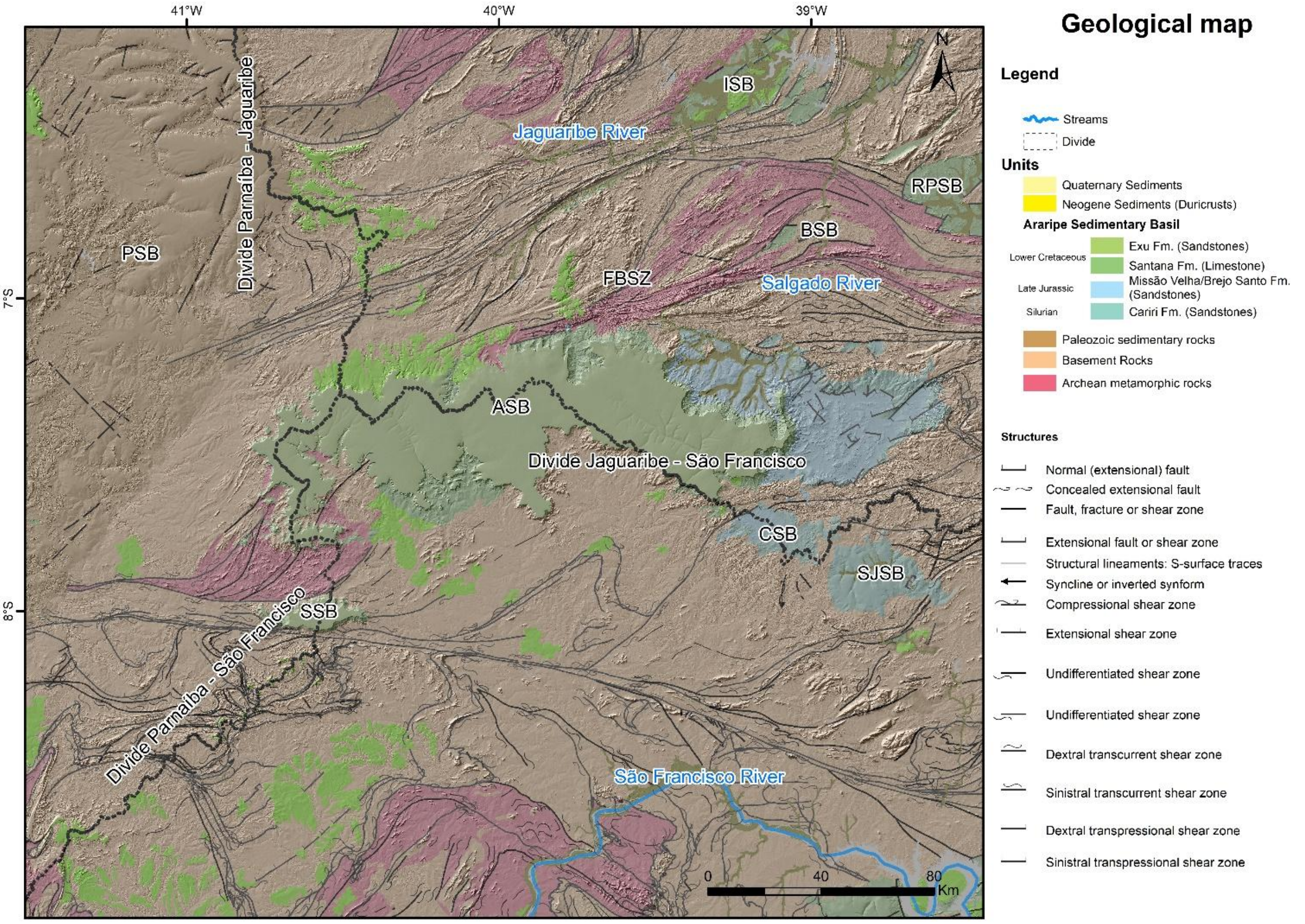

Figure 2. Geological map of the study area. The abbreviations in the map represent the sedimentary basins of the Cariri Valley rift: ASB – Araripe, BSB – Barro, CSB – Cedro, ISB – Iguatu, RPSB - Rio do Peixe, SSB – Socorro, SJSB - São José do Belmonte. Sources: Adapted from Angelim et al (2004); Valença; Neumann; Mabesoone (2003); Peulvast; Bétard (2015).

The crystalline basement comprises Archean to Paleoproterozoic rocks, including TTG gneisses (tonalite–trondhjemite–granodiorite), migmatites, and high-grade granulites, which crop out in the lowlands surrounding the Chapada. These terrains belong to the Central Ceará and Rio Grande do Norte domains (Van Schmus et al., 1995), separated by Neoproterozoic shear zones.

The relief of northeastern Brazil is classically organized into stepped planation surface levels, produced by successive uplifts followed by generalized erosion under dry or alternating climatic conditions (Maia; Bezerra; Sales, 2010). Drawing on King (1956) and Mabesoone and Castro (1975), Ribeiro (2012) distinguishes four planation phases:

I. The first phase — a broad regional planation likely occurring in the Early Jurassic, prior to the Wealdenian reactivation — gave rise to the Gondwana Surface.

II. The second phase, spanning the Albian to Oligocene during slow epeirogenic uplift, produced the South American Surface, expressed at two levels: Cariris Velhos and Borborema, accompanied by crustal doming and deposition of correlative sediments.

III. The third phase, in the Early Pleistocene, involved dissection of the South American Surface and elaboration of the regional planation surface, exhuming extensive areas of the Gondwana Surface. It corresponds to the Sertaneja Surface inland and the Tabuleiros Surface along the coast.

IV. The fourth phase — the polyphasic Paraguaçu Cycle — produced two generations of pediments and terraces on this younger surface.

As Demangeot (1983, p. 56) noted, these planation cycles result in a relief whose "originality stems from the remarkable nesting of cyclic planation surfaces, the juxtaposition of distinct erosional systems, and structural influences that remain poorly understood."

Although the principle of increasing surface age with elevation generally holds, Maia, Bezerra and Sales (2010) note important exceptions: coeval aggradational paleosurfaces can occur at markedly different elevations. The Albian–Cenomanian surface identified by Peulvast and Claudino Sales (2004) illustrates this clearly — the equivalent surface in the Potiguar Basin (RN) does not exceed 180 m, while in the Araripe Basin (CE) it reaches ~900 m.

Structural control on relief is also well-established in the region (Maia; Bezerra, 2014). Two mechanisms are particularly significant: differential erosion along shear zones flanked by more resistant granitic bodies, which produce topographic ridges; and brittle reactivation of shear zones generating localized subsidence and uplift, imprinting a landscape marked by structural lineament trends.

3. Materials and Methods

The digital elevation model (DEM) used in this study was obtained from the FABDEM project, derived from the global Copernicus DSM at a spatial resolution of 30 m (1 arc-second grid at the equator) (Hawker et al., 2022).

Prior to analysis, the DEM was filtered to remove spurious noise using the fill algorithm in *ArcMap 10.3*, which eliminates pixel-level irregularities that would otherwise compromise drainage network extraction. Tests on unfiltered DEMs produced networks with substantial noise artifacts, introducing inconsistencies in basin delineation. The drainage network was extracted using a minimum contributing area threshold of 10,000 m².

Longitudinal profiles and normalized channel steepness indices (Ksn) were computed in MATLAB using the *TopoToolbox* (Schwanghart; Scherler, 2014). Ksn was derived from the relationship between local channel slope and upstream drainage area following the stream power law (Whipple; Tucker, 1999), adopting a reference concavity index (θref) of 0.45. This value was determined using the mnoptmin function, which identifies the θ that minimizes Ksn dispersion across the drainage network, thereby maximizing its statistical representativeness of regional concavity. Sensitivity tests with θref values of 0.35, 0.40, and 0.50 confirmed that, while absolute Ksn values varied, the relative differences among basins remained consistent, with no changes in the ranking of high- and low-Ksn reaches. Results were exported in shapefile format.

3.1. Planation Surfaces

Planation surfaces were mapped by targeting areas meeting three criteria: hilltop position, low relief, and a minimum area of 20,000 m². The workflow began with slope extraction, reclassified into two classes — 0–10% and >10% (Figure 3c) — to isolate low-gradient terrain.

Slope and elevation rasters were then combined through map algebra, producing elevation classes at 100 m intervals (Figure 3d) from which all areas with slopes exceeding 10% were excluded. The resulting raster, retaining only low-gradient surfaces stratified by elevation, was converted to vector format.

To distinguish hilltop from valley features, the Topographic Position Index (TPI; Weiss, 2001) was applied with a 2 km analysis radius. Pixels with values below the neighborhood mean were selected and converted to polygons, representing surfaces not classified as hilltops (Figure 3b). These valley polygons were then subtracted from the low-slope surface layer, yielding a dataset of topographically elevated, low-gradient surfaces classified into 100 m altimetric intervals.

Small polygons below the 20,000 m² threshold were removed using the Eliminate Polygon Part tool in ArcMap. This threshold was defined empirically: exploratory tests showed that removing fragments smaller than this limit did not compromise the integrity of mapped features, while effectively suppressing artifacts linked to DEM resolution (30 m).

Parameter thresholds were established through systematic sensitivity testing. The 10% slope limit was selected to exclude any areas with irregular or non-planar relief. The 2 km TPI radius — tested at 1, 2, and 3 km — proved optimal for discriminating valley heads at the regional scale. The 20,000 m² minimum area balances artifact suppression against the preservation of meaningful surface remnants.

The complete mapping workflow is illustrated in Figure 3.

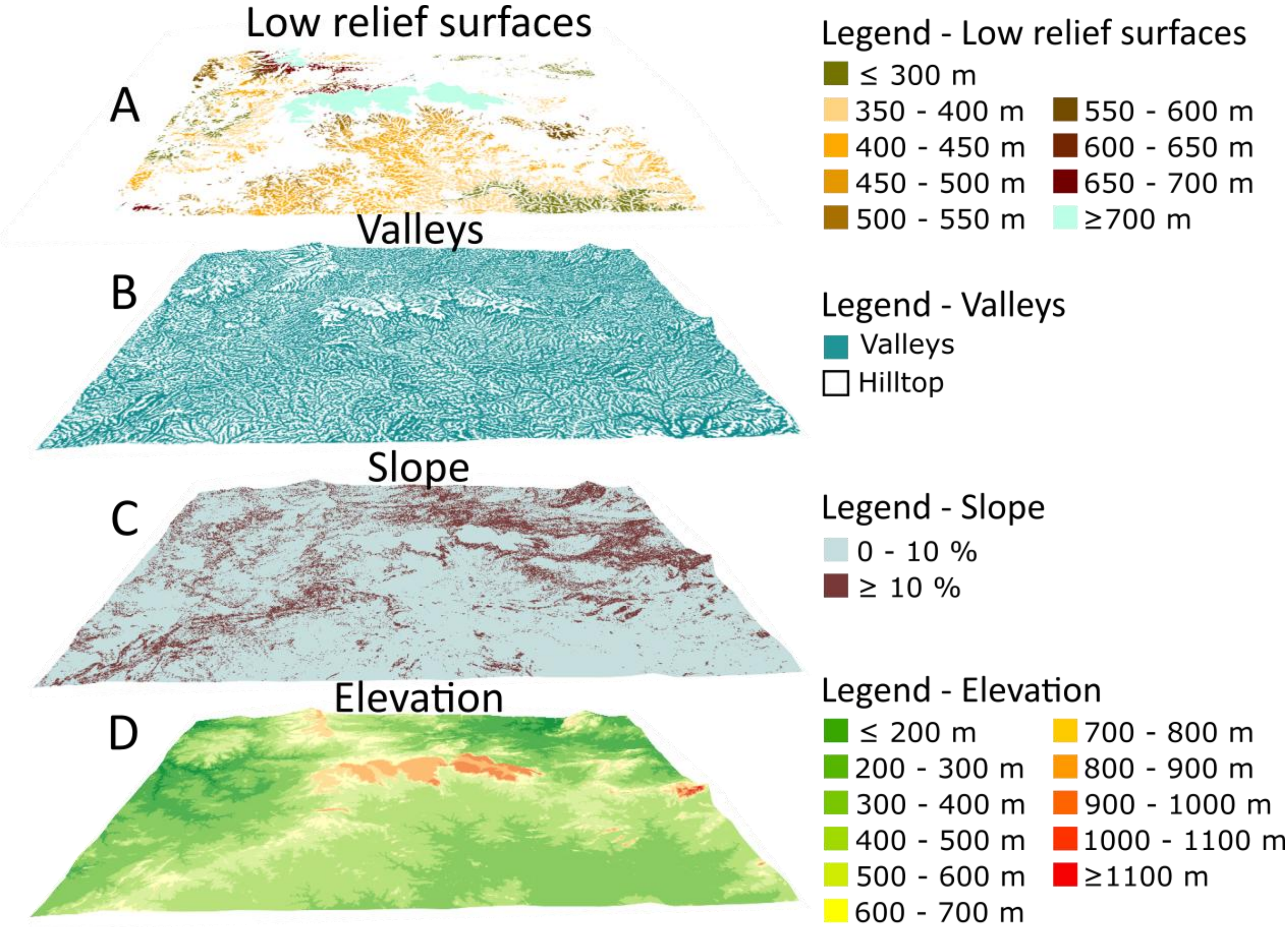

Figure 3. Layers used in the creation of the low relief surface map: a) low relief surfaces; b) valleys; c) slope; d) elevation.

The mapped surfaces were grouped into three altimetric classes (S1, S2, and S3) based on the frequency distribution of pixel elevation values. Class boundaries were defined at natural breaks in the histogram, corresponding to elevations of 485 m and 710 m, which mark the S3–S2 and S2–S1 transitions, respectively.

3.2. Divide mobility

The χ index was extracted using *TopoToolbox* (Schwanghart; Kuhn, 2010; Schwanghart; Scherler, 2014), following the stream power law framework. The base level was set at 350 m, corresponding to the elevation of the highest outlet in the study area (São Francisco Basin). This ensures that all basin headwaters share a common reference level — a necessary condition for comparing χ values across basins of contrasting geometry and size

(Forte; Whipple, 2018). A θref of 0.45, determined using the mnoptmin function, was applied consistently across all extractions.

Divide stability was further assessed using the metrics proposed by Gilbert (1877), later operationalized by Forte and Whipple (2018) in Python within the TopoToolbox framework. These metrics — elevation, gradient, and relief — evaluate the current state of the drainage network by comparing topographic conditions on either side of a divide. The underlying premise is that divide migration occurs when erosion rates are unequal across the divide, a disparity most likely driven by differences in hillslope gradient.

Whereas χ captures the potential for future divide movement through asymmetric basin growth, Gilbert metrics reflect the present-day erosional state of the divide flanks. Together, they provide complementary perspectives on divide dynamics.

Divide behavior was analyzed across three interbasin boundaries: Jaguaribe–Parnaíba, Jaguaribe–São Francisco, and Parnaíba–São Francisco, with the aim of characterizing the mobility and reorganization of the regional drainage network.

Longitudinal profiles (Figures 8, 9, and 10) include reference lines to facilitate cross-profile comparison. The red line marks the 350 m base level used for divide metrics. The green line (485 m) and blue line (710 m) indicate the boundaries between planation surfaces S3–S2 and S2–S1, respectively. Knickpoints shown on the profiles were automatically extracted using the *knickpointfinder* function in *TopoToolbox* (Schwanghart; Scherler, 2017).

4. Results

4.1. Distribution and characterization of planation surfaces

Figure 4 presents the distribution of planation surfaces around the Chapada do Araripe, consistent with the regional framework proposed by Oliveira et al. (2025) from DEM analysis and geochronological constraints. Three altimetric classes are recognized: S1 (above 710 m), S2 (485–710 m), and S3 (below 485 m).

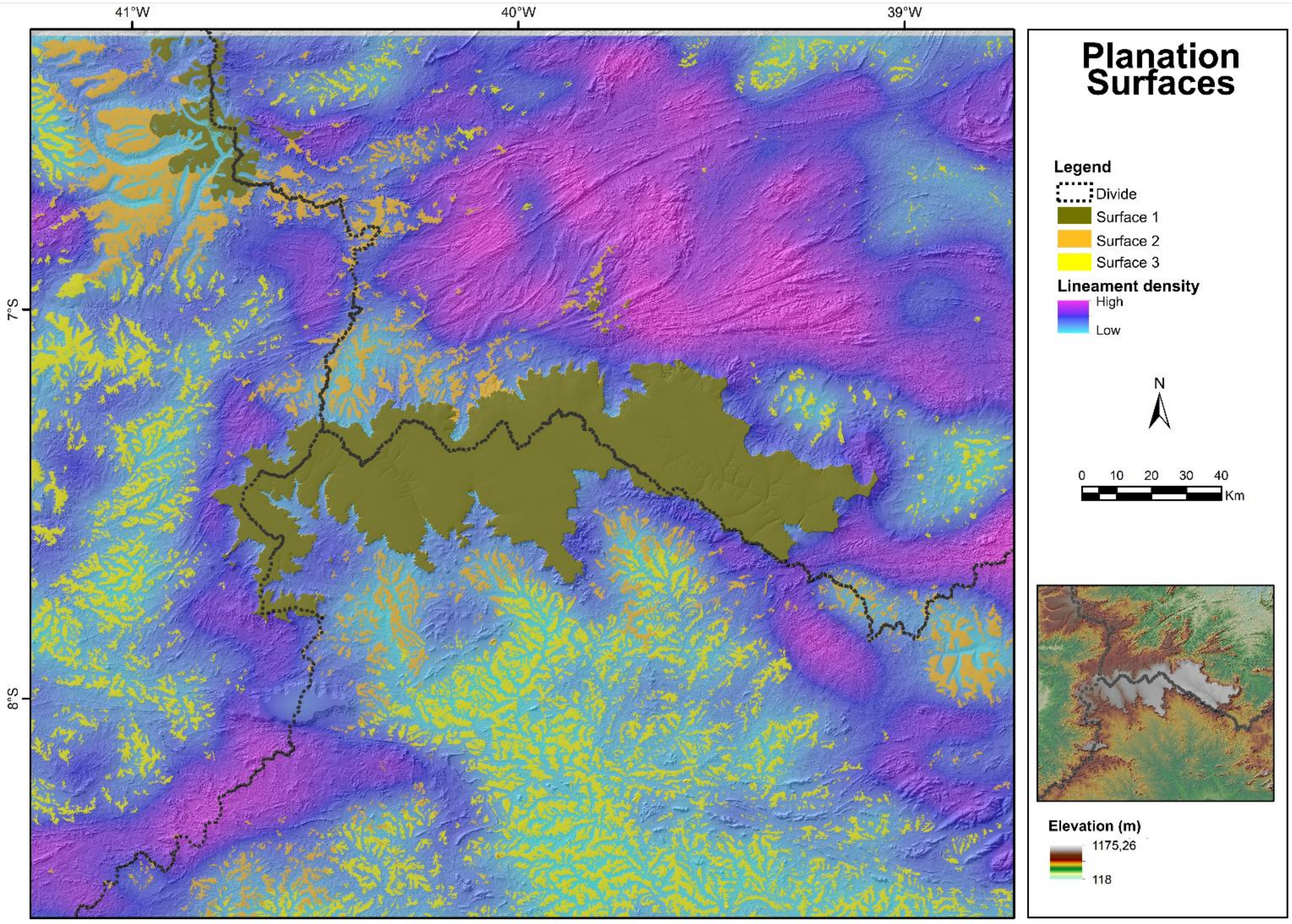

Figure 4. Planation Surfaces around the Chapada do Araripe.

S1 occupies the summit of the Chapada do Araripe and the Ibiapaba Plateau. On the Chapada, it is bounded by steep escarpments and high local relief. On the Ibiapaba Plateau, it extends continuously for approximately 380 km across the states of Ceará and Piauí (Moura Fé, 2015). South of the Poti River basin, the altimetric contrast between sandstone cuestas and the surrounding planated basement diminishes progressively, with sertaneja surfaces in this sector reaching elevations above 400 m. Souza (2000) designates these as the Old Sertaneja Surface, preserved 200–300 m above the New Sertaneja Surface (below 200 m), the latter predominating in the northern portions of the basement area.

S2 comprises partially dissected intermediate plateaus concentrated in the southwestern sector of the study area, at elevations of 600–700 m. These residual reliefs preserve in-situ ferruginous duricrusts.

S3, mapped between 300 and 485 m, is the most extensive unit in the study area. Its distribution is discontinuous, with greater expression in the southern and eastern sectors. Elevation varies systematically, with lower surfaces in pre-coastal zones and higher ones in the interior, separated by residual granitic, quartzitic, and orthogneissic inselbergs.

Figure 4 also reveals an inverse relationship between surface preservation and structural lineament density. Areas with high concentrations of faults and shear zones correspond to more dissected sectors, where planation surfaces have been partially or fully obliterated.

4.2. Divide Mobility Using Gilbert Metrics and the χ Index

The Jaguaribe–São Francisco divide (Figure 5) lies predominantly on the Chapada do Araripe summit. Its flat topography imparts distinctive morphometric characteristics relative to the other divides analyzed. The χ index indicates apparent instability, with a southward migration tendency suggesting potential capture of São Francisco headwaters by the Jaguaribe basin.

The elevation metric shows marked asymmetry: the highest values occur in the Jaguaribe basin, which drains most of the eastern Chapada at higher elevations, whereas in the western portion the highest values shift to the São Francisco side. This spatial variability produces high standard deviations, such that mean values for both basins fall within the stability range — a pattern reproduced in the slope and relief amplitude metrics. The elevated relief values on the São Francisco side reflect the fact that many mapped channels lie on or near the escarpment, where the analysis radius incorporates steep terrain. Gradient follows a similar pattern, with higher values in the southern sector.

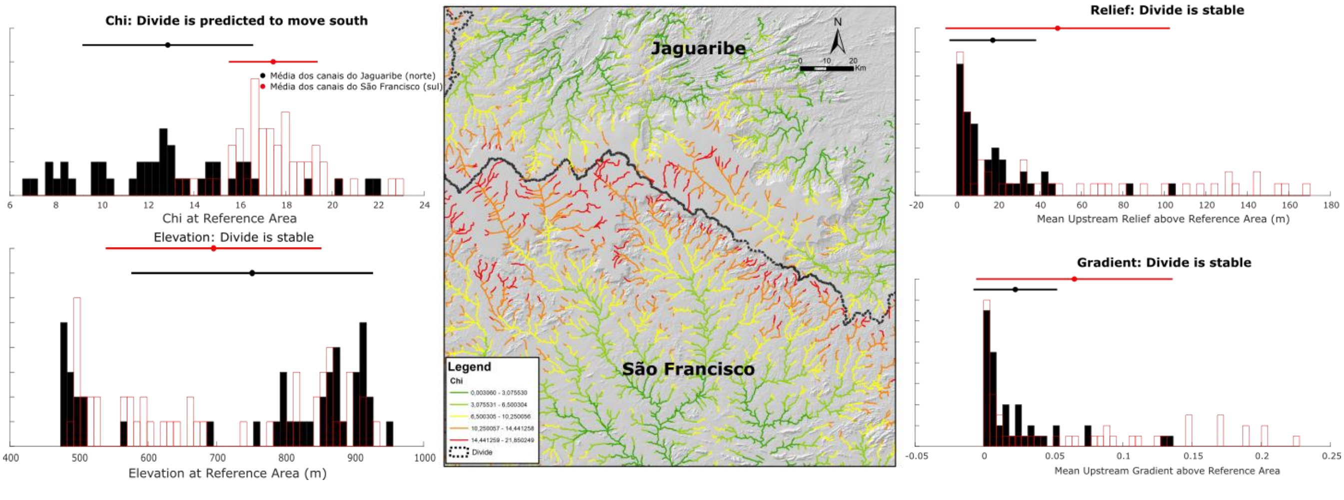

Figure 5. Analysis of the Jaguaribe-São Francisco divide.

The Parnaíba–Jaguaribe divide (Figure 6) indicates stability across all metrics, including χ. Relief and gradient are similar between the two basins in both mean and distribution. The elevation metric shows greater variance, with Parnaíba channels recording slightly higher mean values than their Jaguaribe counterparts.

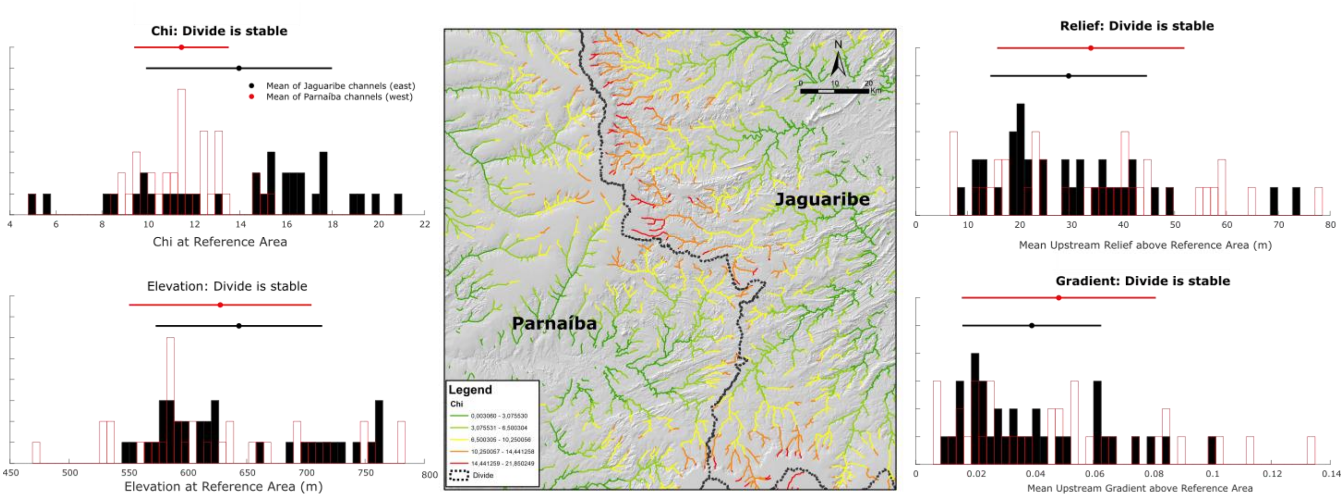

Figure 6. Analysis of the Parnaíba-Jaguaribe divide.

The Parnaíba–São Francisco divide (Figure 7) displays the clearest asymmetry among the three cases. São Francisco channels exhibit higher χ values, indicating greater adjustment to the current base level, while Parnaíba channels show lower values, suggesting a network still in disequilibrium. This contrast points to long-term eastward migration of the divide, favoring Parnaíba basin expansion. The histogram contrast is sharpest for χ; distributions of elevation, relief, and gradient show no significant differences between the two basins. Gilbert metrics thus indicate a currently stable divide, while χ reveals an underlying long-term disequilibrium with reorganization potential.

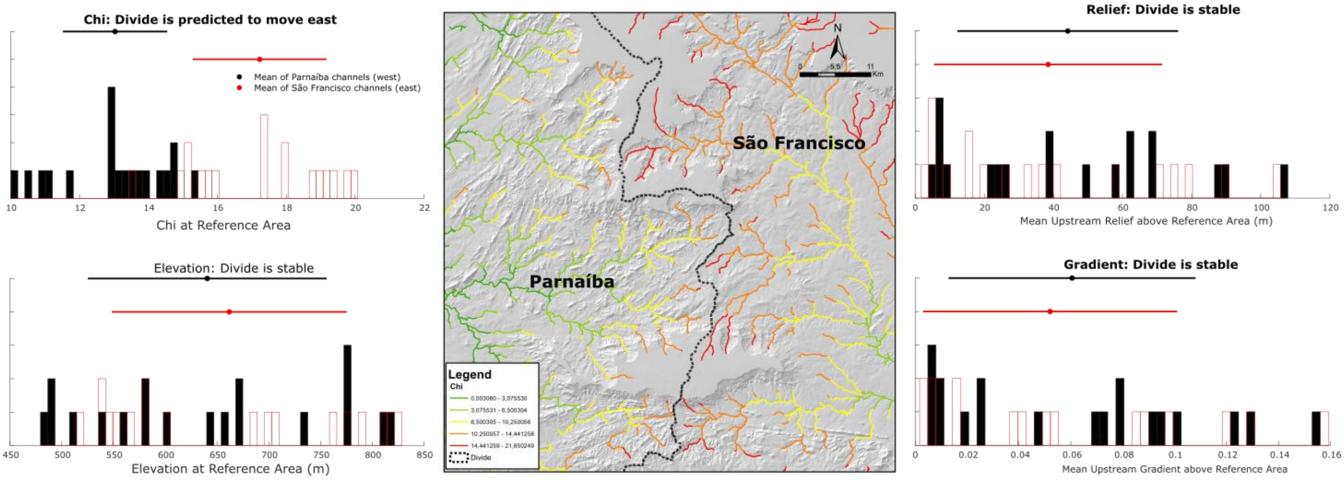

Figure 7. Analysis of the Parnaíba-São Francisco divide.

Across all three divides, the São Francisco basin consistently shows the highest χ values and the greatest vulnerability to capture (Table 1). The Parnaíba emerges as the most aggressive basin, while the São Francisco faces the greatest probability of retraction.

Table 1. Summary of divide metrics.

Divide	χ	Elevation	Relief	Gradient	Interpretation
Jaguaribe – São Francisco	Instability (χ Higher on SF side)	Stability	Stability	Stability	Potential southward migration
Parnaíba - Jaguaribe	Stability	Stability	Stability	Stability	Stable divide
Parnaíba - São Francisco	Instability (χ higher on SF side)	Stability	Stability	Stability	Potential eastward migration

Jaguaribe basin channels (Figure 8) exhibit high steepness across all altimetric ranges, reflecting strong relief compartmentalization. In S1 (>710 m), mean Ksn of 32.9 is concentrated along the Chapada escarpments, where dissection is most intense; summit channels are comparatively low-gradient. In S2 (485–710 m), mean Ksn of 26.4 characterizes the zone of greatest fluvial incision, except in southwestern Ceará where lateritic surfaces confer greater stability. In S3 (350–485 m), mean Ksn of 17.7 marks the transition to broader valleys and lower relief energy.

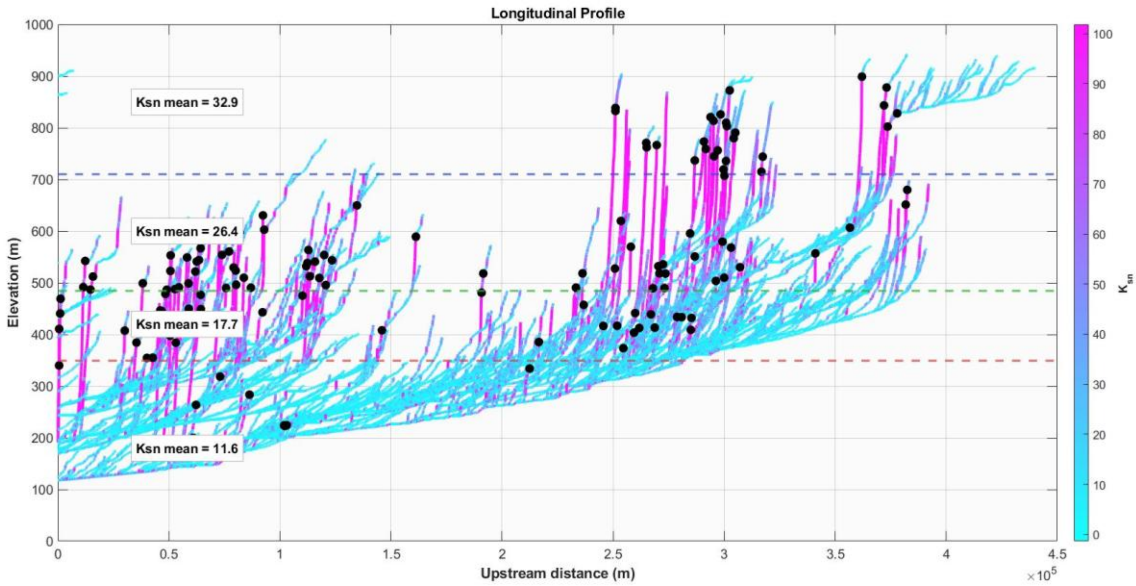

Figure 8. Longitudinal profiles of the rivers in the Jaguaribe basin. Black dots indicate knickpoints.

São Francisco basin channels (Figure 9) follow a similar altimetric pattern but with systematically lower Ksn values, indicating reduced erosive activity and a more advanced stage of adjustment. Mean values of 30.6 (S1), 18.9 (S2), and 9.4 (S3) reflect a landscape with subdued morphostructural contrasts, well-adjusted drainage, and comparatively low erosional intensity.

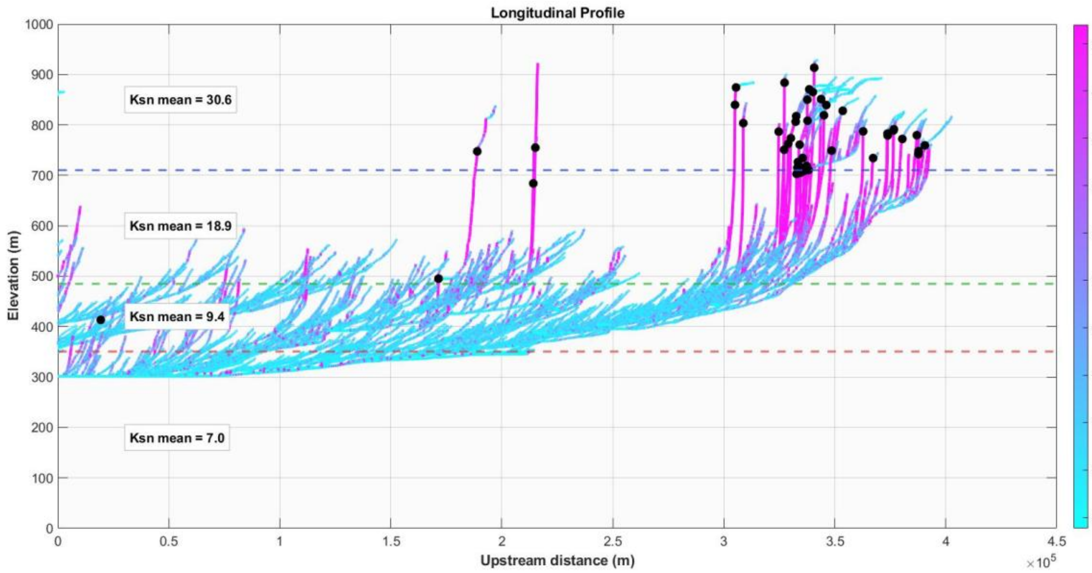

Figure 9. Longitudinal profiles of the rivers in the São Francisco basin. Black dots indicate knickpoints.

Parnaíba basin channels (Figure 10) show peak erosive activity in S2 (485–710 m), with mean Ksn of 27.9, entrenched channels, and active slope retreat fronts. In S1 (>710 m), Ksn of 32.4 combined with low drainage density suggests partial preservation of hilltop surfaces. In S3 (350–485 m), Ksn of 15.5 marks the transition to gentler gradients and a closer balance between incision and sediment transport.

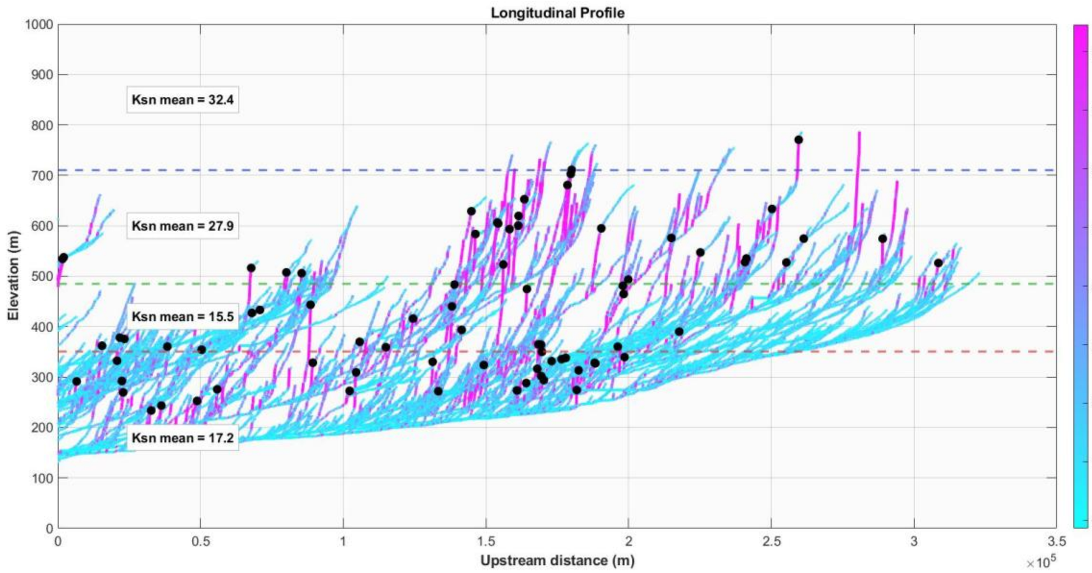

Figure 10. Longitudinal profiles of the rivers in the Parnaíba basin. Black dots indicate knickpoints.

5. Discussion

5.1. Interpretation of planation surfaces

The three altimetric compartments — S1 (>710 m), S2 (485–710 m), and S3 (<485 m) — reflect successive stages of pediplanation and denudation over geological time, arranged from oldest to youngest (Peulvast; Bétard, 2015; Claudino-Sales, 2016).

S1 is primarily associated with the differential erosion of resistant rocks of the Exu Formation, whose lithological competence favored the preservation of tabular morphology at high elevations (Peulvast; Bétard, 2015, 2021; Oliveira et al., 2025). The original extent of this surface was considerably larger: residual reliefs capped by units equivalent to the Exu Formation occur far from the Chapada — including in the Jatobá Basin (Bastos et al., 2024) — pointing to a regional-scale post-Cretaceous relief inversion. Escarpment retreat has been driven by sapping, mass movements (Peulvast et al., 2011), and fluvial erosion (Lima et al., 2022).

Although the Ibiapaba Plateau meets the S1 altimetric criterion, it has a distinct geomorphic history: it represents exhumed patches of a sub-Paleozoic (post-Brasiliano) surface, uplifted from the Coniacian (89.9–86.3 Ma) by transcurrent reactivation of the Sobral–Pedro II Shear Zone under compression along the equatorial margin (Claudino-Sales; Peulvast, 2007; Peulvast et al., 2008; Szatmari et al., 1987). The contrasting substrates — Exu Formation on the Chapada, Serra Grande Group on the Ibiapaba — confer distinct formation histories and preservation chronologies on the two areas, with the Ibiapaba retaining older surfaces.

S2 comprises autochthonous lateritic surfaces at 485–710 m, concentrated in the southwestern sector of the Jaguaribe Basin. The in-situ ferruginous duricrusts are interpreted as relicts of Paleogene humid paleoclimatic conditions, recording an interval of tectonic quiescence and wet climate (Gunnell, 1998; Harris; Mix, 2002; Lima, 2008; Cordeiro; Bastos; Maia, 2018). Lateritic cappings at ~700 m, supporting escarpment bases at ~750 m, are interpreted as remnants of pre-Cenomanian surfaces (Peulvast; Bétard, 2015; Angelim et al., 2004).

S3 represents the most recent pediplanation stage, linked to Neogene–Quaternary fluvial incision and corresponding to the Sertaneja Surface (Peulvast; Claudino-Sales, 2004). Its discontinuous distribution — more expressive in the southern and eastern sectors — reflects the differential efficiency of Neogene regressive denudation across the region's lithological diversity. This is also consistent with the lowest Ksn values recorded along this surface (São Francisco: 9.4; Parnaíba: 15.5; Jaguaribe: 17.7). S3 underlies much of the relief across Ceará state, encompassing residual inselbergs and inselgebirges (Claudino-Sales, 2016).

5.2. Integration of planation surfaces with divide metrics

The divide metrics reinforce the geomorphic interpretation outlined above. The χ index reveals erosional imbalances between basin pairs, identifying sectors prone to divide migration — most notably the Jaguaribe–São Francisco divide, where a southward retreat tendency is apparent.

Gilbert metrics, by contrast, indicate that divides are currently stable. This result is particularly significant in tectonically stable settings, where divide migration tends to be slow and governed by asymmetries in lithological erodibility or climatic forcing (Willett et al., 2014; Whipple et al., 2017).

The apparent contradiction between χ-based instability and Gilbert-based stability reflects processes operating on different timescales. While χ integrates the long-term evolutionary history of the drainage network (Willett et al., 2014), Gilbert metrics capture instantaneous morphological conditions. This decoupling is common in tropical cratons, where low present-day erosion rates (as expressed by Gilbert metrics) tend to mask slow but continuous fluvial reorganization (Whipple et al., 2017). In the Chapada do Araripe, the differential resistance of the Exu Formation sandstones limits local erosion and stabilizes divides, while base-level contrasts — particularly those associated with the São Francisco Basin — sustain long-term disequilibria captured by χ.

The integrated analysis of planation surfaces, longitudinal profiles, and divide metrics clarifies how each altimetric level contributes to the dissection dynamics of the Chapada and adjacent areas.

In S1 (>710 m), profiles are dominated by short, steep channels confined to headwaters along the plateau escarpment. These act as agents of progressive escarpment retreat, gradually dismantling the outer limits of the surface.

S2 (485–710 m) is the most morphodynamically active compartment. All three basins show a strong concentration of high-Ksn channels in this range, reflecting intense erosive activity driven by lower lithological resistance and the reactivation of Neoproterozoic structures favoring fluvial incision. S2 thus functions as the main dissection front — a transition zone between preserved hilltops and lowered relief sectors.

S3 (<485 m) corresponds to the most recent pediplanation stage, largely represented by the Sertaneja Surface. Longitudinal profiles in this range show longer, lower-gradient channel segments, reflecting greater drainage adjustment and subdued morphostructural contrast. S3 expresses a relative landscape stabilization at lower elevations, where incision rates are slow.

Interbasin differences in longitudinal profiles highlight the role of drainage in surface fragmentation. Jaguaribe profiles are steeper and denser in the S2 range, suggesting active dismantling of intermediate surfaces and reduced S3 preservation — consistent with greater fluvial incision activity (Oliveira et al., 2022). São Francisco profiles are gentler with lower channel density above 710 m, indicating greater S3 preservation and a more advanced stabilization stage. The Parnaíba shows an intermediate pattern, with well-defined channels and steeper gradients that diminish at higher elevations.

This analysis supports a three-tier model of drainage-driven relief evolution: (i) headwater channels along escarpment margins progressively dismantle S1; (ii) erosive energy is concentrated in S2, the key compartment for fluvial reorganization, except where lateritic cappings locally stabilize relief; and (iii) drainage gradually adjusts to S3, which consolidates as the new regional base level.

The integration of planation surfaces with divide metrics further reveals how inherited altimetric levels condition current fluvial reorganization:

- *S1 (>710 m): Low channel density on the plateau surface acts as a barrier to river capture, explaining the apparent stability of the Jaguaribe–São Francisco divide.*
- *S2 (485–710 m): Maximum Ksn values and knickpoint concentration mark this as the zone of greatest instability and reorganization potential.*
- *S3 (<485 m): Progressive drainage adjustment toward the new regional base level.*

5.3. Landscape evolution model

The results reveal a complex interplay between structural inheritance, lithological resistance, and fluvial reorganization in shaping the current landscape (Figure 11). Geomorphological, morphometric, and structural evidence collectively indicate that relief evolution across the Chapada do Araripe proceeded through successive phases of pediplanation and dissection, producing a stepped topography organized into three levels (S1, S2, S3).

S1 (>710 m) is the oldest preserved level, anchored in the resistant sandstones of the Exu Formation. Its tabular morphology and steep escarpments reflect both the differential resistance of the sandstones and the legacy of post-Cretaceous tectonic inversion, which isolated the Chapada as an extensive residual relief. High Ksn values at headwaters (30–32) indicate localized ongoing incision, but low drainage density points to overall morphological stability.

S2 (485–710 m) is the most morphodynamically active compartment, concentrating the highest mean Ksn values (18–32, depending on the basin). These reflect intensified dissection controlled by reactivated Neoproterozoic structures. Longitudinal profiles confirm that S2 functions as the main incision front between the preserved S1 summit and the lowered S3 sector. This surface thus records two superimposed signals: a Paleogene humid episode expressed by lateritic duricrusts, and an ongoing phase of fluvial reorganization.

S3 (<485 m) represents the most recent pediplanation stage, correlative to the Sertaneja Surface and linked to Neogene–Quaternary fluvial incision. Lower mean Ksn values (≈9–15) and the prevalence of long, low-gradient channels indicate near-equilibrium longitudinal profiles and subdued morphostructural contrast, reflecting relative landscape stabilization. S3 constitutes the current regional base level and expands preferentially across zones of lower lithological resistance.

Taken together, these patterns indicate that relief evolution was discontinuous — driven by pulses of erosion and stability controlled by climatic variations and tectonic reactivations. The upward increase in Ksn from S3 to S2, coupled with variable channel density, records cycles of regressive incision most active along Chapada escarpments and tributary headwaters.

The proposed evolutionary model comprises three phases:

I. Post-Cretaceous pediplanation. Genesis of S1 and relief inversion of the Chapada. Following post-Cenomanian inversion, S1 was maintained at high elevation by the resistance of Exu Formation sandstones. Long-term denudation rates estimated from the S1–S3 elevation difference (~3–6 m/Myr over ~100 Myr) are consistent with cosmogenic rates corrected for burial (Oliveira et al., 2025, Figure 9A), and corroborated by contrasting local rock lowering rates between granite (2–3 m/Myr) and sandstone (16–24 m/Myr).

II. Paleogene readjustment. Laterite development and progressive S2 fragmentation. Laterite formation at 600–700 m during the Paleogene (Cordeiro; Bastos; Maia, 2018) marks a phase of tectonic and climatic stability. The ~200 m S1–S2 elevation difference implies ~4.8 ± 2.1 m/Myr of denudation over ~53 Myr (Eocene–Oligocene), consistent with Pleistocene cosmogenic rates from the Jaguaribe and São Francisco rivers (6.3–12.5 m/Myr). This agreement suggests relatively constant erosive processes since the Paleogene, characteristic of stable cratonic settings.

III. Neogene–Quaternary dissection. S2 fragmentation and S3 establishment as the new regional base level. This phase accelerated in response to Pleistocene climatic oscillations. Cosmogenic denudation rates (20–200 ka) document this recent pulse, with spatial variability (6–19 m/Myr) controlled by lithology and local hydrogeology.

Divide dynamics further illuminate the current reorganization. In the Jaguaribe–São Francisco divide, higher slope values and greater relief amplitude on the São Francisco side — combined with lower χ values — indicate that the Jaguaribe basin is positioned to expand across the divide, progressively capturing smaller São Francisco tributaries. This is consistent with elevated Ksn values in Jaguaribe headwaters, which suggest sufficient stream power to drive regressive incision and escarpment retreat.

In the Parnaíba–São Francisco divide, the pattern reverses: higher χ and slope values concentrate on the Parnaíba side, while the São Francisco shows lower averages and greater erosional vulnerability. This points to long-term eastward divide migration and gradual capture of São Francisco tributaries by the Parnaíba — a slow, ongoing reorganization not yet expressed in abrupt morphological discontinuities.

In both cases, Gilbert metrics confirm that capture is localized and gradual, governed by lithological contrasts and Neoproterozoic structural inheritance. Headwater advance into zones of lower resistance — particularly along contacts between contrasting lithologies in the crystalline basement — produces subtle but cumulative adjustments in the drainage network.

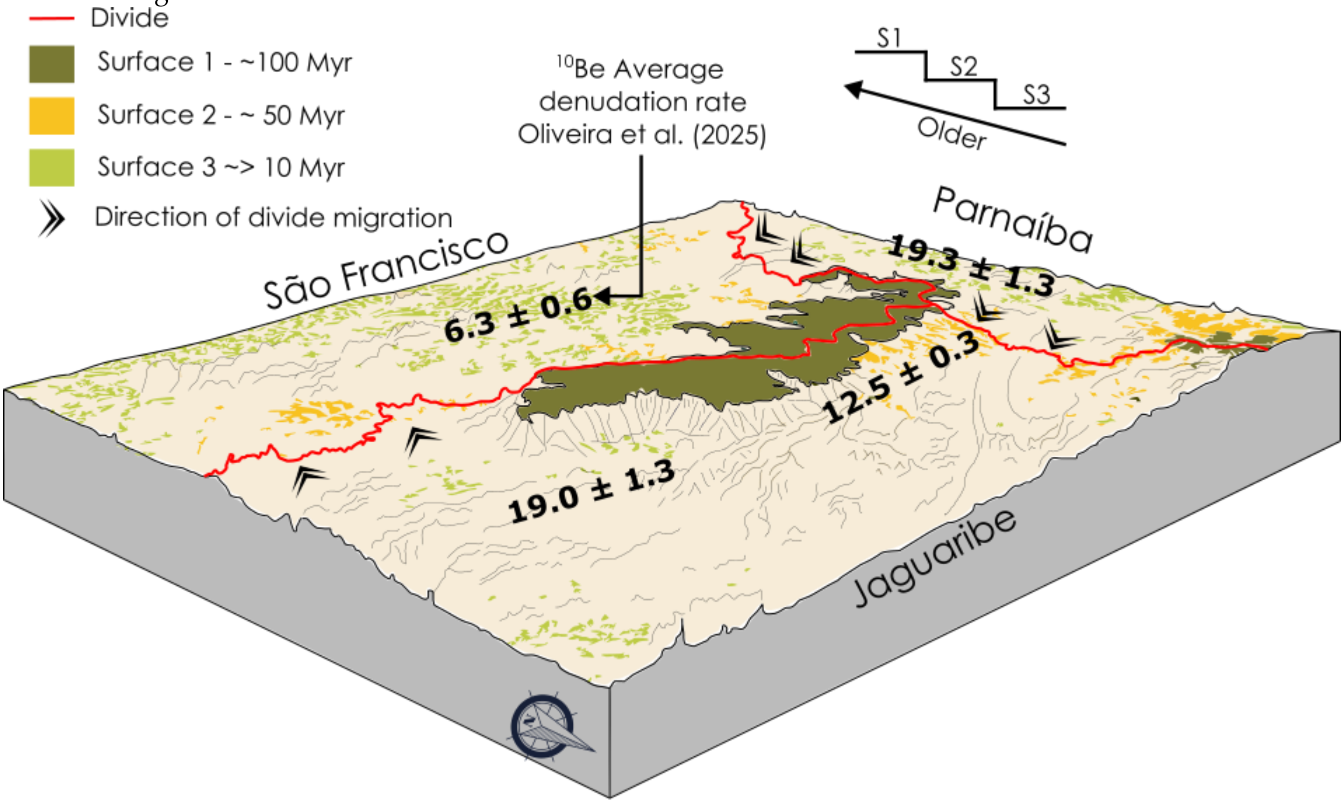

Figure 11. Synthesis of the distribution of surfaces and divide mobility.

Table 2 synthesizes the main attributes of each surface, including altimetric range, estimated age, dominant processes, associated lithology, and mapping evidence.

Table 2. Planation surfaces and associated processes.

Surface	Elevation (m)	Estimated age	Dominant processes	Associated lithology	Mapping evidence
S1	> 710	Post-Cretaceous (Cenomanian–Paleogene)	Relief inversion, differential erosion	Exu Formation (resistant sandstone)	Tabular morphology, steep escarpments, broad preserved summits
S2	485 – 710	Paleogene (Eocene–Miocene)	Laterite formation, tectonic and climatic stability	Autoctone laterites, crystalline basement	Plateaus with ferruginous duricrusts, localized low dissection
S3	< 485	Neogene–Quaternary	Fluvial incision, regressive erosion	Crystalline basement	Inselbergs and fragmented Sertaneja surface

The Chapada do Araripe results fit within a broader pattern of landscape evolution in tropical cratonic settings of northeastern Brazil. The consistency between long-term denudation rates derived from the surfaces and cosmogenic rates reported by Oliveira et al. (2025) supports relatively constant erosive processes since the Paleogene — a hallmark of tectonically stable domains. The identified fluvial reorganization trends — Jaguaribe expanding over the São Francisco, and Parnaíba expanding over the São Francisco — align with documented captures in adjacent areas, including the Poti River canyon (Rodrigues et al., 2024) and asymmetric denudation in the Parnaíba Basin (Bastos et al., 2024), reinforcing that drainage reorganization is an ongoing regional-scale phenomenon. The stepped surface distribution and differential divide mobility thus reflect not only local structural and lithological inheritance, but an evolutionary pattern shared across the northern Northeast under similar morphostructural and climatic conditions.

6. Conclusions

This study examined relief evolution and drainage divide dynamics in the Chapada do Araripe region by integrating planation surface mapping, morphometric indices, and longitudinal profile analysis.

Three altimetric levels were identified — S1 (>710 m), S2 (485–710 m), and S3 (<485 m) — corresponding to successive pediplanation stages since the Cretaceous. Surface preservation is spatially uneven, reflecting the combined influence of lithological, structural, and climatic factors. The differential resistance of Exu Formation sandstones is the primary control on S1 preservation. Autochthonous lateritic duricrusts in S2 record a Paleogene interval of tectonic quiescence and humid climate. S3 expresses the most recent pediplanation stage, with a fragmented distribution controlled by regional lithological diversity and Neogene–Quaternary regressive erosion. The inverse relationship between structural lineament density and surface preservation confirms the decisive role of Neoproterozoic shear zones in shaping current relief.

Divide stability analysis reveals a transitional framework between equilibrium and reorganization. The Parnaíba–Jaguaribe divide is stable across all metrics. The Jaguaribe–São Francisco and Parnaíba–São Francisco divides show χ asymmetries indicating migration tendencies — southward and eastward, respectively — while Gilbert metrics suggest near-equilibrium morphological conditions. This apparent contradiction is interpreted as the expression of processes operating on contrasting timescales: χ captures long-term drainage imbalances, whereas Gilbert metrics reflect the instantaneous morphological state. Together, they are consistent with slow, continuous fluvial reorganization typical of cratonic settings.

These results demonstrate that the Chapada do Araripe landscape is the product of superimposed long-term geological inheritances and active erosional processes. The combined use of planation surface mapping and divide metrics proves an effective framework for decoding this complexity in tropical cratonic contexts.

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