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Technical note

Geomorphological mapping of the state of Mato Grosso: taxonomic hierarchy and geomorphometric parameters

Mapeamento geomorfológico do estado de Mato Grosso: hierarquia taxonômica e parâmetros geomorfométricos

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Abstract: The geomorphological mapping of the state of Mato Grosso is presented, integrating theoretical and methodological perspectives of geomorphometry, the history of local geomorphological cartography and discussions within the scope of the SBCR. A hierarchical classification was established in four taxons with morphological emphasis (macro landforms, morphostructures, geomorphological units and landform patterns), whose mapping parameters were based on geomorphometric attributes. The proposal focused on the semantic issues used to express the conceptual (qualitative) models of landforms and the classification parameters (quantitative) linked to geometry and morphological homogeneity. The Copernicus DEM and the geomorphometric attributes of mean slope, altimetric amplitude, topographic position index and white top hat were used. The 1st taxon was classified as plateaus, plains, lowlands and mountains. In the 2nd taxon, sedimentary basins, orogenic systems and cratons were mapped. The 3rd taxon resulted in 67 geomorphological units and the 4th taxon indicated a new subdivision into 16 landform patterns. Considering the integration of the four hierarchical levels, 376 landform classes were mapped in the state of Mato Grosso. It is concluded that the combination of local and focal geomorphometric attributes was successful in generalizing and distinguishing morphologies in terrains with varied characteristics and dissections.

Keywords: Digital Elevation Model; Geomorphological cartography; Landforms of Mato Grosso; Pantanal.

Resumo: Apresenta-se o mapeamento geomorfológico do estado de Mato Grosso, vinculando perspectivas teórico-metodológicas da geomorfometria, do histórico da cartografia geomorfológica local e das discussões no âmbito do SBCR. Estabeleceu-se uma classificação hierárquica em quatro táxons com ênfase morfológica (macroformas de relevo, morfoestruturas, unidades de relevo e padrões de relevo), cujos parâmetros de mapeamento se apoiaram em atributos geomorfométricos. A proposta se ateve às questões semânticas usadas para expressar os modelos conceituais (qualitativos) sobre o relevo e aos parâmetros de classificação (quantitativos) vinculados à geometria e à homogeneidade morfológica. Utilizou-se o MDE Copernicus (30 m) e os atributos geomorfométricos da declividade média, amplitude altimétrica, índice de posição topográfica e white top hat. No 1º táxon foram classificados planaltos, planícies, superfícies rebaixadas e montanhas. No 2º táxon foram mapeadas as bacias sedimentares, os sistemas orogênicos e os crátons. O 3º táxon resultou em 67 unidades de relevo e o 4º táxon indicou uma nova subdivisão em 16 padrões de relevo. Considerando a integração dos quatro níveis hierárquicos, foram mapeadas 376 classes de relevo no estado de Mato Grosso. Conclui-se que a combinação de atributos geomorfométricos locais e focais foi exitosa na generalização e distinção de morfologias em relevos com características e dissecações variadas.

Palavras-chave: Modelo Digital de Elevação; Cartografia geomorfológica; Relevo de Mato Grosso; Pantanal.

1. Introduction

The landforms of Mato Grosso developed in accordance with lithological variability and the effects of differential erosion; tectonics/neotectonics and the resulting isostatic processes which, favored by structural lineaments and faults, gave rise to grabens, horsts and regional base levels; climatic fluctuations; and the process of territorial occupation, from a current geomorphological perspective. Mato Grosso is encompassed by cratonic portions, Neoproterozoic orogens and sedimentary basins, subjected to paleoclimates that resulted in polygenetic paleosurfaces, in addition to extensive plains and fluvial megafans, residual landforms, dissected plateaus and summits preserved in the form of tablelands (Silveira, 2023). It is, therefore, a representative and diverse area for geomorphological mapping, evidenced by previous mappings that adopted different methodologies or mapping categories.

Geomorphological maps, by integrating multiscale characterizations of the landforms, constitute elementary cartographic products for environmental management and territorial planning. However, there is a major current challenge linked to regional geomorphological mapping: how to reconcile the history, new techniques, and taxonomic systematization of geomorphological mappings? This question implies, respectively, the articulation of qualitative aspects (geomorphological classes or toponyms), quantitative aspects (modeling or mapping parameters), and conceptual aspects (categories and hierarchies), as an attempt to overcome a supposed dichotomy between traditional and digital geomorphological maps.

In operational terms, the use of Digital Elevation Models (DEMs) and geomorphometric techniques has been favoring the processing, modeling, representation, and application of topographic data for the identification, analysis, and quantification of geomorphological landforms and processes. Geomorphometry is defined as the science of topographic quantification (Hengl; Reuter, 2009; Xiong; Tang; Strobl, 2022) and uses DEMs as basic data for calculating geomorphometric attributes (continuous surface) that can be employed to distinguish objects (discrete surface) that comprise classifications of geomorphological maps.

Following the popularization of global DEMs and the consolidation of the use of geomorphometric attributes as basic data for geomorphological mapping, such as slope and curvature, many metrics have been derived to support multidimensional analyses of terrain. Newman et al. (2018) discussed multiscale geomorphometric attributes, essential for geomorphological mapping at a regional scale, which aim to represent patterns with topographic homogeneity. Another recent potential is the segmentation of features applied to digital geomorphological mapping, as presented by Minár et al. (2024). On this topic, Sofia (2020) presents an overview of the applications of Geomorphometry, highlighting, as advantageous aspects, the objectivity in defining landforms, multiscale, the relationship between forms and processes, and the use of open-source codes, in addition to statistical methods and automation.

Alongside the theoretical and methodological advancements in digital terrain modeling, the Brazilian Landform Classification System (SBCR) is under development in Brazil, continuing the historical legacy of Brazilian geomorphological cartography (Botelho; Pelech, 2019; CEN/SBCR, 2022). This creates a favorable scenario for discussions encompassing past geomorphological production, conceptual discussions, and evaluations of the limitations and potential of mapping methodologies.

Regarding the historical context, the first records characterizing the landforms of Mato Grosso date back to the mid-19th century, with descriptions by Castelnau (1859). However, systematized geomorphological classifications date from the mid-20th century, with macro-compartmentalizations that express morphological and morphogenetic characteristics from a regional perspective, according to a survey by Silveira (2023). Among the pioneering works, the publications of Rondon (1933), Löfgren (1946), Ab'Saber (1954), Brito Junior (1955), and Almeida (1959) stand out, characterizing: landforms units and morphogenesis in the context of the Amazon, Cerrado, and Pantanal; the main morphostructures; paleosurfaces and the evolution of landforms; and regional morphometry.

Subsequently, the development of the RadamBrasil Project (1975-1985) resulted in the publication of nine 1:1,000,000 scale maps covering the state of Mato Grosso. The emphasis of these geomorphological maps was on morphological units (divided into structural, erosional, dissection, and accumulation forms) and the representation of linear and point features and dissection indices. Although categorized as small-scale geomorphological maps, they present a level of conceptual and cartographic detail superior to many subsequent published proposals. They constitute highly relevant cartographic products, and the technical reports accompanying the maps provide a broad and meticulous geomorphological characterization, with extensive field data and associations with geology and pedology.

Other subsequent mappings, at the state level, adapted the representation of homogeneous geomorphological units, such as: i) Werle; Silva (1996), who classified 37 geomorphological units consistent with Ross's 3rd taxon (1992); ii) Santos (2000), in the Socio-Economic-Ecological Diagnosis of the state of Mato Grosso, which categorized and mapped 6 morphogenetic groups subdivided into 36 systems, as proposed by Latrubesse, Rodrigo and Mamede (1998); iii) mapping of the Geodiversity of Mato Grosso, by CPRM (MORAES, 2010), with the distinction of 54 geological-environmental units; iv) relief compartmentalization by IBGE (2019).

More recently, geomorphological mapping in Mato Grosso has been favored by mapping with regional studies and specific applications (derived, above all, from digital databases, remote sensing, and DEMs in a GIS environment). Examples include studies in hydrographic basins concerning morphodynamics (Jesuz; Cabral, 2016), the compartmentalization of floodplains in the Pantanal context (Meira et al., 2019), and morphographic mapping in relation to land cover and land use (Sales; Cabral; Jesuz, 2021). In the Mato Grosso Pantanal, with its complex fluvial dynamics and relationship with the surrounding plateaus, the publication by Assine et al. (2014) synthesizes the geomorphological diversity of the floodplains.

Also noteworthy are the publications by Valente and Latrubesse (2012) on the Bananal basin, Irion et al. (2016) on the Araguaia River floodplain, and Pupim, Assine, and Sawakuchi (2017) on the Cuiabá River megafan. In the context of mapping using modeling techniques, the study of Rocha et al. (2022) brought advances with the application of a semi-automatic method for classifying landforms supported by geomorphometric variables (amplitude, slope, aspect and curvature), encompassing Cerrado areas in the state of Mato Grosso.

In this context, and based on the issues raised, the main objective of this research was to evaluate the applicability of geomorphometric attributes for multiscale geomorphological mapping, adopting the state of Mato Grosso as a study area and linking three aspects: i) theoretical and methodological perspectives of geomorphometry; ii) history of local geomorphological cartography; iii) recent discussions within the SBCR. It was considered that parameterized modeling favors methodological reproducibility and reduces subjectivity in the delimitation of mapped classes. In this sense, this article presents the geomorphological mapping developed for the state of Mato Grosso at four taxonomic levels.

2. Materials and methods

A hierarchical classification into four taxa was established with a morphological emphasis, whose mapping criteria were based on geomorphometric techniques. The Copernicus Digital Elevation Model (ESA, 2023), from the European Union, with a spatial resolution of 30 meters, was used as a reference data, as it is the most accurate free global DEM (Cremon et al., 2022; Guth et al., 2024).

The geomorphometric attributes used in the classifications were calculated. The operational steps were performed using QGIS 3.22 software. The tool used for neighborhood analysis (radius for regional calculations) of the geomorphometric attributes was "r.neighbors" from GRASS GIS, available in QGIS.

For the first taxon, the state of Mato Grosso included plateaus, plains, lowlands and mountains. The second taxon mapped sedimentary basins, orogenic systems and cratons. The third taxon resulted in 67 geomorphological units, and the fourth taxon indicated a further subdivision into 16 landform patterns, totaling 376 classes.

2.1. Concepts of geomorphological classes

The mapping process initially focused on the semantic issues used to express the conceptual (qualitative) models of landforms and, subsequently, on the classification parameters (quantitative) linked to the geometry of the objects to be mapped. In short, the geomorphological map sought to reconcile the theoretical and methodological perspectives of digital terrain modeling and geomorphometry with the history of geomorphological cartography production in Mato Grosso and the fruitful recent debates within the national geomorphological community.

Conceptually, the assignment of classes belonging to the 1st taxonomic level (macro landforms) and the 2nd taxonomic level (morphostructural units) followed the discussions that have been addressed within the scope of the Brazilian Relief Classification System (Botelho; Pelech, 2019; CEN/SBCR, 2022; Botelho; Silveira, 2024). Examples are included in the discussion of the paper.

The 3rd taxon (geomorphological units) relied on the equivalent categorization of Ross (1992) and IBGE (2009), whose individualization was based on regional morphographic patterns (morphological homogeneity) and/or regional morphogenetic patterns (homogeneity of processes). For this taxonomic level, the aim was to reconcile quantitative and qualitative aspects of the geomorphological units. The delimitation itself considered homogeneity based on the interpretation of geomorphometric attributes. The qualitative attribution, in turn, categorized distinct plains, wetlands (flooded plains), depressions, plateaus, and tablelands with the addition of toponyms – notably those established in the local geomorphological literature, as presented in Ross (1998) or in the maps of the RadamBrasil Project.

It was understood that lowlands (*superficies rebaixadas*) – defined as "reliefs lower than adjacent areas, resulting from denudational processes, with low and medium slopes and altimetric variations, which may be located in interplateau, intermontane or marginal regions and contain residual landforms" (CEN/SBCR, 2022, p. 216) – are more comprehensive than traditional depressions, whose identity from past mappings was maintained in the geomorphological units, corresponding to the 3rd taxon of the mapping. Thus, the subdivision of lowlands (1st taxon of the SBCR), which represent macro landforms, may contain distinct morphological units with internal homogeneity and external heterogeneity categorized as depressions (morphological units of the 3rd taxon).

The concept of a "*chapada*", defined as a "sedimentary plateau with stratified horizontal or sub-horizontal layers, flattened tops" (Rossato, 2008, p. 120), highlights the morphological subdivision between the 1st and 3rd taxa. The units "Chapadas dos Guimarães" and "Chapada dos Parecis", for example, have geomorphometric characteristics that express homogeneity without, however, spatial contiguity between them. Hence the choice to differentiate them by toponyms.

The 4th taxon (landform patterns) was primarily based on the geomorphological mapping of Paraná (Silveira et al., 2025), especially through parameterization using digital terrain modeling, resulting in geomorphometric descriptors that characterize the landform patterns (Table 1).

The alluvial plains were classified into two patterns: recent and sub-recent. The subdivision indicating morphological/morphodynamic patterns was based on the proposal by Argento (2001). In the Pantanal, it is considered that the recent and sub-recent alluvial plains are related to the active and abandoned forms, respectively, characterized by Corradine and Assine (2012). The authors also adopted the mapping class of "peripheral fluvial plains," in the Pantanal context, which are included in the sub-recent fluvial plains in the 4th taxon of this study.

The recent alluvial plains in the Pantanal, when associated with depositional lobes, meander belts and fluvial fans, preserve biogeomorphological characteristics with more developed vegetation. The sub-recent alluvial plains (which may be distal) are related to the arrangement of fluvial sediments in five terrace levels of the Pantanal, according to Ramalho (1978).

While alluvial plains are predominantly extensive, the other plain patterns within the 4th taxon are more confined. Interhill plains are predominant in river systems located on undulating plateaus. Alluvial-colluvial plains represent gradational river sections with the presence of colluvial material from nearby higher areas (plains located in canyons or on the edges of plateaus, for example).

The pattern of dissected plains followed the proposal of classic geomorphological mappings, such as the categories of "fluvial destructive" by Klimaszewski (1963; 1982) and "fluvial-denudation" by Demek (1972), with the subdivision of units with degradational and aggradational patterns (or destructive and constructive, of dissection and accumulation). Thus, dissected plains represent areas of fluvial deposition that, due to adjacent steep slopes or valley incision, have active morphodynamics and sediment remobilization. They differ from alluvial-colluvial plains by having a lower altimetric amplitude (Table 1).

For the landform pattern of the *bajadas* (lowlands), the concept of Guerra and Guerra (2008, p. 79) was adopted, whose authors defined *bajadas* (lowlands) as "depressed areas in relation to the contiguous terrain" and highlight the specificities of the terminology in the state of Mato Grosso, due to the Pantanal. In the geomorphological map report of the RadamBrasil Project (1982), for example, there is a reference to different lowlands in Mato Grosso, with emphasis on the so-called "Depressão Cuiabana". Lowlands are predominant in the macroforms of lowered surfaces, but can also appear as patterns in transitional areas of dissected plateaus.

Regarding denudational landform patterns, hills and escarpments were distinguished with emphasis on morphography, adapting the precepts of Silveira et al. (2025). As a reference, exemplified in the national literature, Rossato et al. (2008, p. 125) characterized a hill as a "small elevation of the surface, generally concave-convex [...], quite smoothed due to erosive processes". Florenzano (2008, p. 13) defined hills as low elevations of the terrain with amplitudes between 20 m and 60 m, which differ in the characteristics of their tops (almost flat and rounded) and slopes (low and high, respectively). Mountains, in turn, were defined by the author as medium features, with amplitudes between 100 m and 200 m and high slopes. Therefore, the morphometric aspects inherent to the concept, which were adapted to the representativeness of these landforms in the state of Mato Grosso, are evident, as shown in Table 1. The pattern of escarpments and dissected hills was treated as a unified class.

The so-called flat reliefs, from the 4th taxon, represent denudational morphological patterns of low slope and altimetric amplitude, with dissection less than hills, which may include the planed surfaces characterized by Ab'Saber (1965), especially the pediplains in the interior plateaus, and remnants of polygenetic paleosurfaces (Silveira; Silveira, 2023). The landform pattern of the summits corresponds to the higher flat areas, present on the reverse side of the main escarpments in cuestiform reliefs of the Paraná Sedimentary Basin. This class was characterized, by the products of the RadamBrasil Project (1982), as a summit surface.

The compartmentalization of the mountains, in the 4th taxon, distinguished four characteristic landform patterns. The piedmont class, based on Ab'Saber (1988), represents the aggradational morphology of the mountainous environment, with "lateral erosion ramps along the axis of the intermontane depressions". Complementarily, the classified intermontane plateaus indicate surface levels between the crests of folded structures that make up the mountain macroform. The distinction between the pattern of high mountains and dissected mountains was attributed to the predominance of altimetric amplitude and slope (Silveira et al., 2025). The highest portions, with a variation greater than 300 meters (the main morphometric criterion for defining mountains), represent the mountain cores. The adjacent portions, with lower amplitude, were shaped by erosive processes that resulted in a distinct morphological pattern, defined in the mapping as dissected mountains.

2.2. Classification and mapping parameters

Operationally, after defining the objects to be mapped, the geomorphological classification parameters were established. The 1st taxon was mapped using morphometric criteria with attributes derived from the Copernicus DEM.

- The plains were mapped using the attribute called White Top Hat (Equation 1), calculated with a radius of 10 km and with values less than 10 as the representation threshold, the result of which overwhelmed the other classes in the final product.

$$WTH = Z_0 - Z_{maxmin} \quad \text{(Equation 1)}$$

where Z_0 is the DEM and Z_{maxmin} is the maximum elevation of the minimum elevation within a predetermined radius.

- The mountains were modeled using as a reference the altimetric amplitude value greater than 300 meters (within a 1 km radius), high slope in the upper third of the slopes (> 4.5° or 15%) and the presence of sharp peaks (thus excluding the escarpments of sedimentary plateaus with flat tops on the reverse side), in addition to presenting spatial continuity.

- For the lowlands (LW), the regional analysis of the altimetry values (DEM) was considered based on the following criterion: LW < (AverageDEM5km – 0.5 StDevDEM5km), that is, the threshold was considered to be the average elevation within a 5 km radius minus half (0.5) the standard deviation of the elevation value (also with a 5 km radius).

- Finally, the plateaus were represented by the inverse parameters of the other landforms mentioned.

The 2nd taxon, related to structural constraints, was mapped from an adaptation of the units proposed by IBGE (2019) and CPRM (Lacerda Filho et al., 2004; Moraes, 2010), with the reinterpretation of the units and the refinement of the boundaries based on geomorphometric attributes, mainly multidirectional hillshade.

The 3rd taxon maintained the identity of some morphological units from previous mappings (whose toponyms are well-established in the local geomorphological literature), while others were subdivided due to the identification of distinct roughness patterns. All, however, were delimited based on homogeneous patterns of geomorphometric attributes, mainly slope and hillshade. The classes included plateaus, terraces, mountain ranges, depressions, fluvial fan systems, alluvial plains and wetlands, interplateau plains, plateaus at different levels of dissection, and pediplaned surfaces, for example. The conceptual discussion on geomorphological categories is presented as a previous subtopic (2.1).

Finally, the 4th taxon was classified into 16 landform patterns, modeled from four geomorphometric attributes (WTH, average slope, altimetric amplitude and TPI) with neighborhood analysis (radii of 1 km and 10 km), according to the parameters set out in Table 1.

Table 1. Geomorphometric parameters for classifying landform patterns (4th taxon).

Landform patterns	**Geomorphometric parameters**			
	WTH (radius of 10 km)	Average slope (1 km radius) (degrees)*	Altimetric amplitude (radius of 1 km) (m)	TPI (10 km radius)
Recent alluvial plains	< 10 m	> 1.7° and < 4.5°	< 30 m	> -2.5 stdv
Subecent alluvial plains	< 10 m	< 1.7°	< 30 m	> -2.5 stdv
Interhill plains	< 10 m	> 1.7° and < 4.5°	> 30 and < 80 m	> -2.5 stdv
Dissected plains	< 10 m	> 4.5°	> 30 and < 80 m	> -2.5 stdv
Alluvial-colluvial plains	< 10 m	-	> 80 m	< -2.5 stdv
Bajadas (lowlands)	> 10 m	-	< 250 m	< -2.5 stdv
Low hills	> 10 m	> 1.7° and < 4.5°	> 30 m	> -2.5 stdv
Hills	> 10 m	> 1.7° and < 4.5°	> 80 and < 150 m	> -2.5 stdv
	> 10 m	> 16.7°	> 30 and < 80 m	> -2.5 stdv
High hills	> 10 m	> 8.5° and < 16.7°	> 150 and < 250 m	> -2.5 stdv
	> 10 m	> 16.7°	> 80 and < 250 m	> -2.5 stdv
Escarpments and dissected hills	> 10 m	-	> 250 m	-
Flat relief	> 10 m	< 1.7°	< 30 m	> -2.5 stdv
Summits	> 10 m	>4.5° and < 8.5°		> 2.5 stdv
Piedmont	> 10 m	> 8.5° **	< 80 m *	< -2.5 stdv
Intermontane levels	> 10 m	> 8.5° **	> 80 and < 300 m *	< -2.5 stdv
Dissected mountains	> 10 m	> 8.5° **	> 80 and < 300 m *	> -2.5 stdv
High mountains	> 10 m	> 8.5° **	> 300 m *	> -2.5 stdv

* Equivalence of slope values in degrees and percentage: 1.7° = 3%; 4.5° = 8%; 8.5° = 15%; 16.7° = 30%.
** In mountain macroforms (1st taxon). stdv = standard deviation.

The landform patterns correspond to morphographic units with regional homogeneity, which justifies the use of distinct radii in the calculation of geomorphometric attributes. The WTH was used to individualize the plains, the average slope and altimetric amplitude for the dissection and roughness of the terrain and the TPI aimed to distinguish aggradational and degradational patterns.

The qualitative assignments of the classes focused on the morphological and morphogenetic representation that distinguishes them in the landscape. The fieldwork was divided into two stages: i) surveying for the categorical and conceptual definition of landform patterns; ii) verification of the modeling results and the mapped classes, especially in transition areas between landform patterns (exemplified in the results), followed by adjustments and refinement of the geomorphometric parameters. It should be considered that the 4th taxon, in this mapping, is suitable up to a scale of 1:100,000.

3. Results and discussion

The hierarchical geomorphological mapping included macroforms in the 1st taxon (Figure 1), morphostructural units in the 2nd taxon (Figure 2), geomorphological units in the 3rd taxon (Figure 3), and landform patterns in the 4th taxon (Figure 5). Comparatively, the south-central portion of Mato Grosso presents greater geomorphological diversity as denoted by the mapping. The highest elevation in the state is the Serra do Monte Cristo, with an altitude of 1118 meters, located in the Serra de Santa Bárbara State Park.

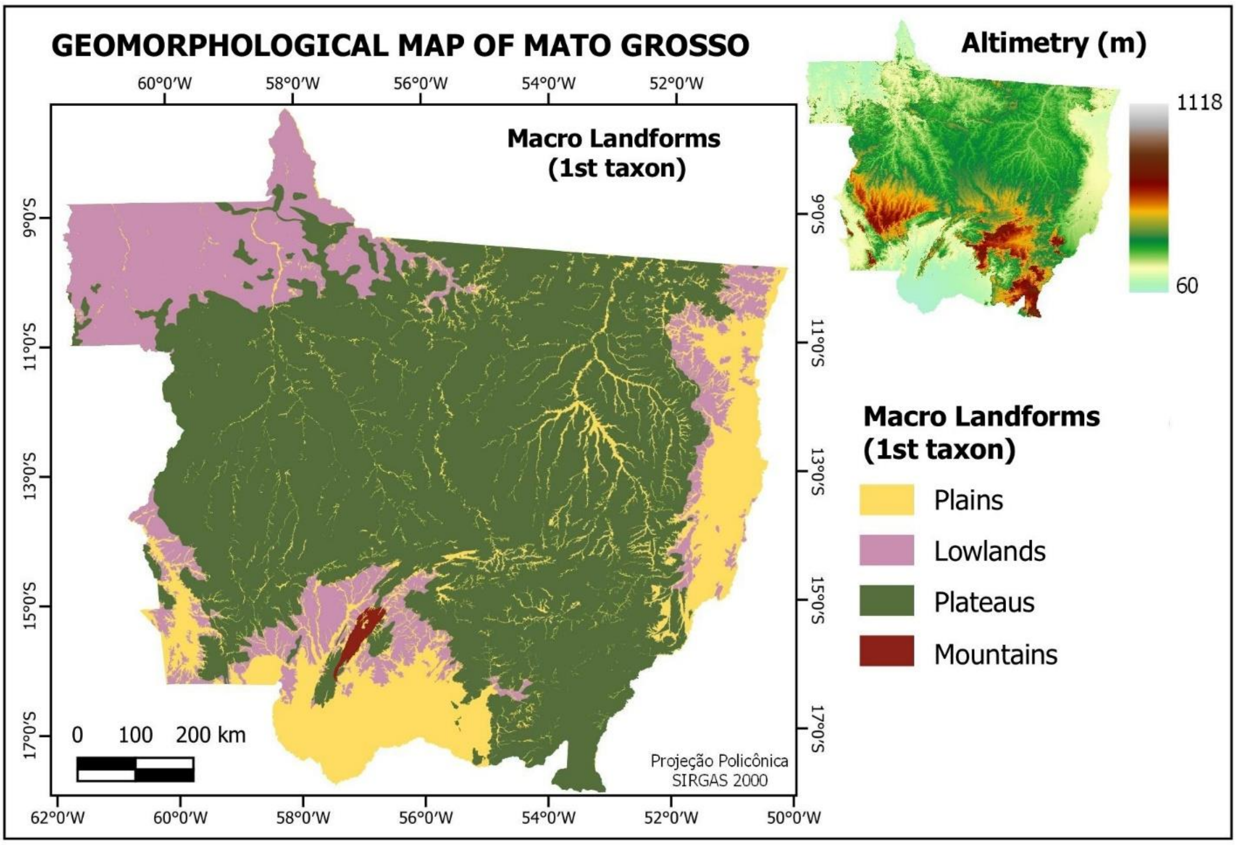

Figure 1. Mapping of macro landforms (1st taxon).

The macroforms represented the morphological evidence, highlighted in the landscape, of the folded reliefs of ancient orogens that preserve mountain characteristics, of the epeirogenic movements that supported plateaus and promoted the development of lowered surfaces, of the processes of dissection and sedimentary input in the Neogene and Quaternary, with the fluvial plains, in addition to the variations in landforms under the action of differential erosion in distinct lithologies.

The large plains indicate the agradational portions of the Madeira, Tapajós, and Xingu river systems, as well as the floodplains in the context of the Araguaia and Paraguay rivers (Pantanal Matogrossense). Structural control is highlighted, with North-South faults that favored the development of the drainage network in Mato Grosso. In the case of the Pantanal, although its genesis is related to isostatic compensation in the Paleogene with the uplift of the Andes and intraplatonic adjustments that resulted in the subsidence of the Pantanal depression, the characteristic of unconsolidated sedimentary deposits was considered prevalent for macroform classification purposes. The Pantanal is, therefore, an active plain developed on a lowered surface with sedimentary input from the surrounding plateaus.

The lowlands characterize important transitional areas in the state of Mato Grosso. The lowlands to the northwest and west correspond to the dissection of the intracratonic portion of the Solimões and the Xingu-Tapajós craton. To the south, the lowlands originate from the denudation of the sedimentary basins (Parecis and Paraná) and the folded relief mountains of the Paraguay Belt.

Plateaus were the predominant macroform in terms of area occupied in the state of Mato Grosso, accounting for 65%. The highest nuclei of the plateaus are associated with the summits that border the sedimentary basins, commonly associated with the presence of erosive escarpments, mesas, canyons, pediment slopes dipping towards the regional base levels, flattened tops (with the presence of *chapadas*), and extensive slopes. While in north-central Mato Grosso the topographic discontinuities are predominantly due to the effects of differential erosion from the geological complexity of the cratonic context, in south-central Mato Grosso the greater amplitudes are strongly influenced by tectonic and neotectonic factors.

The category of "serra", in a broad sense, has been assimilated to mean a rugged, dissected relief with significant altimetric differences. *Serras* can indicate mountainous landforms, as is the case with the Serra das Araras, but they can also refer to the edges of plateaus or residual plateaus, such as the Serra do Roncador. The concept of *serra*, from this perspective, is polysemous.

The presence of mountains in the state of Mato Grosso is supported by the literature, since publication such as that of Ross (2014, p. 181) and CPRM (MORAES, 2010), for example, characterize the terrain of the Paraguay Belt as a mountainous domain. The report of the Cuiabá sheet map (SD-21), from the RadamBrasil Project (1982, p. 493), describes the area as mountainous landform. Other publications cite the region as "Serrana Province" or similar terminologies. Furthermore, from a morphometric perspective, the mountainous areas mapped in the 1st taxon met all the conceptual criteria of this macroform, defined as “elevated features with an altimetric amplitude greater than 300 meters in relation to the surrounding areas, predominantly with peaks or ridges and steep slopes, whose occurrence is normally associated with continuous dissected sets, in orogenic systems or cratons” (CEN/SBCR, 2022, p. 215). Ross (2013) points out that the ancient Brazilian orogens underwent severe erosive phases and that some still maintain a mountainous aspect.

The subdivision of macroforms into morphostructures (2nd taxon), as shown in Figure 2, highlighted the lithostructural conditioning factors of the geological substrate and long-term morphodynamics. The state of Mato Grosso has three major geotectonic provinces: i) Amazon Craton, which encompasses the oldest morphostructures in the state, whose rocks are dated to ages greater than 960 Ma; ii) Tocantins Province, linked to the Brasiliano Orogenic Cycle (960 to 540 Ma), which includes the belts of the Paraguay-Araguaia Belt, which originated ancient mountain ranges; iii) Phanerozoic Sedimentary Basins, whose accumulation processes began before 540 Ma.

The cratons of the South American Platform are ancient and stable lithospheric portions that were not directly affected by Neoproterozoic collisional processes, characterizing themselves as internal parts of the plates that converged during the formation of Western Gondwana (Alkmin, 2015). On the margins of the Amazon craton, the diachronic collisions of the Paranapanema, São Francisco–Congo and Amazon paleocontinents, also involving a magmatic arc and a microcontinent, resulted in the closure of the Goianides Ocean and the uplift of the Tocantins mountain system during the Brasiliano Cycle orogeny in the Lower Cambrian. The Araguaia belt, approximately 1,200 km long and 150 km wide, is composed of an Archean and Paleoproterozoic basement overlain by Neoproterozoic metasedimentary successions (Salgado et al., 2015). From a morphological perspective, only 0.3% of the territory of Mato Grosso preserves mountain formations, which denotes the erosion and reconfiguration of orogenic systems.

Ancient orogens also mark a boundary between the two main sedimentary basins outcropping in the state of Mato Grosso: the Parecis Basin, in the north-central region, and the Paraná Basin, in the southeast. These are typical intracratonic basins, whose evolution includes sedimentary successions defined by transgressive-regressive cycles linked to oscillations in relative sea level during the Paleozoic, effects of epeirogenesis, and sedimentary formations of fluvial, desert or deltaic origin in diverse climates. The sedimentary records are the result of successive phases of sedimentary accumulation that alternated between periods of generalized erosion and marine regressions and transgressions.

The mapping of the 3rd taxonomic level, referring to geomorphological units, reconciled established toponyms from the geomorphological cartography of Mato Grosso with detailed descriptions of morphosculptures with morphological homogeneity: 6 wetlands, 9 plains, 15 depressions (located on lowlands, which is the macroform of the 1st taxon), 32 plateaus, 4 tablelands and the mountainous unit of the Serrana Province were distinguished. This is the hierarchical level of classification closest to the representation of pre-existing regional-scale mapping. From this perspective, in order to preserve the qualitative/historical identity of local landforms, units such as the "Cuiabana Depression", the "Chapada dos Guimarães" and the "Planalto dos Alcantilados" were maintained, even though the delimitation was refined according to the taxonomic subdivision and the geomorphometric attributes employed.

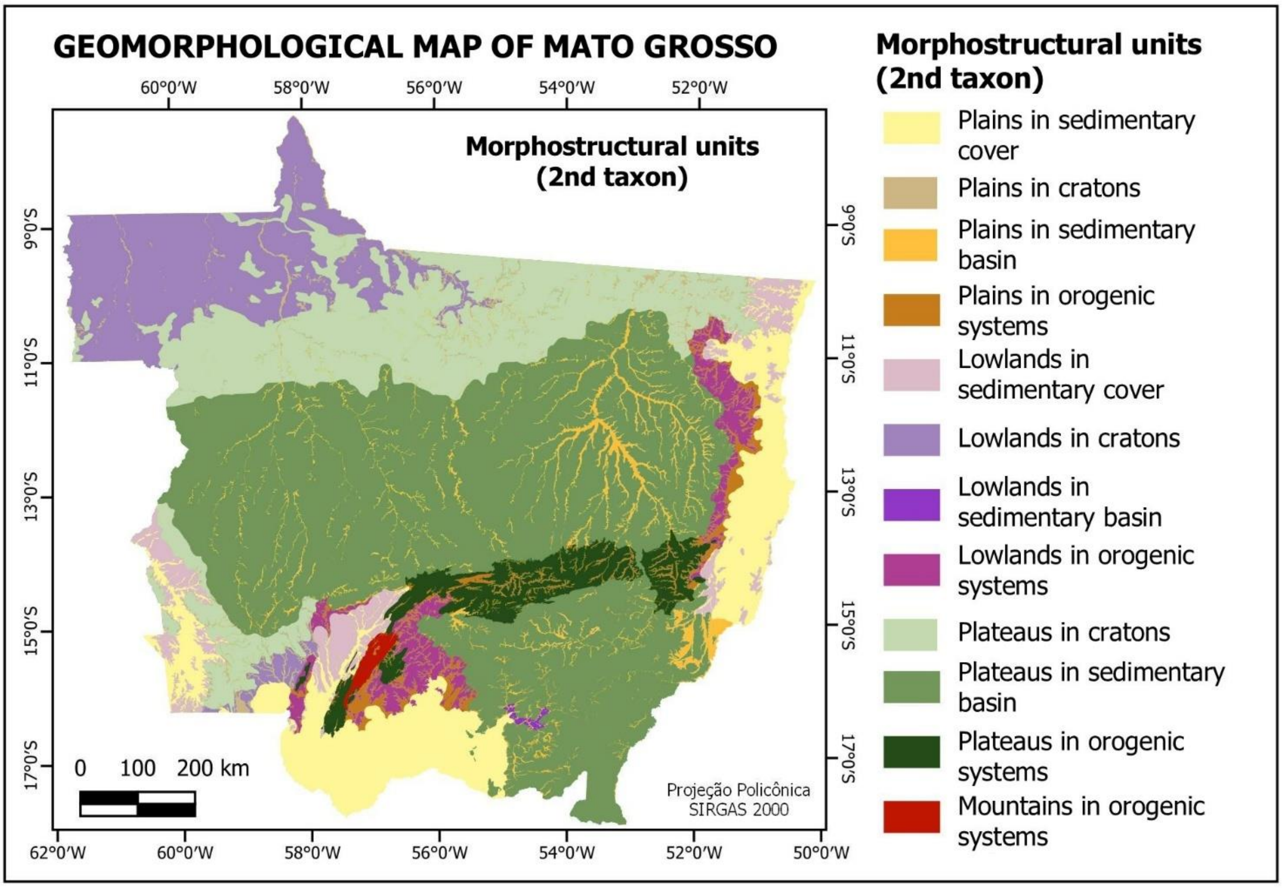

Figure 2. Mapping of morphostructural units (2nd taxon).

As an example, Figure 4 presents a section in western Mato Grosso comparing the current mapping with two previous classifications at the same taxonomic level. Note that the current mapping is more detailed, especially with the compartmentalization of generalized plateaus in previous proposals. The Parecis Plateau (Werle; Silva, 1996; IBGE, 2019) has distinct morphological patterns, as evidenced by the altimetric amplitude inscription in Figure 4. Considering that the 3rd taxon, according to Ross (1992; 1998), should be classified based on "top altitudes, slope dominance, top and slope morphology, interfluvial dimensions, and drainage channel incision," it was found necessary to revise the delimitations using geomorphometric attributes that synthesize these characteristics.

Silveira and Silveira (2021), in a historical analysis, identified that mappings with homogeneous morphological units with toponyms are the main identity of the Brazilian school of geomorphological cartography. This, however, may carry subjectivities and conceptual inaccuracies.

It is also noteworthy, as shown in Figure 4, that the geomorphological units of IBGE (2019) largely preserve the legacy of the RadamBrasil geomorphological maps. The units immediately north of the Parecis Plateau, in the pre-existing mappings, correspond to depressions. In the current study, these areas were classified as plateaus, considering that the lowlands (defined by quantitative criteria) of the Amazonian sedimentary basin (Figure 2) begin further north.

In the 4th taxon, the definition and mapping of landform patterns (Figure 5) represent the main advances in geomorphological cartography presented in this study. Because it is a proposal based exclusively on geomorphometric attributes, it is noteworthy that even in agradational environments with little altimetric variation, the modeling was effective in identifying and characterizing morphological patterns.

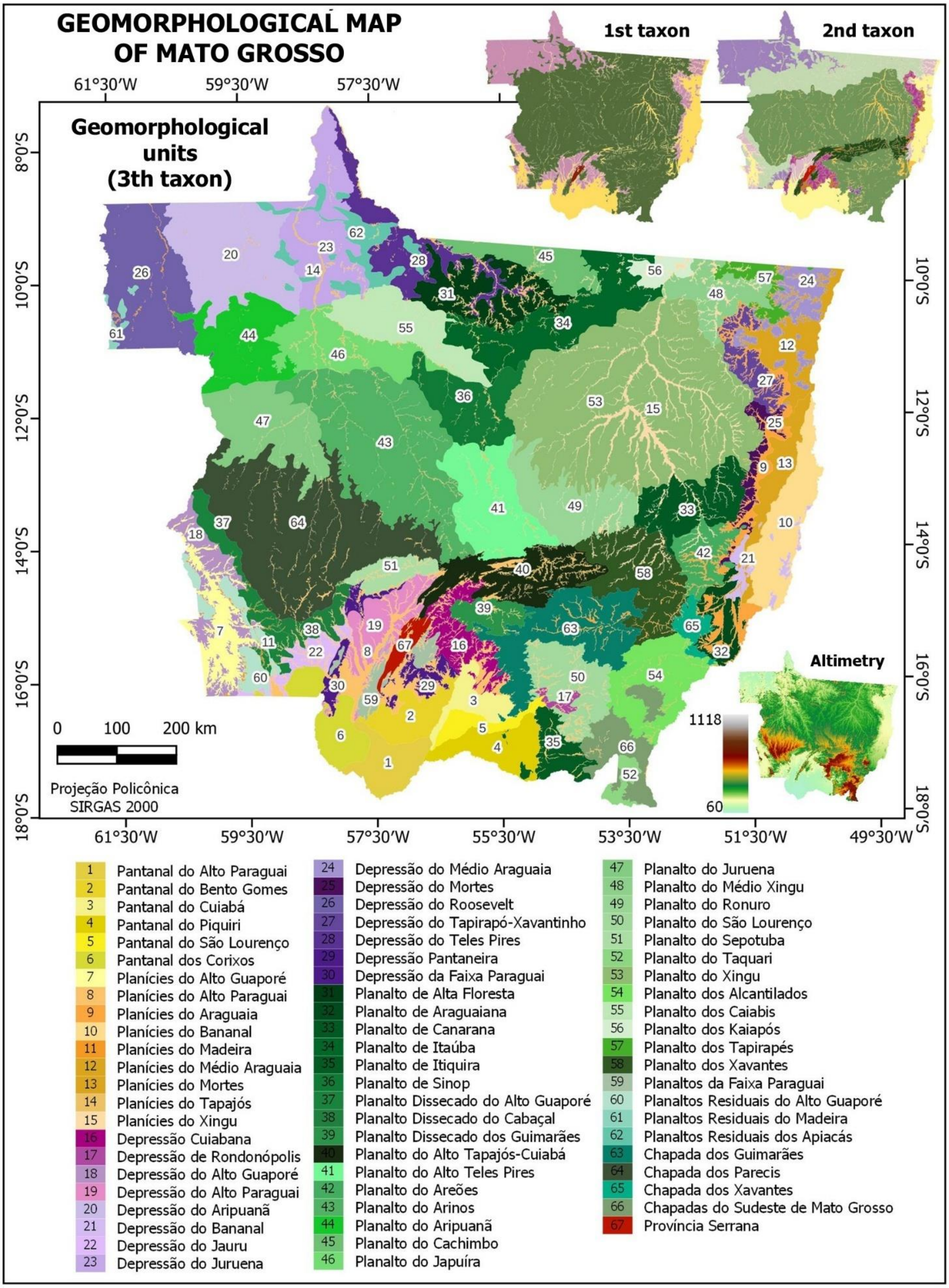

Figure 3. Mapping of geomorphological units (3rd taxon).

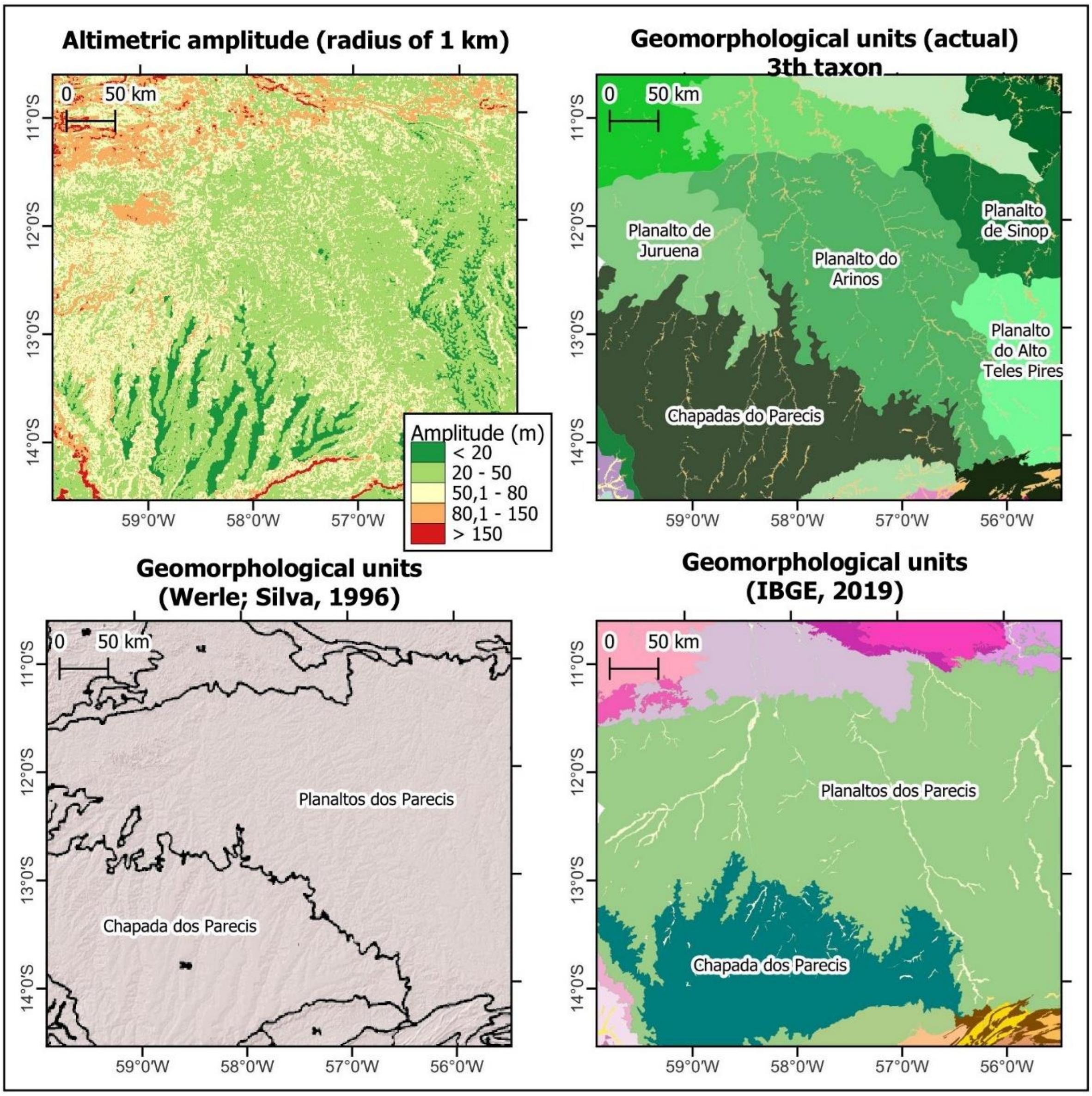

Figure 4. Comparison of geomorphological units (3rd taxon) in a section of the Chapada and Planalto dos Parecis.

Interhill plains represent areas of sedimentary input in low-order fluvial channels, situated in low-slope relief with flat, open valleys, while dissected plains indicate constructive portions where fluvial incision occurs (although deposition still exceeds erosion), with more confined valleys and dissected terrain in the vicinity, possibly related to the lowering of the local base level. The mapped alluvial-colluvial plains are formed by the interaction of fluvial and slope processes, with lateral erosion, gravitational transport, past deposits from mass movements and remobilization of colluvial slopes, and may include sediments distal to the current riverbed and ancient fluvial terraces. These were the three predominant plain patterns in the context of the Mato Grosso plateaus.

Upon entering the Pantanal floodplain, most of the rivers draining the plateaus acquire a distributary drainage pattern and form fluvial fan depositional systems. The São Lourenço River, for example, exhibits a distributary pattern in the Pantanal and has been building a mega-fluvial fan since the Pleistocene (Corradini; Assine, 2012). The mega-fan was identified by mapping the 4th taxon in the category of recent alluvial plains, whose pattern highlights the fluvial avulsions in the region, which can reach tens of kilometers in a few decades. This pattern also records the areas with more active morphodynamics in the transport and deposition of sediments, including the depositional lobes characterized by Corradini and Assine (2012), derived from the deconfinement of the flow from the drainage basins of the adjacent plateaus. The subrecent alluvial plains, in turn, are limited to the portions less affected by the morphodynamics of recent fluvial avulsions.

One interesting characteristic of the methodology used in the Pantanal stands out. The Copernicus DEM is a product of synthetic aperture radar, and the elevation values consider objects present on the surface, such as vegetation and buildings. This is commonly a limiting factor in the use of global DEMs, but in this work, this characteristic was used as a complementary variable in mapping patterns in the floodplains. Areas with greater intensity in fluvial morphodynamics have more developed vegetation, as is the case with the megafan of the São Lourenço River. The tree canopy and forest fragments result in elevation discontinuities, measured by slope. If the modeling were performed with a DTM (digital terrain model, which considers the altimetry of the surface without any objects), such variations in the Pantanal would not be evident, as it is a very flat area – varying from 3 to 15 centimeters per square kilometer, according to Alvarenga et al. (1980). The DEM, therefore, represented a biogeomorphological feature that helped distinguish recent alluvial plains from subrecent ones.

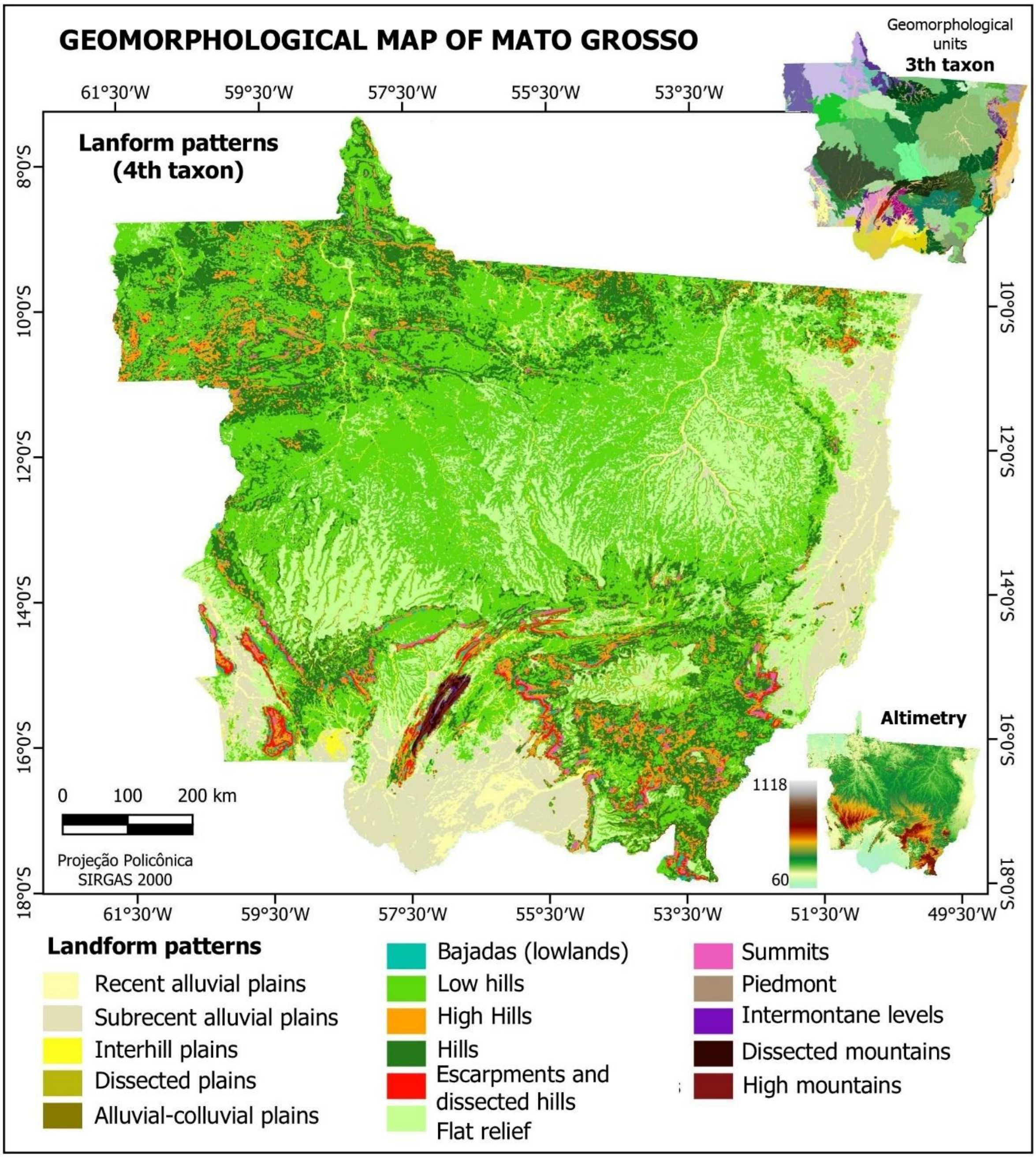

Figure 5. Mapping of landform patterns (4th taxon). The subdivision of landform patterns (4th taxon) in relation to geomorphological units (3rd taxon) resulted in 376 landforms at this taxonomic level (see digital file provided).

Figure 6 exemplifies the representativeness of the patterns linked to the plains, in a section of the municipality of Barão de Melgaço, within the Pantanal region. The folded relief in an orogenic system, with synclines and anticlines supported by Neoproterozoic phyllites and metarenites, preserves in the current landscape the morphology of high hills with altimetric amplitude between 80 m and 150 m. The erosion of these features produced, in the surrounding area, the alluvial-colluvial plain pattern. The Cuiabá Riverbed guides the recent alluvial plain, while the other areas correspond to the subrecent alluvial plain.

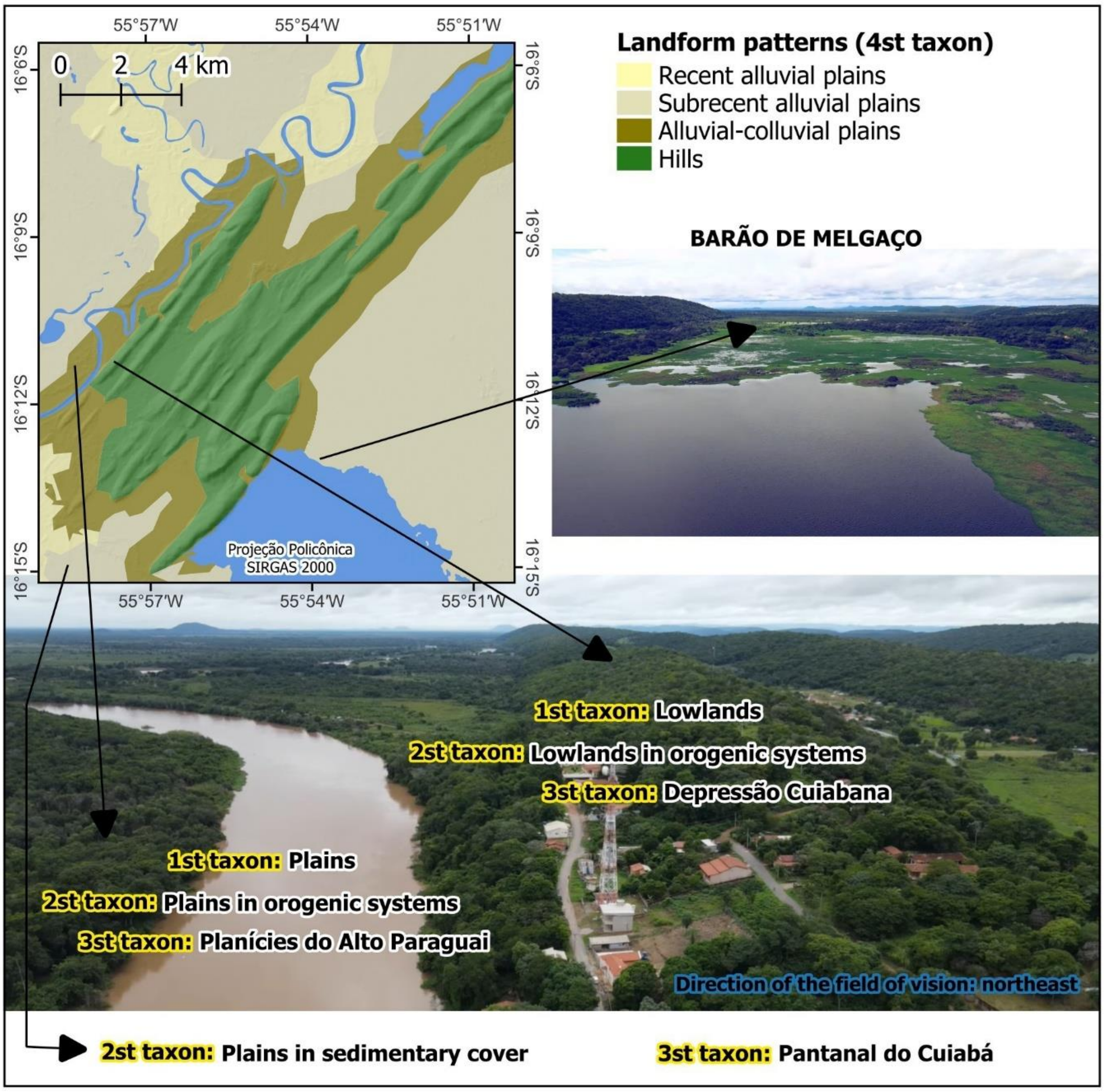

Figure 6. Results of geomorphological mapping in Barão de Melgaço (transition to the Pantanal wetlands of Mato Grosso).

Low hills represented the predominant landform pattern in the state of Mato Grosso, accounting for 41.7% of the relative area. Along with the flattened landform pattern, the geomorphological conditions of these landforms favor the implementation of extensive monoculture. Thus, the advance of the agricultural frontier in these landform patterns gives morphodynamic significance to the effects of deforestation, the use of center pivot irrigation systems and water management, soil impermeability in agribusiness urban centers, siltation and contamination of rivers, and susceptibility to sheet and linear erosion processes. In the evolution of landforms, hills and flattened refliefs indicate current and past climatic characteristics, along with polygenetic (paleo)surfaces.

The high hills category, in the 4th taxon, was most prominent in the lowlands of the Amazon craton and in the São Lourenço River basin (mostly located in the plateaus of the Paraná Sedimentary Basin). Small hills are distinguished by their lower dissection and/or altimetric amplitude (Table 1). Figure 7 illustrates the mapping results in a transition area between plateau and lowland (1st taxon), in the Rondonópolis depression (3rd taxon), and in the lower course of the São Lourenço River, shortly before entering the Pantanal plain. The set of ruiniform features in the sandstones of the so-called "Cidade de Pedra" (Furnas and Ponta Grossa formations) was represented by the pattern of escarpments and elevated hills, whose environment, along with the gravitational deposits of the slopes, constitutes the pattern of the lowlands. This is a section with great geomorphological diversity that highlights the conceptual and semantic assumptions of the geomorphological mapping carried out.

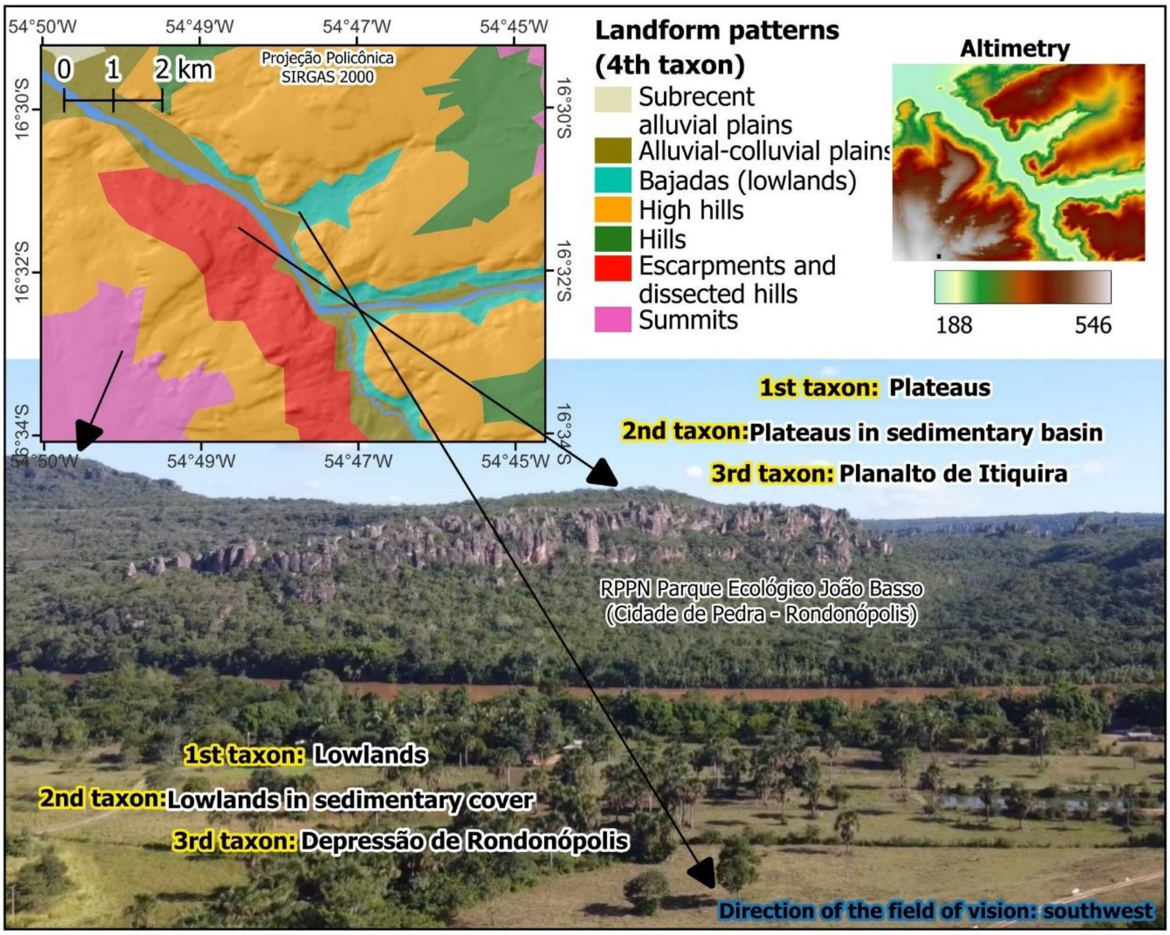

Figure 7. Results of geomorphological mapping in Rondonópolis (Cidade de Pedra and São Lourenço River).

The class of escarpments and high hills (unified) encompassed features with an altimetric amplitude greater than 250 m considering a radius of 1 km. If the difference in elevation is in all directions relative to the summit, they are characterized as high hills (predominantly in the folded reliefs of the Paraguay Belt). In the case of escarpments, the difference in elevation for one of the slopes relative to the ridgeline is what characterizes this feature. The example in Figure 7, in the Chapada dos Guimarães, shows the landform patterns in the transition from a plateau in a sedimentary basin to a lowland, with the Cuiabana Depression (3rd taxon).

The representation of the escarpment, at this taxonomic level, grouped the cuesta front, the cornice and the talus deposits. As occurs in other escarpments in the state of Mato Grosso (Chapada dos Parecis, Chapada dos Xavantes and the Residual Plateaus of Alto Guaporé, for example), festooning occurs through regressive erosion, and the accommodation of material at lower levels is related to the formation of lowlands. Lowlands can be shaped in a confined environment and linked to leveled reliefs on lowered surfaces. In this geomorphological evolution of the plateau escarpments, there are two conditioning factors: the Meso-Cenozoic tectonic events that uplifted the sedimentary basins, exposing them to degradational processes; and denudation linked to oscillations between dry and humid climates, mainly with the lateral retreat of the front and vertical incisions on the reverse side of the escarpments, commonly with associated residual landforms.

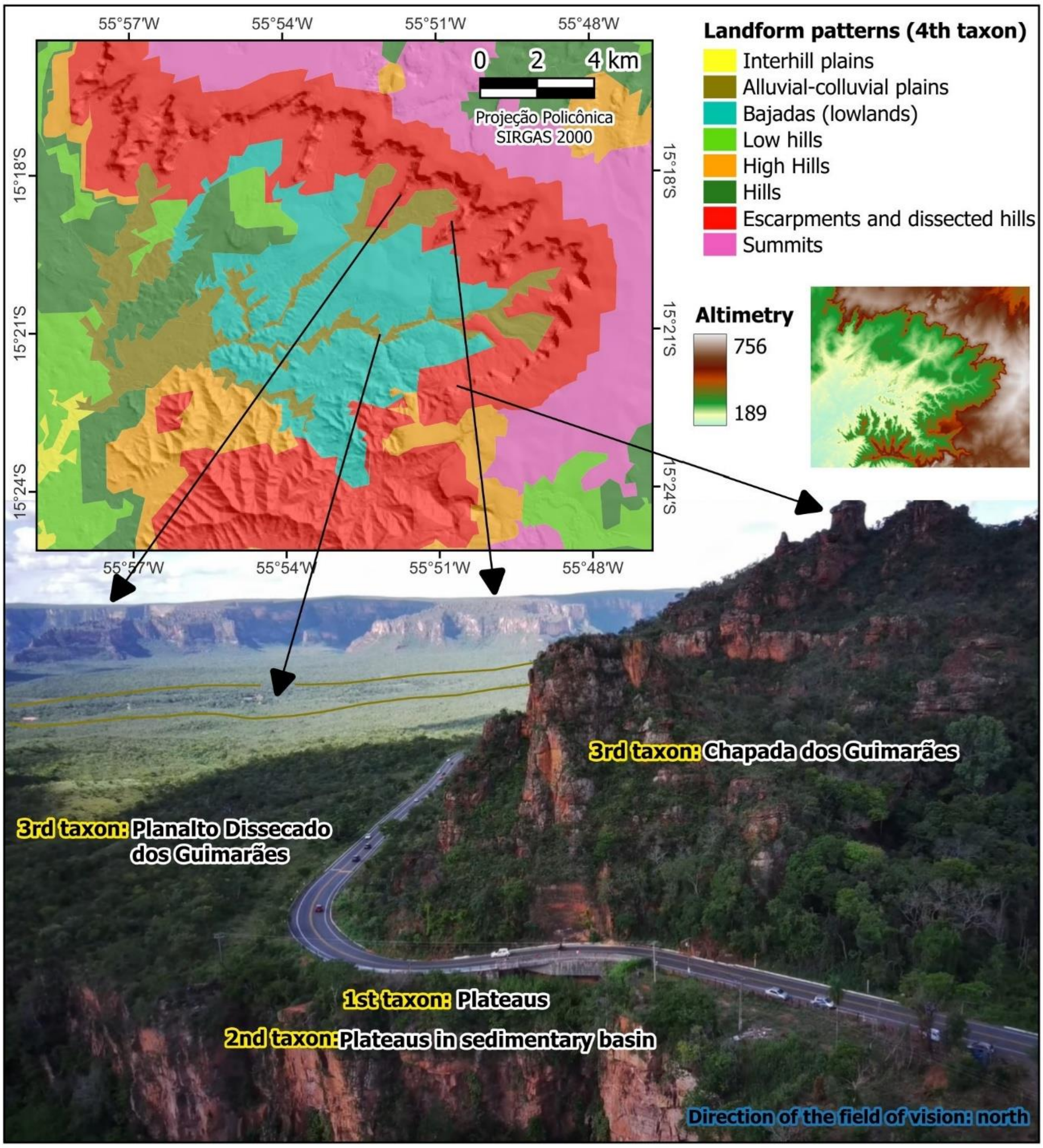

Figure 8. Results of geomorphological mapping in Chapada dos Guimarães (Portão do Inferno).

In plateaus, escarpments are directly associated with another landform pattern, known as summits, which represent the peaks on the reverse side of the escarpments. Summits have important morphogenetic and morphochronological significance, since these elevated portions – associated with circumdenudational erosion in sedimentary basins – bear witness to levels of flattened surfaces and aid in long-term geomorphological interpretations. The erosive resistance of the summits is linked to the presence of lateritic formations. Prado et al. (2014) considered models of groundwater and pedogenic oscillation in the interpretation of laterites in the Chapada dos Guimarães, highlighting two vertical types of iron transport: descending (dissolution of surface iron by chemical weathering from rainfall) and ascending (fluctuation in groundwater level).

In the areas mapped as mountains at the 1st taxonomic level, the classification of the 4th taxon indicated four landform patterns: high mountains, dissected mountains, intermontane levels and piedmonts (whose parameters are shown in Table 1). Figure 9 illustrates the results in the Serra das Araras Ecological Station, whose altimetric amplitude is greater than 400 meters. After half a billion years of erosion by the orogens of the Brasiliano Cycle, the current landscape consists of parallel mountain ranges containing rock structures of highly silicified sandstones. There is a correlation between the dissected mountains and the Araras Formation (developed in a carbonate platform environment between 650 Ma and 541 Ma), while the elevated mountains are mostly found in the Raizama Formation (developed in a transitional deltaic plain environment between 650 Ma and 541 Ma), both from the Neoproterozoic, according to the geological map of CPRM (Lacerda Filho et al., 2004).

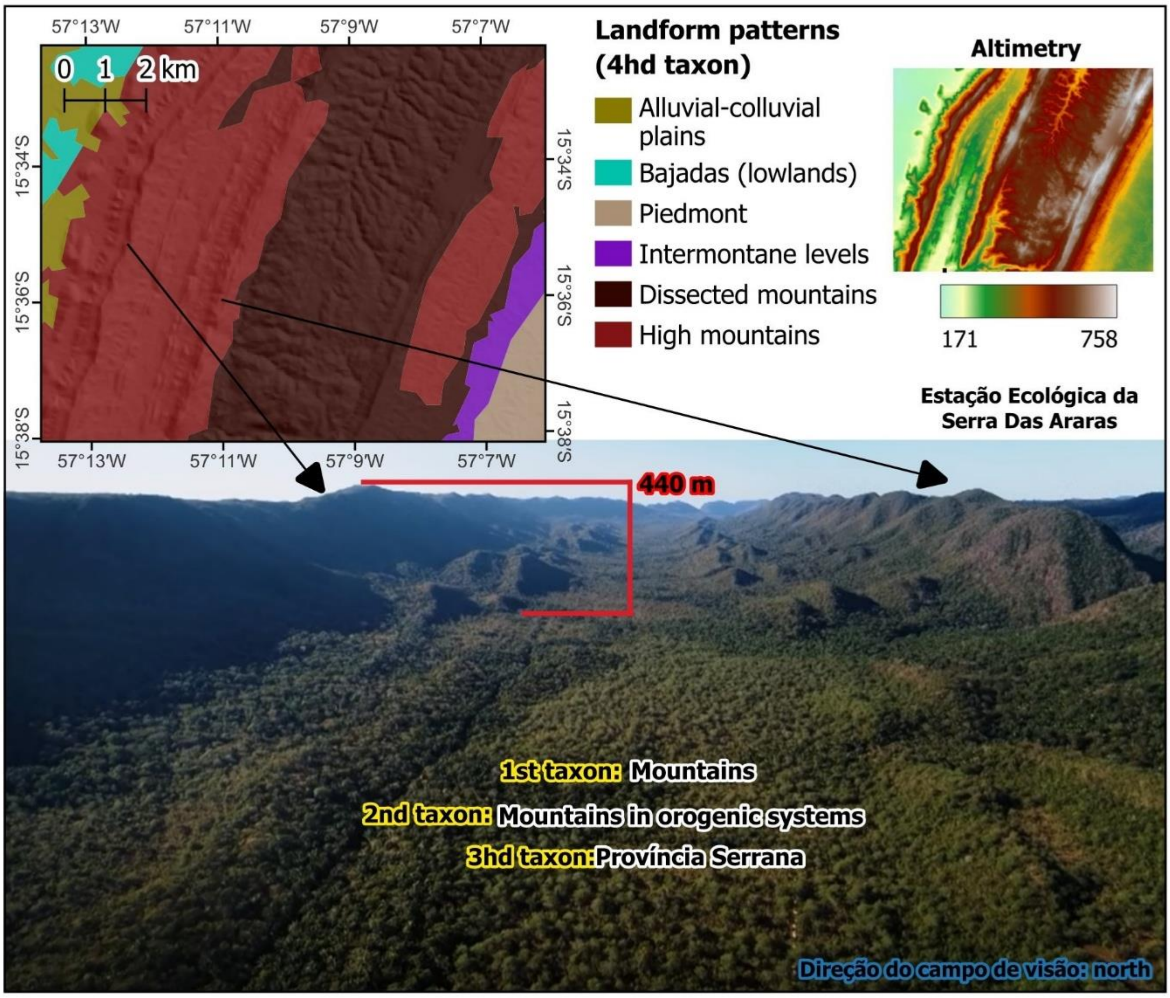

Figure 9. Results of geomorphological mapping in Cáceres (Serra das Araras).

The preserved mountainous core in the state of Mato Grosso corresponds to a strip with a maximum extension of 150 km (NE-SW) and 35 km (NW-SE), following the axes of the folds of the Paraguay Belt. Ross (1991) states that the folds are associated with strike-slip and reverse faulting, followed by various erosive phases, resulting in the sculpting of the reliefs into the most preserved folded structures in Brazil.

High mountains preserve their most prominent peaks, as indicated in Figure 9, in accordance with the CEN/SBCR (2022) concept of mountains, with the characteristics of amplitude, extent/continuity and summit morphology. Dissected mountains, in turn, have less altimetric difference (segments with amplitude less than 300 m) and indicate erosion in the vicinity of elevated mountain cores, originating mainly from lithological variations and differential erosion in the sequence of anticlines and synclines. It is considered that the mountain environment involves landform patterns in addition to the degradational portions sustained in the landscape, which denotes the importance of morphological homogeneity for the delimitation of the whole – a generalization inherent to higher taxa. In Figure 9, for example, the axis of the eroded syncline belongs, in this taxon, to the pattern of high mountains.

From this perspective, the landform patterns of piedmonts and intermontane plateaus were distinguished as aggradational sectors of the mountainous environment. The Topographic Position Index was used for classification, which made it possible to represent the energy relationships between degradational and aggradational processes in the terrain, according to the proposal of Silveira; Silveira (2023). Piedmonts represent the morphology of the foothills of mountains, with the break in slope that evidences the cumulative result of gravitational slope transport, where deposition exceeds erosion. Intermontane indicate transitional levels between the elevated/dissected slopes, preserving detrital deposits not remobilized by fluvial action and rocks with less weathering resistance.

Regarding the limitations of the modeling, the main noise in the classifications comes from edge effects caused by the regional calculation of geomorphometric attributes (neighborhood size), especially at the boundaries between all categories of hills. It is considered that the method ensures internal generalization (morphological homogeneity), but that it can, however, generate extrapolated external boundaries. The results presented correspond to the digital classification without any manual edits in the 1st and 4th taxons, in order to emphasize the characteristics and representativeness of the mapping with the exclusive application of morphometric parameters.

4. Conclusions

The research demonstrated the potential application of geomorphometry as a fundamental theoretical and methodological resource for multiscale geomorphological mapping. Considering the integration of the four categorized taxonomic levels, 376 relief classes were mapped in the state of Mato Grosso, each with branching characteristics that describe their genesis, forms, and active processes. The hierarchical organization into macroforms, morphostructures, geomorphological units and landform patterns is suitable for the compartmentalization of the landscape as a support for geomorphological analyses, from geological aspects to land cover and use. The unified classification rules, with a reduced number of variables, represented the diversity of the Mato Grosso landforms in distinct dissection contexts.

It is concluded that the products derived from DEMs, combined with knowledge of the study area and conceptual clarity, enable morphological, morphogenetic and morphodynamic characterization from a taxonomic and integrated perspective based on quantitative terrain attributes. The combination of local (3x3 windows) and focal (neighborhood analysis) geomorphometric attributes was successful in generalizing and distinguishing morphologies, emulating the roughness effect (textural homogeneity) adopted as a criterion in traditional geomorphological maps at a regional scale. In later stages, the mapping will undergo a refinement of the delimitations, since the edge effect produces inaccuracies in the contours.

From an operational standpoint, one of the main advantages of digital terrain modeling is considered to be the possibility of reproducing or adapting the method, making the proposal open to the inclusion of multiple variables (geomorphometric or otherwise), tests with other values/thresholds and DEMs. For replication purposes, the main limitations may be linked to the lack of methodological rigor in the steps preceding the creation of the map itself, from considerations about the quality of the model (processing characteristics and resolution/scale) to imprecise definitions regarding the geomorphological objects to be modeled. Semantic and conceptual issues, therefore, should underpin geomorphological mapping projects, and the characteristics of the DEM should be consistent with the level of detail intended for the mapping.

The geomorphological map of the state of Mato Grosso sought to synthesize past contributions and current discussions mediated by a parameterized and open methodology, which reinforces the research's intention to ensure the continuity of geomorphological mapping in the area, whether with the inclusion of new geomorphological categories – given that this one presented a morphological emphasis – or the detailing at other levels or taxonomic systems. This study highlights the advancement in relation to the 4th taxon mapped in the state of Mato Grosso and the use of geomorphometric attributes (calculated from a global DEM) as a reference at all hierarchical levels.

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Data availability: The vector files of the geomorphological map for this work are available at https://zenodo.org/records/19893071

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Declaration of Artificial Intelligence Use: The authors declare that no generative artificial intelligence tools were used at any stage of the development of this manuscript (conception, writing, data analysis, or submission).

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