Mercator, Fortaleza, v. 23, e23021, 2024. ISSN:1984-2201

RECOGNITION OF DURICRUST GEOMORPHIC SURFACES USING A RELIEF DISSECTION MATRIX

https://doi.org/10.4215/rm2024.e23021

Brizzi, R.R. [a]* - Villela, F.N.J. [b] - Catarucci, A.F.M. [c] - Palma, H.P. [d] - Torrado, P.V. [e]

(a) Phd Student in Agronomy
ORCID: https://orcid.org/0000-0002-4150-6484. **LATTES:** http://lattes.cnpq.br/3489401112005596.
(b) Phd in Geography
ORCID: https://orcid.org/0000-0002-7804-6565. **LATTES:** http://lattes.cnpq.br/7784362002921788.
(c) Phd Student in Geography
ORCID: https://orcid.org/0009-0009-7266-0052. **LATTES:** http://lattes.cnpq.br/2872828167323397.
(d) Phd Student in Agronomy
ORCID: https://orcid.org/0009-0006-2428-365X. **LATTES:** http://lattes.cnpq.br/9803886320013379.
(e) PhD in Soils and Plant Nutrition.
ORCID: https://orcid.org/0000-0001-9228-9910. **LATTES:** http://lattes.cnpq.br/3097898945075293.

Article history:
Received 15 August, 2024
Accepted19 September, 2024
Published 10 October, 2024

(*) CORRESPONDING AUTHOR
Address: ESALQ-USP, Avenida Pádua Dias, 11, CEP 13418-900, Piracicaba (SP), Brasil. Tel (+ 5519) 3447-6033
E-mail: raphael.brizzi@usp.br

Abstract

Landforms can orientate the hydrodynamics and distribution of materials on the ground, producing flattened and/or lowered geomorphic surfaces given the evolutionary characteristics from climatic, morphogenetic and pedogenetic factors. This work aims to demonstrate the compartmentalization and association of geomorphic surfaces covered by ferruginous duricrusts in Savannah areas in Brazil according to a relief dissection matrix. This matrix indicates the vertical cutting of the valleys and the interfluvial horizontal dimension of the hills through landform measurements in radar images, classification in alphanumeric codes and statistical correlations. The results indicated details in the compartmentalization of the surface according to the landform roughness, making it possible to link, through data from the dissection matrix and the statistical correlation, the association between the compartments according to summit positions and remaining depressed areas. Despite the fact that more robust measurements obtained from high-precision mappings can point out further landform evolutionary stages, it is understood that a dissection matrix and its statistical correlations can not only compartmentalize the landscape and provide an initial overview of the landscape's evolution, but also indicate geomorphic surfaces that could have been worked at the same time. In this sense, the recognition of geomorphic surfaces, occurrence of duricrusts and landforms in this work allowed a certain morphogenetic correspondence that can contribute to geomorphological studies, although the results must be observed with caution when verified from the tropical perspective of relief evolution.

Keywords: Valley Cutting; Interfluvial Dimension; Dissection Matrix; Geomorphic Surfaces; Duricrusts.

Resumo / Resumen

RECONHECIMENTO DE SUPERFÍCIES GEOMÓRFICAS LATERITIZADAS POR MEIO DA MATRIZ DE DISSECAÇÃO DO RELEVO

A morfologia do relevo pode condicionar a hidrodinâmica e a distribuição de materiais no nível da superfície, produzindo superfícies geomórficas aplainadas e/ou rebaixadas, dadas as características evolutivas provenientes de fatores climáticos, morfogenéticos e pedogenéticos. Este trabalho tem como objetivo demonstrar a compartimentação e associação de superfícies geomórficas encimadas por duricrusts ferruginosos em áreas de Savana no Brasil, de acordo com uma matriz de dissecação do relevo. Esta matriz indica o entalhamento vertical dos vales e a dimensão horizontal interfluvial dos interflúvios por meio de medições do relevo em imagens de radar, classificação em códigos alfanuméricos e correlações estatísticas. Os resultados indicaram detalhes na compartimentação da superfície de acordo com a rugosidade do relevo, permitindo vincular, por meio dos dados da matriz de dissecação e da correlação estatística, a associação entre os compartimentos de acordo com as posições de cimeira e as áreas depressionadas remanescentes. Apesar de medições mais robustas obtidas a partir de mapeamentos de alta precisão poderem apontar estágios evolutivos mais detalhados do relevo, entende-se que uma matriz de dissecação e suas correlações estatísticas podem não apenas compartimentar a paisagem e fornecer uma visão inicial de sua evolução, mas também indicar superfícies geomórficas que podem ter sido trabalhadas simultaneamente. Nesse sentido, o reconhecimento de superfícies geomórficas, a ocorrência de duricrusts ferruginosos e modelados de relevo neste trabalho permitiram certa correspondência morfogenética que pode contribuir para estudos geomorfológicos, embora os resultados devam ser observados com cautela quando verificados a partir da perspectiva tropical de evolução do relevo.

Palavras-chave: Entalhamento dos Vales; Dimensão Interfluvial; Matriz de Dissecação; Superfícies Geomórficas; Duricrusts Ferruginosos.

FORME MILICIENNE ET SES PARADIGMES DANS L'ESPACE-TEMPS DE L'URBAIN DANS LA METROPOLE DE RIO DE JANEIRO

Las formas del relieve pueden orientar la hidrodinámica y la distribución de materiales en el terreno, produciendo superficies geomórficas aplanadas y/o rebajadas de acuerdo con las características evolutivas de factores climáticos, morfogenéticos y pedogenéticos. Este estudio tiene como objetivo demostrar la compartimentación y asociación de superficies geomórficas cubiertas por costras ferruginosas en áreas de Sabana en Brasil, según una matriz de disección del relieve. Esta matriz indica el corte vertical de los valles y la dimensión horizontal interfluvial de las colinas mediante mediciones de formas de relieve en imágenes de radar, clasificación en códigos alfanuméricos y correlaciones estadísticas. Los resultados indicaron detalles en la compartimentación de la superficie según la rugosidad del relieve, permitiendo la asociación de los compartimentos de acuerdo con las posiciones de las cumbres y las áreas deprimidas restantes, a través de los datos de la matriz de disección y su correlación estadística. El reconocimiento de superficies geomórficas, la ocurrencia de costras ferruginosas y formas del relieve permitió una cierta correspondencia morfogenética, aunque los resultados deben observarse con cautela al verificarse desde la perspectiva tropical de la evolución del relieve.

Palabras-clave: Corte de Valle; Dimensión Interfluvial; Matriz de Disección; Superficies Geomórficas; Costras Ferruginosas.

INTRODUCTION

Landforms can orientate the hydrodynamics and distribution of materials on the ground, whose shapes and features point to the complex relationships involving denudation, weathering/pedogenesis processes and the formation of deposits throughout the geological time (TROEH, 1965; COOKE; DOORNKAMP, 1990; IMAIZUMI et al., 2010; VILLELA et al., 2015). This is a fundamental premise for understanding the landscape surface and a constant concern of geomorphological cartography in detailing landforms (DEMEK et al., 1972; ROSS, 1992; MINÁR; EVANS, 2008; COLTRINARI, 2011).

The geomorphological cartography deals with the dimension of landforms (morphometry), its implications regarding genesis (morphography), the origin of landforms and their sculptural processes (morphogenesis) and the chronology considering the distinction between functional and inherited relief forms (morphochronology), in addition to processes associated with water flows (morphodynamics) (TRICART, 1965; TRICART, 1977; SMITH et al., 2011).

Morphodynamics can, through surface and subsurface water flows, originate in situ and debris coverings that act in conjunction with climatic variations and denudation, defining levels supported by alteration mantles and their respective source materials (ALEVA, 1983; BIGARELLA et al., 2003; COLTRINARI, 2011; GUILLOCHEAU et al., 2018). From a morphogenetic point of view, these levels can be mapped as geomorphic surfaces (WAMBEKE, 1992; VILLELA et al., 2013), corresponding to covering elevations remaining from current and past processes, generally arranged in levels dependent on the conjugation with bedrock and soils (RUHE, 1956; WILSHIRE; RENEAU, 1992; CAMPOS et al., 2012; SILVA; CALEGARI, 2022). Its identification and compartmentalization commonly occur according to the morphoclimatic zoning and lithostructural conditions to which the investigated relief belongs (PELTIER, 1950; ZHU et al., 2015; SU et al., 2023).

In the Brazilian Savannahs there are very important testimonies of these flattened and/or depressed geomorphic surfaces, given the climatic, morphogenetic and pedogenetic evolutionary characteristics (BRASIL, 1981; RIBEIRO; ALVES, 2017). Examples of this are associated with tabular landforms covered by ferruginous duricrusts (ALEVA, 1993) and limited by cliffs or stepped levels, enabling compartmentalization (ROSS, 2016).

To contribute to the identification of these areas, this work aims to demonstrate the compartmentalization and association of geomorphic surfaces in two distinct Brazilian Savannah areas, where the occurrence of ferruginous duricrusts topographically highlights the landforms, constituting plateaus or flattened resistant zones. Reproducible methods will be presented for the geomorphological compartmentalization, indication of geomorphic surfaces and consequent morphogenetic correspondences, involving areas in which lateritization phenomena occur commonly.

METHODS

The Savannah region researched in this work is located in the Central-North of Brazil, in the state of Tocantins (Figure 1). Tracing from East to West, i.e. Palmas state capital to the fluvial plain of the Araguaia River, there are several geomorphological compartments subdivided into plateaus and depressions (BRASIL, 1981; ROSS, 2019; DANTAS et al., 2019) (Figure 2). The compartmentalization reflects the transition from the Parnaiba Sedimentary Basin, with siltstones and sandstones of Silurian-Devonian age supported by Precambrian granitic suites, to a mobile zone of metamorphic rocks from Neoproterozoic times (DANTAS et al., 2022) (Figure 3). This setting is accompanied by the wide occurrence of ferruginous duricrusts, corresponding to the transition between the Tocantins River Watershed (TRW) to the Araguaia River Watershed (ARW), the latter the main regional drainage unit. The current climate is tropical rainy savanna – Aw according to Köppen classification, with alternation of South Atlantic and Polar Migratory anticyclones, which dominates the region's humid climate (EVANGELISTA et al., 2022).

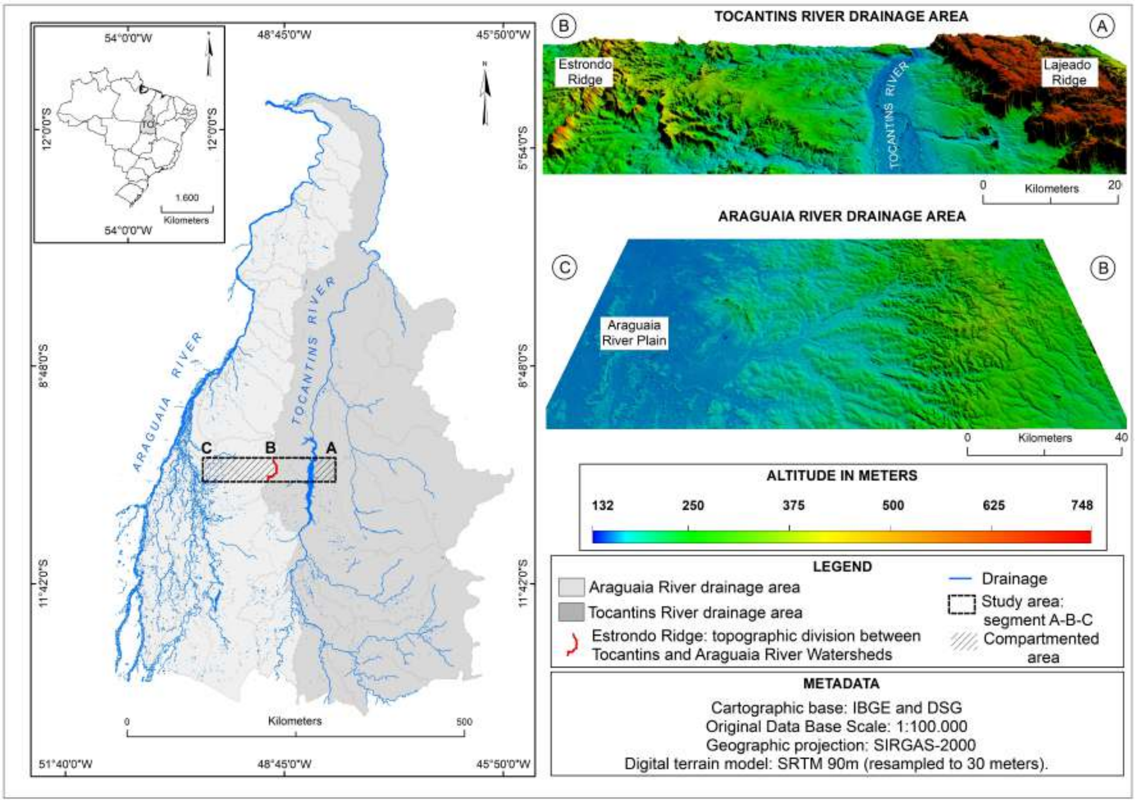

Figure 1 - Study area regional configuration. See Figure 2 for section A-B-C.

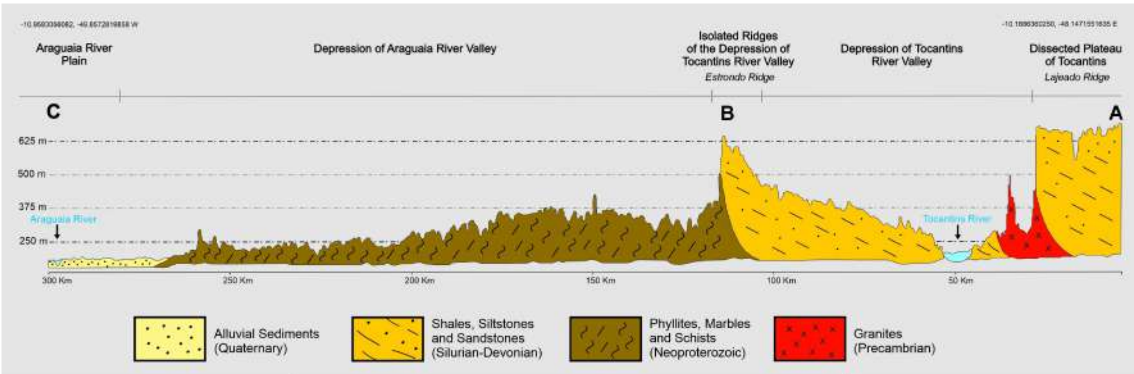

Figure 2 - Study area section A-B-C, with the lithology and regional geomorphological compartmentalization (according to Ross et al., 2019; Dantas et al., 2019).

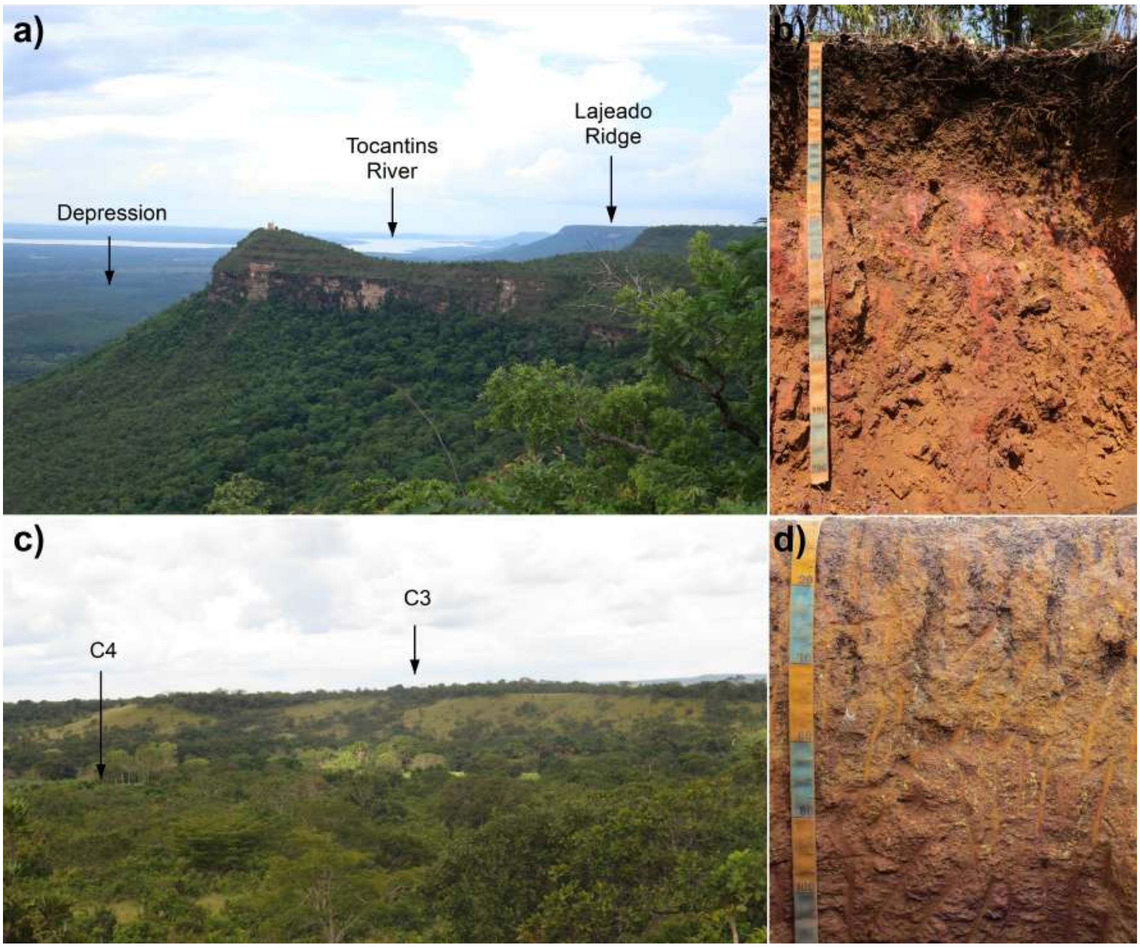

Figure 3 - Study area relief compartments and ferruginous duricrusts. a) Dissected Plateau of Tocantins (Lajeado Ridge) surrounded by the Tocantins Depression and Tocantins River, with the escarpment at the contact Plateau/Depression; b) Duricrust in the top of the Plateau; c) Stepped levels in the Araguaia River Watershed; d) Example of duricrust in a stepped level.

The geomorphological compartmentalization was created from SRTM images available in the Global Mapper software database. The sectors were manually delimited according to roughness (relief dissection) and a previous physiognomic division of the study area into residual plateaus, depressions and stepped lowered levels (ROSS, 2016; DANTAS et al., 2019). The dissection was given by the vertical cutting of the valleys (i.e., height between summit and valley bottom) and the horizontal dimension of the interfluves (i.e., hill width), whose coding could be adapted to a matrix oriented according to the propositions of Demek (1967) and Mescerjakov (1968), used in Brazil at multiple scales (BRASIL, 1981; ROSS , 1992; ROSS, 1994).

The vertical and horizontal extensions of the interfluves were manually measured and mean values were produced between the valley cuts (i.e. MVC, vertical column) and the interfluvial dimensions (i.e. MID, horizontal line), being grouped by compartments in a MVC/MID relief dissection matrix (Figure 4). Orders of magnitude and increasing numbers were assigned to represent the MVC and MID measurements, where “very large”/“very weak” with the set “11” characterizes a lowered and flattened landform unit, and gradually the classification “very strong”/“very small” with the set “55” characterizes a sharp and narrow landform area (ROSS, 1992). The compartments were also coded by sets of letters, in which the denudational landforms (D) were accompanied by information about the dominant hill shape type (“c” for convex and “t” for tabular) (ROSS; MOROZ, 1997).

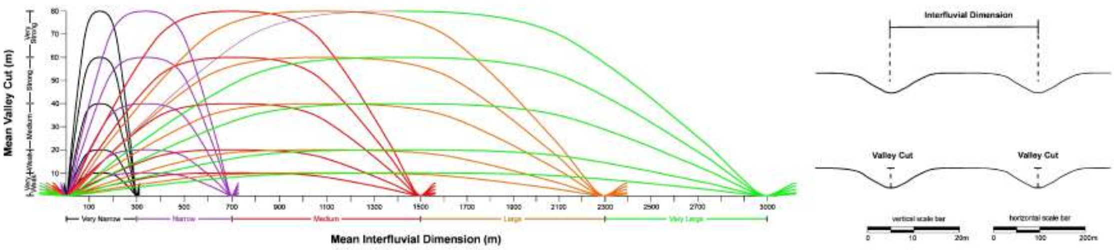

Figure 4 - Relief dissection matrix schematic representation. The mean vertical dimensions from the top of the interfluve to the bottom of the valley correspond to the mean valley cut or MVC; the mean horizontal dimensions of the interfluve from valley bottom to valley bottom correspond to the mean interfluvial dimension or MID.

Each number obtained between the association of the horizontal line and the vertical column characterizes the differentiated dissection, thus enabling quantitative and qualitative geomorphological compartmentalization based on the surface roughness and its association with the initial physiognomic compartmentalization (BRASIL, 1981; ROSS, 1991; 1992).

In this sense, it is understood that a reasonable number of manual measurements referring to the horizontal dimensions of interfluves and vertical valley cuts, which can satisfy statistical correlations, can not only compartmentalize the landscape and provide an initial overview of the landscape's evolution, but also indicate geomorphic surfaces that could have been worked at the same time. To recognize geomorphic surfaces linked to the compartments covered by duricrusts, it was made a statistical correlation according to the multiple values measured, where the dissection would reflect possible similarities in the time of denudation and genesis as a configuration resulting from landform characteristics. For this, the Spearman method was used (SPEARMAN, 1907; MITUSOV et al., 2013), since it distributes data in linear and non-linear correlations (HU et al., 2014; ZHANG; WANG, 2023). By ordering the categories, the data could be related to a correlation coefficient (r) measuring the strength of association between the MVC/MID relief dissection matrix variables, indicating how closely two sets agreed with each other. A higher correlation value implied in a stronger temporal stability of spatial patterns (HU et al., 2014), allowing associations of valley cutting or interfluvial dimensions between different compartments.

RESULTS AND DISCUSSION

For TRW, the application of relief dissection matrix resulted in 11 compartments (Figure 5), divided between the Dissected Plateau of Tocantins and the Depression of Tocantins River Valley. The passage from the plateau sector to the adjacent pedimented and depressed area is visible, showing positive breaks of slope in the escarpment that characterize a residual plateau of tabular structure and erosional nature (BRASIL, 1981; ROSS et al., 2019). In the Depression the low valley cutting interfluves increase their width as they advance towards the Tocantins River, creating an extremely low altitude and flat landform shape.

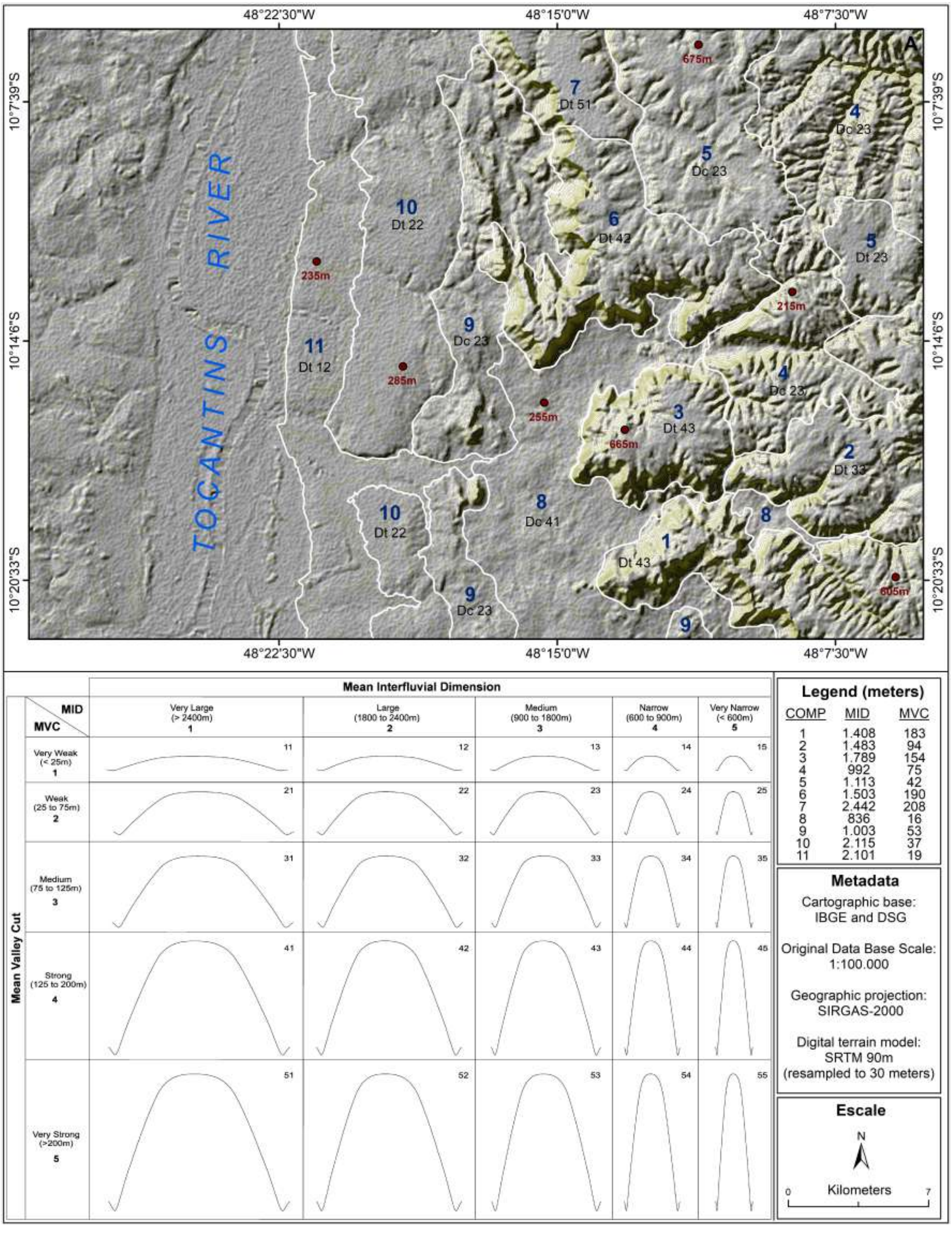

Figure 5 - Relief dissection matrix for TRW.

On the upper portion, compartments 1 to 7 belong to the Tocantins Plateau (Lajeado Ridge), characterized by an extensive flat surface whose tops are predominantly tabular, with a smaller occurrence of convex tops. Both types are delimited by steep slopes in contact with the free face of the escarpment. The matrix of the tabular hill shape denudational landforms indicates the classifications Dt51, Dt42, Dt43 and Dt33, pointing very strong to strong MVCs and very large, large and medium MIDs, while the convex hillshape present weak MVC and medium MID (basically Dc23 shapes). For the Tocantins Depression, the matrix vary from compartments 8 to 11 in tabular and convex hillshapes, from very weak to weak MVCs and from large to medium MIDs. Compartment 8 is marked by a strong

MVC and a very large MID, characterizing the Depression area in contact with the Plateau escarpment.

The Plateau and Depression dissection matrix showed five levels of surface elaboration: (1) a flattened summit surface in the Plateau itself; (2) a free face escarpment and the beginning of the Depression in a pedimented surface downslope; (3) a lower compartment with a landform of rougher appearance; and 4 and 5) a higher and flat stepped level followed by a lower one preceding the fluvial plain of the Tocantins River, respectively.

In the Dissected Plateau, duricrusts developed over Silurian-Devonian sedimentary rocks delay the erosion and infiltration capacity, rearranging drainage in the dissection of these upper levels. Although discontinuous, the duricrusts contribute to the maintenance of the flattened summit surface morphogenetically associated with the South American Surface in the scientific literature (KING, 1956; KING, 1967; BARTORELLI et al., 2010), which can set from Plateau to Depression a sequence type Crest - Free Face - Debris Slope - Pediment, representative of pediplaned savannah areas cited by King (1967) as existing in Brazil and Africa.

Spearman's r coefficient indicates positive and negative weak correlations between the geomorphological subdivisions in TRW (Figure 6). Comparing the compartments in the Plateau/Depression contact, there are the stronger negative correlations, such as the mean valley cuttings of compartments 6 and 9 or 1 and 8, or the mean interfluvial dimensions of compartments 6 and 11. On the other hand, there are no significant positive correlations, making exception to some MVCs and MIDs of the compartments themselves, besides an isolated correlation between the MVC of compartments 6 and 10.

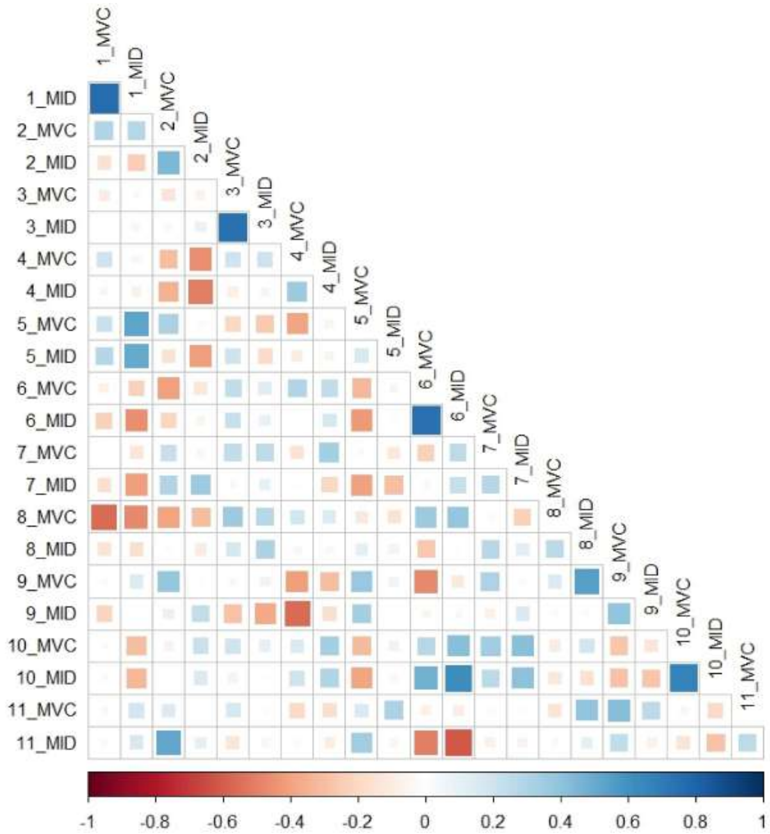

Figure 6 - Spearman correlation coefficients from the relief dissection matrix for TRW.

The weak correlations suggest that the denudation work took place at different conditions of time and space regarding genesis and magnitude of processes. In contrast, the strongest negative correlations between the compartments in the Plateau/Depression transition are expected, especially regarding the valley cuttings since the gradient between these ones can reach more than 400 m high. In the same way, the stronger positive correlations between the compartments themselves demonstrate the flattened characteristic of the relief, with a greater elevation gradient in the Plateau and a lesser gradient in the Depression.

These associations and indeterminacies (LEOPOLD; LANGBEIN, 1963) may also indicate differences in dissection regarding the drainage network erosion, as the ferruginous duricrusts delay surficial flow and infiltration due to its hardness, leading to the formation of geomorphic surfaces similar in space but not in time (WAMBEKE, 1992; TOY; CHUSE, 2005; GOUDIE, 2006). Moreover, given the granitic basement in the Depression of Tocantins and the superposition of Paleozoic sediments, with a characteristic smoothed landform and the occurrence of duricrusts, there are chances that denudation may have evolved partially according to etchplanation processes (BÜDEL, 1982), even more so if one consider the tropical climate involved.

As for ARW, the relief dissection matrix indicated 6 compartments, divided according to smoothed levels into truncated stairs, with several flattened parts due to the presence of outcropped duricrusts (Figure 7). Matrix indicates the predominance of Dt32, Dt33 and Dt22 classifications (tabular hillshapes), pointing the most common MVC and MID classifications, i.e. medium to large and medium. In general, it is possible to identify in the Depression of Araguaia River Valley firstly on a higher level, developed from the western slope of the Estrondo Ridge, to be followed by another 5 levels successively lowered until terraces of the Araguaia River plain.

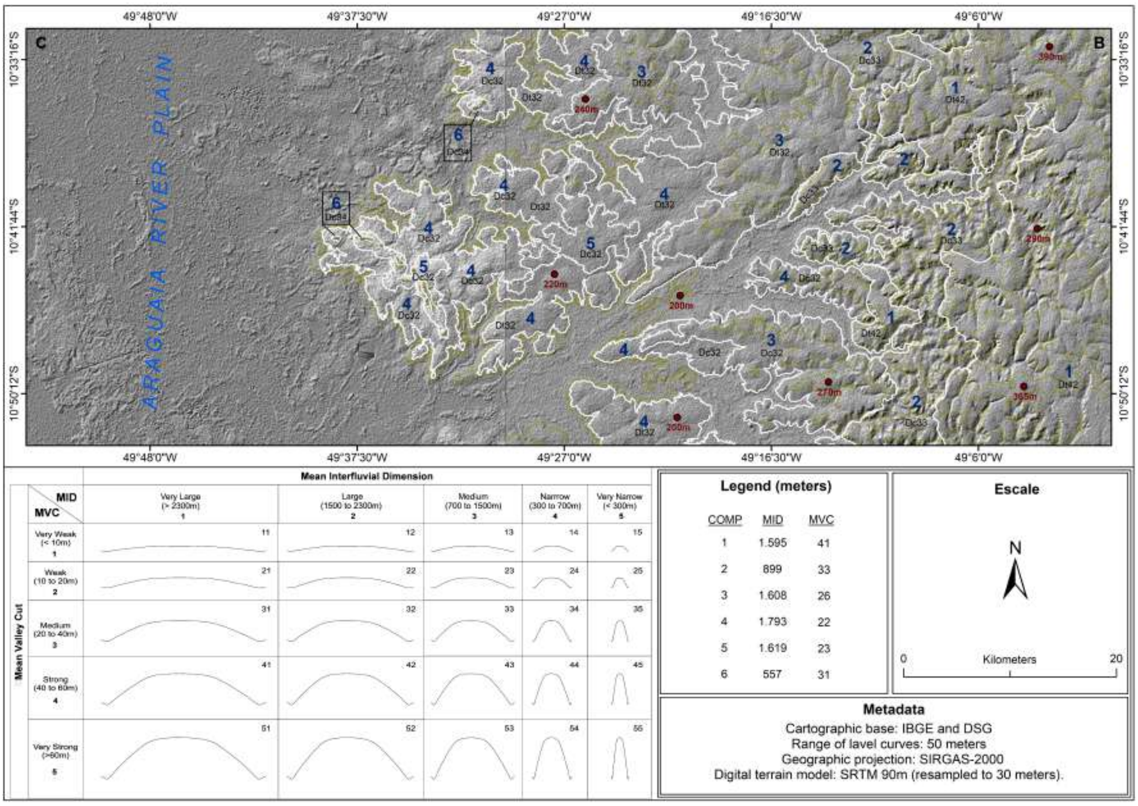

Figure 7 - Relief dissection matrix for ARW.

Compartment 1 has a flattened surface with flat to rounded tops, forming extensive interfluves, while in the second level 2 there are hills dissected between spurs with aligned ridges and short ramps. This pattern changes for compartments 3 and 4, which appear to be more controlled by the structural characteristics of the metamorphic lithology, as the drainage system cuts E-W longitudinal hillslopes until fluvial plain terraces. Compartments 5 and 6 correspond to truncated levels, sometimes in elongated and aligned interfluves, sometimes in isolated hills in the landscape. Occasionally, the outcropping duricrusts or the most resistant lithology coincides with the most evident topography, where the residual characteristic contrasts with the surrounding flat landforms.

Spearman correlations in ARW are also not strong, mostly varying between positive and negative weak correlations (Figure 8). There is a discontinuous setting between the areas divided into the most strongly negative and positive correlations, such as the mean valley cuttings between compartments 2 and 4 or 1 and 5 respectively, which suggests that compartments 2 to 5 are transitional levels from the summit position (1) to the beginning of River plain level (6).

Such indications point to the elaboration of remaining geomorphic surfaces according to the uneven development of dissection levels combined with alteration fronts and the formation of lateritic benches, as pointed out by Aleva (1983) in the humid tropics of Brazil. According to this model of landscape evolution, double change fronts, armored profiles and a level of denudation corresponding to the current surface would characterize triple planation surfaces (ALEVA, 1983; PHILLIPS et al., 2019).

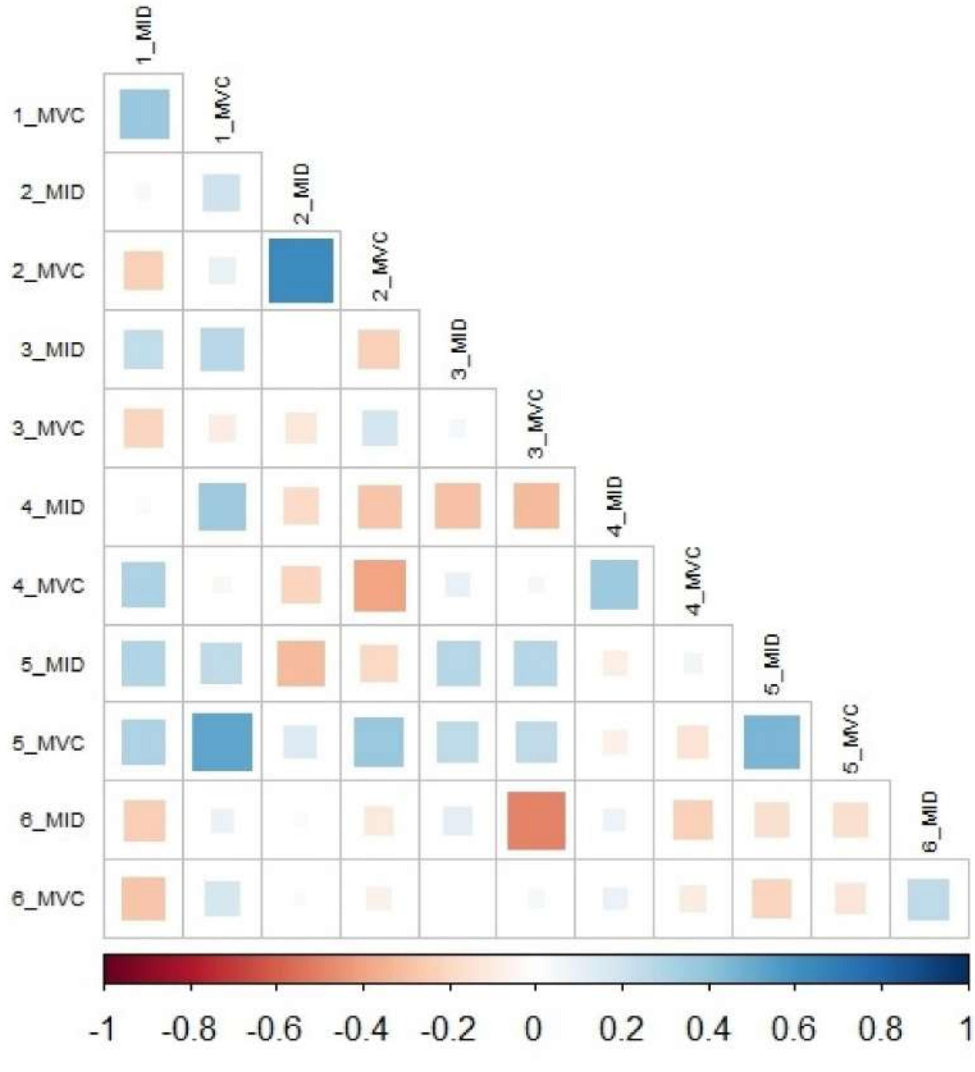

Figure 8 - Spearman correlation coefficients from the relief dissection matrix for ARW.

In short, for TRW the relief dissection matrix suggests a summit surface contrasted with a large depressed and pediplaned area, both discontinuously covered by ferruginous duricrusts, with parts possibly evolved by etchplanation in the depressed portion; weak correlations between the compartments point out that the denudation work took place at different time and space regarding genesis and processes in the landform flattening. As for ARW, the dissection matrix indicated smoothed levels landforms with flattened sectors characterized by the presence of outcropped duricrusts, whose weak correlations indicated the presence of a higher summit position and scattered remaining areas that suffered uneven dissection, which could be related to the creation of triple planation surfaces.

CONCLUSIONS

The compartmentalization of relief and the recognition of geomorphic surfaces, in a genetic affiliation with denudation, have always been themes worked in geomorphology and geomorphological cartography. When these surfaces are lateritized, which is common in tropical savannah environments, geochemical and pedogenetic processes must be considered in their occurrence. The construction of a relief dissection matrix, based on the measurement of the valley cut and the interfluvial dimension, provides criteria for recognition and compartmentalization of such surfaces. Furthermore, as long as keeping the appropriate proportions, the compartments can be correlated using the Spearman coefficient to indicate some genetic association and the probable relationship with surface processes, not necessarily needing to follow classical models of evolution constructed for landscapes leveled by steps and the presence of tabular landforms, e.g. pediplains.

The method of relief dissection matrix allows coherent division into contrasting reliefs (e.g. TRW), but also into homogeneously flattened landforms (e.g. ARW), with its execution dependent on the accuracy of the digital elevation model and the researcher's systematics. In this work, the association of geomorphic surfaces by statistical correlation in two distinct areas of Savannah environments, in which the occurrence of duricrusts topographically influence the landform shape, allowed a certain morphogenetic correspondence. Nevertheless, the results must be observed with caution from the perspective of relief evolution, being better contextualized when focused on the reality of the tropics.

It should also be added that more robust measurement results must be obtained from high-precision Digital Elevation Models (e.g. Light Detection and Ranging – LIDAR), especially when the aim is to compartmentalize areas with low topographic contrast. Statistical correlations can lead to a morphogenetic interpretation, but they can induce to interpretations not always accurate with the evolutionary stage of the landforms being studied.

SOFTWARE

The software used was Global Mapper v. 23.

ACKNOWLEDGMENTS

We thank the National Council for Scientific and Technological Development (CNPq) by its financial support (401787/2023-0) and research grant 305472/2021-6 of the last author. We also thank to the Federal Institute of Education, Science and Technology of Rio de Janeiro for the license granted to the first author to carry out his PhD and the Coordination for the Improvement of Higher Education Personnel (CAPES) for the scholarship granted to the third author. Finally, we also would like to thank Dr. Daniela Schievano de Campos for the important contributions to the text quality.

DISCLOSURE STATEMENT

There is no conflict of interest reported by the authors.

DATA AVAILABILITY STATEMENT

Data will be made available by the authors according to requests to be evaluated.

REFERENCES

ALEVA, G. J. J. On weathering and denudation of humid tropical interfluves and their triple planation surfaces. Geologie en Mijnbouw, 1983.

BARTORELLI, A.; ASSINE, M. L.; PIRES NETO, A. G.; AB'SÁBER, A. N. Dunas do Jalapão: uma paisagem insólita no interior do Brasil. In: MODENESI-GAUTTIERI, M. C.; BARTORELLI, A.; MANTESSO-NETO, V.; CARNEIRO, C. D. R.; LISBOA, M. B. A. L. (Orgs.). A Obra de Aziz Nacib Ab'Sáber. São Paulo: Beca, 2010. p. 588.

BIGARELLA, J. J.; PASSOS, E.; HERMANN, M. L. P.; SANTOS, G. F.; MENDONÇA, M.; SALAMUNI, E., et al. Estrutura e Origens das Paisagens Tropicais e Subtropicais. Florianópolis: UFSC, 2003.

BRASIL – MME – DNPM. Projeto Radambrasil. Folha SC.22 Tocantins. Série Levantamento dos Recursos Naturais 22. Rio de Janeiro: DNPM, 1981. p. 520.

BÜDEL, J. Climatic Geomorphology. New Jersey: Princeton University Press, 1982.

CAMPOS, M. C. C.; MARQUES JÚNIOR, J.; DE SOUZA, Z. M.; SIQUEIRA, D. S.; PEREIRA, G. T. Discrimination of geomorphic surfaces with multivariate analysis of soil attributes in sandstone-basalt lithosequence. Revista Ciência Agronômica, v. 43, n. 3, p. 429–438, 2012. DOI: https://doi.org/10.1590/S1806-66902012000300003.

COLTRINARI, L. Paleosurfaces in southeastern Brazil: São José dos Campos plateau landform evolution. Geociências, v. 30, n. 1, p. 113–120, 2011.

COOKE, E. U.; DOORNKAMP, J. C. Geomorphology in Environmental Management. Clarendon Press, 1990. p. 410.

DANTAS, M. E.; SHINZATO, E.; CARVALHO FILHO, A.; LUMBRERAS, J. F.; TEIXEIRA, W. G.; ROCHA, M. G.; MACHADO, M. F. Origem das Paisagens do Estado do Tocantins. In: ROCHA, M. G. (Org.). Geodiversidade do Estado do Tocantins. 1. ed. Goiânia: CPRM - Serviço Geológico do Brasil, 2019. p. 47-84.

DANTAS, M. E.; JACQUES, P. D.; NUMMER, A. R. Síntese geológica dos Estados de Goiás e Tocantins: roteiro compreendido entre as cidades de Goiânia e Palmas. Guia de Campo da XIV Reunião Brasileira de Classificação e Correlação de Solos, p. 15-39, 2022.

DEMEK, J. Generalization of Geomorphological Maps. Progress Made in Geomorphological Mapping, Brno, p. 36-72, 1967.

DEMEK, J.; EMBLETON, C.; GELLERT, J.; VERSTAPPEN, H. (Eds.). Manual of Detailed Geomorphological Mapping. Praha: Czech Academy of Sciences, 1972. p. 1-344.

EVANGELISTA, B. A.; SIMON, J.; DIAS, T. S. S.; PAZ, L. R. S.; LIMEIRA, A. S.; ALMEIDA, R. E. M. Clima dos Estados de Goiás e Tocantins. Guia de Campo da XIV Reunião Brasileira de Classificação e Correlação de Solos, p. 89-115, 2022.

GOUDIE, A. S. (Ed.). Encyclopedia of Geomorphology. London: Routledge, 2006. p. 1156.

GUILLOCHEAU, F.; SIMON, B.; BABY, G.; BESSIN, P.; ROBIN, C.; DAUTEUIL, O. Planation surfaces as a record of mantle dynamics: The case example of Africa. Gondwana Research, v. 53, p. 82-98, 2018. DOI: https://doi.org/10.1016/j.gr.2017.05.015.

HU, W.; BISWAS, A.; SI, B. C. Application of multivariate empirical mode decomposition for revealing scale-and season-specific time stability of soil water storage. Catena, v. 113, p. 377–385, 2014. DOI: https://doi.org/10.1016/j.catena.2013.08.024.

IMAIZUMI, F.; HATTANJI, T.; HAYAKAWA, Y. S. Channel initiation by surface and subsurface flows in a steep catchment of the Akaishi Mountains, Japan. Geomorphology, v. 115, n. 1-2, p. 32-42, 2010. DOI: https://doi.org/10.1016/j.geomorph.2009.09.026.

KING, L. C. A Geomorfologia do Brasil Oriental. Revista Brasileira de Geografia, São Paulo, v. 18, n. 2, p. 147-265, 1956.

KING, L. C. The Morphology of the Earth: A Study and Synthesis of World Scenery. Edinburgh: Oliver & Boyd Ltd, 1967. p. 726.

LEOPOLD, L. B.; LANGBEIN, W. B. Association and determinacy in geomorphology. In: C. C. A. Jr. (Ed.). The Fabric of Geology. Addison-Wesley Publishing Company, Inc., 1963. p. 184-192. Disponível em: http://pubs.er.usgs.gov/publication/70185692.

MESCERJAKOV, J. P. Les Concepts de Morphostruture et de Morphosculture: un nouvel instrument de l'analyse geomorphologique. Annales de Geographie, v. 77, n. 423, p. 539-552, 1968.

MINÁR, J.; EVANS, I. S. Elementary forms for land surface segmentation: The theoretical basis of terrain analysis and geomorphological mapping. Geomorphology, v. 95, n. 3-4, p. 236-259, 2008. DOI: https://doi.org/10.1016/j.geomorph.2007.06.003.

MITUSOV, A. V.; DREIBRODT, S.; MITUSOVA, O. E.; KHAMNUEVA, S. V.; BORK, H. R. Detection of land surface memory by correlations between thickness of colluvial deposits and morphometric variables. Geomorphology, v. 191, p. 109–117, 2013. DOI: https://doi.org/10.1016/j.geomorph.2013.03.006.

PELTIER, L. The geographic cycle in periglacial regions as it is related to climatic geomorphology. Annals of the Association of American Geographers, v. 40, p. 214–236, 1950.

PHILLIPS, J. D.; PAWLIK, Ł.; ŠAMONIL, P. Weathering fronts. Earth-Science Reviews, v. 198, p. 102925, 2019. DOI: https://doi.org/10.1016/j.earscirev.2019.102925.

RIBEIRO, P. S. E.; ALVES, C. L. Geologia e Recursos Minerais da Região de Palmas: Folha Miracema do Norte (SC.22-X-D), Porto Nacional (SC.22-Z-B) e Santa Teresinha (SC.22-Z-a). Escala 1:250.000. Goiânia: CPRM, 2017. p. 483.

ROSS, J. L. S. Geomorfologia, Ambiente e Planejamento. São Paulo: Contexto, 1991.

ROSS, J. L. S. O Registro Cartográfico dos Fatos Geomórficos e a Questão da Taxonomia do Relevo. Revista do Departamento de Geografia, v. 6, p. 17–28, 1992.

ROSS, J. L. S. Análise Empírica da Fragilidade dos Ambientes Naturais e Antropizados. Revista do Departamento de Geografia, v. 8, p. 63–74, 1994.

ROSS, J. L. S.; MOROZ, I. C. Mapa Geomorfológico do Estado de São Paulo. São Paulo: DG-FFLCH-USP/IPT/Fapesp, 1997.

ROSS, J. L. S. O relevo brasileiro no contexto da América do Sul. Revista Brasileira de Geografia, v. 61, n. 1, 2016. DOI: https://doi.org/10.21579/issn.2526-0375_2016_n1_art_2.

ROSS, J. L. S.; FIERZ, M. de S. M.; NEPOMUCENO, P. L. M.; DE MELO, M. A. Macroformas do Relevo da América do Sul. Geography Department University of Sao Paulo, v. 38, p. 58–69, 2019. DOI: https://doi.org/10.11606/rdg.v38i1.158561.

RUHE, R. V. Geomorphic surfaces and the nature of soils. Soil Science, v. 82, p. 441–445, 1956.

SILVA, B. A.; CALEGARI, M. R. Polygenetic geomorphic surfaces in the context of the landscapes of western Paraná. Revista Brasileira de Geomorfologia, v. 23, n. 3, p. 1634–1655, 2022. DOI: https://doi.org/10.20502/rbg.v23i3.2108.

SMITH, M. J.; PARON, P.; GRIFFITHS, J. S. Geomorphological Mapping: Methods and Applications. Elsevier, 2011.

SPEARMAN, C. Demonstration of Formulæ for True Measurement of Correlation. The American Journal of Psychology, v. 18, n. 2, p. 161–169, 1907. DOI: https://doi.org/10.2307/1412408.

SU, Q.; WANG, X.; YUAN, D.; XIE, H.; LI, H.; HUANG, X. Fluvial entrenchment of the Gonghe Basin and integration of the upper Yellow River - Evidence from the cosmogenically dated geomorphic surfaces. Geomorphology, v. 429, 2023. DOI: https://doi.org/10.1016/j.geomorph.2023.108654.

TOY, T. J.; CHUSE, W. R. Topographic reconstruction: A geomorphic approach. Ecological Engineering, v. 24, n. 1-2, p. 29–35, 2005.

TRICART, J. Observation des Phenómenes et des Faits Geomorphologiques. In: TRICART, J. La Cartographie Geomorphologique Detaillée – Principes et Méthodes de la Geomorphologie. Paris: Masson e Cie Editeurs, 1965. p. 183–233.

TRICART, J. Ecodinâmica. Rio de Janeiro: FIBGE/SUPREN, 1977.

TROEH, F. R. Landform equations fitted to contour maps. American Journal of Sciences, v. 263, p. 616-627, 1965.

VILLELA, F. N. J.; SANCHES ROSS, J. L.; MANFREDINI, S. Relief-Rock-Soil relationship in the transition of Atlantic Plateau to Peripheral Depression, Sao Paulo, Brazil. Journal of Maps, v. 9, n. 3, p. 343–352, 2013. DOI: https://doi.org/10.1080/17445647.2013.805170.

VILLELA, F. N. J.; ROSS, J. L. S.; MANFREDINI, S. Análise geomorfopedológica na borda leste da Bacia Sedimentar do Paraná, Sudeste do Brasil. Revista Brasileira de Geomorfologia, v. 16, p. 669-682, 2015.

WAMBEKE, A. V. Soils of the Tropics: Properties and Appraisal. New York: McGraw-Hill, 1992.

WILSHIRE, H. G.; RENEAU, S. L. Geomorphic surfaces and underlying deposits of the Mohave Mountains Piedmont, Lower Colorado River, Arizona. Zeitschrift Für Geomorphologie, v. 36, n. 2, p. 207–226, 1992. DOI: https://doi.org/10.1127/zfg/36/1992/207.

ZHANG, L.; WANG, L. Optimization of site investigation program for reliability assessment of undrained slope using Spearman rank correlation coefficient. Computers and Geotechnics, v. 155, 2023. DOI: https://doi.org/10.1016/j.compgeo.2022.105208.

ZHU, B.; YU, J.; RIOUAL, P.; GAO, Y.; ZHANG, Y.; MIN, L. Geomorphoclimatic characteristics and landform information in the Ejina Basin, Northwest China. Environmental Earth Sciences, v. 73, n. 11, p. 7547–7560, 2015. DOI: https://doi.org/10.1007/s12665-014-3927-9.

Author's Affiliation

Brizzi, R.R. - Professor at the Federal Institute of Education, Science and Technology of Rio de Janeiro, Arraial do Cabo (RJ), Brazil.

Villela, F.N.J. - Professor at the University of São Paulo, São Paulo (SP), Brazil.

Catarucci, A.F.M. - Professor at the Federal Institute of Education, Science and Technology of Espirito Santo, Nova Venécia (ES), Brazil.

Palma, H.P. - Federal University of Viçosa, Ubá (MG), Brazil.

Torrado, P.V. - Professor at the University of São Paulo, São Paulo (SP), Brazil.

Authors' Contribution

Brizzi, R.R. - The author contributed to the elaboration, realization and manipulation of data and writing.

Villela, F.N.J. - The author contributed to the elaboration, realization and manipulation of data and writing.

Catarucci, A.F.M. - The author contributed to the elaboration, realization and manipulation of data and writing.

Palma, H.P. - The author contributed to the elaboration, realization and manipulation of data and writing.

Torrado, P.V. - The author contributed to the elaboration, realization and manipulation of data and writing.

Editors in Charge

Alexandra Maria Oliveira

Alexandre Queiroz Pereira