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Research Article

Mapping of planation surfaces in the north-central Amazonia

Mapeamento de superfícies de aplanamento no centro-norte da Amazônia

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Abstract: This study aims to identify planation surfaces and their dissected reliefs in the Amazon, starting from the highlands of the border between Brazil, Venezuela and Guiana and ending near the axis of the Amazon River. Its connection with associated surface formations (regoliths) was also evaluated. The input data for the execution of the algorithm used were generated via geoprocessing techniques, which enabled the identification of five planation surfaces: a summit surface, which was associated with the Gondwana surface, from 855 to 2,745 m; a second surface (525–854 m), associated with the Post-Gondwana surface; a third surface, from 279 to 524 m, associated with the South American surface; a fourth surface, from 114 to 278 m, associated with the Velhas I surface (Early Velhas), and a fifth surface, associated with the Velhas II surface (Late Velhas). Thin soils predominate in the first three surfaces, and their presence is attributed to the erosion of the original surface formations with exposure of rock or iron crusts. The two lower surfaces present greater diversity of soils mainly due to the heterogeneity of soil hydrological conditions. In addition to *Latossolos* (Oxisols) and *Argissolos* (Ultisols), which are dominant, there are *Espodossolos* (Spodosols), *Plintossolos* (Plinthosols), *Gleissolos* (Gleysols) and *Planossolos* (Planosols).

Keywords: Planation surfaces; Geoprocessing; Surface formations (Regoliths); Amazon.

Resumo: Neste trabalho propõe-se identificar as superfícies de aplanamento e seus relevos dissecados na Amazônia, partindo das terras altas da divisa entre Brasil, Venezuela e Guiana até próximo ao eixo do Rio Amazonas. Foi também avaliada sua relação com as formações superficiais associadas. Os dados de entrada para execução do algoritmo utilizado, foram gerados por meio de técnicas de geoprocessamento, o que permitiu a identificação de cinco superfícies de aplanamento: uma superfície cimeira, que foi associada à superfície Gondwana, entre 855 e 2.745 m; uma segunda superfície (525 a 854 m), associada à superfície Pós-Gondwana; uma terceira superfície, entre 279 e 524 m, associada à superfície Sul-Americana; uma quarta superfície, entre 114 e 278 m, associada à superfície Velhas I (*Early* Velhas), e uma quinta superfície, associada à superfície Velhas II (*Late* Velhas). Nas três primeiras superfícies predominam os solos pouco espessos, cuja presença foi atribuída à erosão das formações de superficiais originais com exposição da rocha ou de lateritos. As duas superfícies inferiores apresentam maior diversidade de solos em função, principalmente, da heterogeneidade das condições hidrológicas dos solos. Além dos Latossolos e Argissolos, dominantes, encontram-se Espodossolos, Plintossolos, Gleissolos e Planossolos.

Palavras-chave: Superfícies de aplanamento. Geoprocessamento. Formações superficiais. Amazônia.

1. Introduction

A central theme in Geomorphology until the beginning of the 20th century, planation surfaces lost relative importance for studies focusing on more restricted spatial and temporal scales (OLLIER, 2000). However, the unquestionable existence of flat surfaces in different altitudes or in the form of relict reliefs, associated with past dynamics, shows that reliefs adjusted to current bioclimatic and morphostructural functioning are not the rule and that broader temporal and spatial scales cannot be neglected. The genesis of the current geomorphological landscape of the state of Amazonas dates back to the fragmentation of the Amazon Craton in the early Paleozoic and to the individualization of Guiana and South Amazonian shields (DANTAS and MAIA, 2010). Between these two shields, a syneclisis of an approximate E-W direction was generated, where the great Amazon Sedimentary Basin was implanted (NASCIMENTO et al., 1976). Notably, this basin underwent a filling phase from the Eopaleozoic to the Cretaceous, when the sands that gave rise to the sandstones of the Alter do Chão Formation were deposited.

Franco et al. (1975), responsible for the Geomorphology section of the first volumes of the RADAM Project on the region, identified two levels of planation on the rocks of the Guiana Shield, in the north-central Brazilian Amazon: the first one, older, corresponds to the tops of the rocks of the Roraima Group, on the border with Venezuela, in the form of residual reliefs that reach 1500 m, surrounded by pediments. According to these authors, these are remains of an old planation level, the highest and most clearly identifiable in Brazil. The second level corresponds to the Rio Branco-Rio Negro Pediplain, which is separated from the upper level by a dissection zone on ravine ridges. The Rio Branco-Rio Negro Pediplain has plateaus or dissected reliefs on hills, with great spatial coverage, at altitudes around 150 m, throughout most of the Guiana Shield in the state of Roraima and north of the state of Amazonas. Dantas and Maia (2010) recognize the surfaces identified by Franco et al. (1975), calling them the Amazon-Orinoco Divider Plateau and the Northern Amazon Planation Surface, respectively, but add the unit of the Northern Amazon Residual Plateau to the NE part of the state of Amazonas (north of Balbina Lake). This unit presents itself as a deeply eroded tableland, composed of hills and short plateaus with up to 400 m in altitude (DANTAS and MAIA, 2010).

Several authors have defined a succession of planation surfaces for the Guiana Shield, including King (1962) for the Amazon, Choubert (1957) in French Guiana, and Pollack (1983) and Aleva (1984) in Suriname. The surfaces are more developed along the northern and southern edge of the Shield with varying elevation. The highest point is located in the central part of the Shield, along a NW-SE axis, separating the Amazon basin from the northern coastal watersheds. On the north side of the Shield, all planation surfaces have a monoclinal configuration, which plunges them towards sea level.

In Venezuela there is a region known as "*Gran-Sabana*" (SCHUBERT and HUBER, 1990; BRICEÑO and SCHUBERT, 1990), north of Pacaraima. "*Gran-Sabana*" is a flat area, but there are also several areas of plateaus of "Tepui," notably the "Chimanta Massif." The "Tepuis" are plateaus influenced by geological structure, which in this case are horizontal Proterozoic sedimentary strata. Tepuis are commonly thought to be formed by the differential erosion of these strata. Schubert and Huber (1990) propose that the evolution of planation surfaces in the region extending from the *Gran Sabana* to the Orinoco valley occurred due to repeated planation cycles and escarpment retreat during the Phanerozoic.

Based on Schubert et al. (1986) and on Clapperton (1993), Rabassa (2014) identifies six erosion surfaces in the Guiana Shield in northern Amazonia: the "*Auyán Tepui*," found only in Venezuela, 2000 to 2900 m high, possibly Mesozoic; the "Gondwana" surface, located from 900 to 1200 m, also Mesozoic; the "South American" surface, 600 to 700 m high, from the Eocene; the Velhas I surface (Early Velhas), 200 to 450 m high, Oligo-Miocene; the Velhas

II surface (Late Velhas), from 80 to 150 m, Pliocene-Pleistocene; and the "Paraguaçu" surface, from 0 to 50 m, Holocene.

Bardossy and Freyssinet (2002), based on King (1962), Bardossy and Aleva (1990), and Tardy and Roquin (1998) identified the same surfaces as Rabassa (2014) in the state of Amapá, with the exception of "*Auyán Tepui*" and Gondwana: "South American," at 200 m altitude, from the Paleocene-Eocene; Velhas I (Early Velhas), 5 to 100 m, from the Lower Miocene/Oligocene; Velhas II (Late Velhas), 5 to 70 m, from the Miocene; "Paraguaçu," from 5 to 50 m, of the Quaternary. Vasconcelos et al. (1994) estimated, from $^{40}Ar/^{39}Ar$ analysis over Mn oxides, that the weathering of regolith associated with the "South American" surface, in Carajás-PA, began at least 70 Ma ago (Upper Cretaceous). Allard et al. (2018) dated kaolinites and goethites by the RPE and (U-Th)/He techniques and found ages between 1.7 Ma (Pleistocene) and 16.7 Ma (Miocene) for laterites located on the surface of Velhas II (Late Velhas) and at the water level of rivers in the Rio Negro basin, state of Amazonas.

The identification and cartography of the planation surfaces in the Amazon region can be a starting point to understand the distribution of surface formations (soils, sediments, duricrusts) and the landscapes in the Amazon. In this study, it was assumed that the current Amazonian landscape is derived from the morphogenesis—under different paleoclimates and under the current climate—of a relief composed of ancient planation surfaces that are located at different topographic levels. For presenting different ages, their surface formations should not present the same characteristics, differing in terms of their maturity, physical and chemical properties, and the residual concentration of minerals or chemical elements of economic value, accumulated under the supergene weathering (MELFI and PEDRO, 1977; THOMAS, 1994; VALADÃO, 2009; RIBEIRO and RIBEIRO, 2010).

In tectonically stable areas, planation surfaces commonly have a staggered altimetric distribution, with the highest and lowest surfaces being the oldest and youngest, respectively (KING, 1956). The dissection of planation surfaces by the fluvial incision builds new reliefs, which must necessarily be younger than the planation surfaces from which they were derived. Its surface formations are also younger than those of the surfaces located at an upper altimetry (OLLIER and PAIN, 2000; CAMPY and MACAIRE, 2003). Therefore, this study was guided by the following scientific questions: would semi-automated mapping based on altimetric stratification enable the satisfactory identification of the main planation surfaces of a tectonically stable area and would it be coherent with the surfaces described in the literature? Would the spatial distribution of planation surfaces mapped by altimetric stratification of a tectonically stable region be related to spatial distribution of the types of regional surface formations (soils, sediments, duricrusts, ore deposits)?

Thus, this research was based on the principle that the identification and mapping of planation surfaces provide relief systematization and enable inferring the distribution of surface formations, in addition to enabling a better understanding of landscape genesis and evolution. Therefore, this study aimed to map, in a semi-automated way, planation surfaces and associated dissected reliefs, seeking to verify their connection with the distribution of regional types of surface formations (soils, sediments, duricrusts, ore deposits).

2. Study Area

The studied area comprises a N-S strip with approximately 236,000 km², between the northern divides of the Amazon Basin, in Venezuela and Guyana, and the southern limits of the Guiana Shield, in Brazil, near to the axis of Negro and Amazon rivers (Figure 1). The rocks of the Amazon Sedimentary Basin were excluded since they present layers that deep south and *cuesta* reliefs on its northern limit with the Guyana Shield (IBGE, 2006), which would limit the application of the method based on altimetric stratification. This region shows all Amazonian planation surfaces, ranging from the lowest surface of the Guiana Shield to highly dissected remnants of the

Gondwana surface, in the highlands of Pacaraima, state of Roraima, southeastern Venezuela and southwestern Guiana.

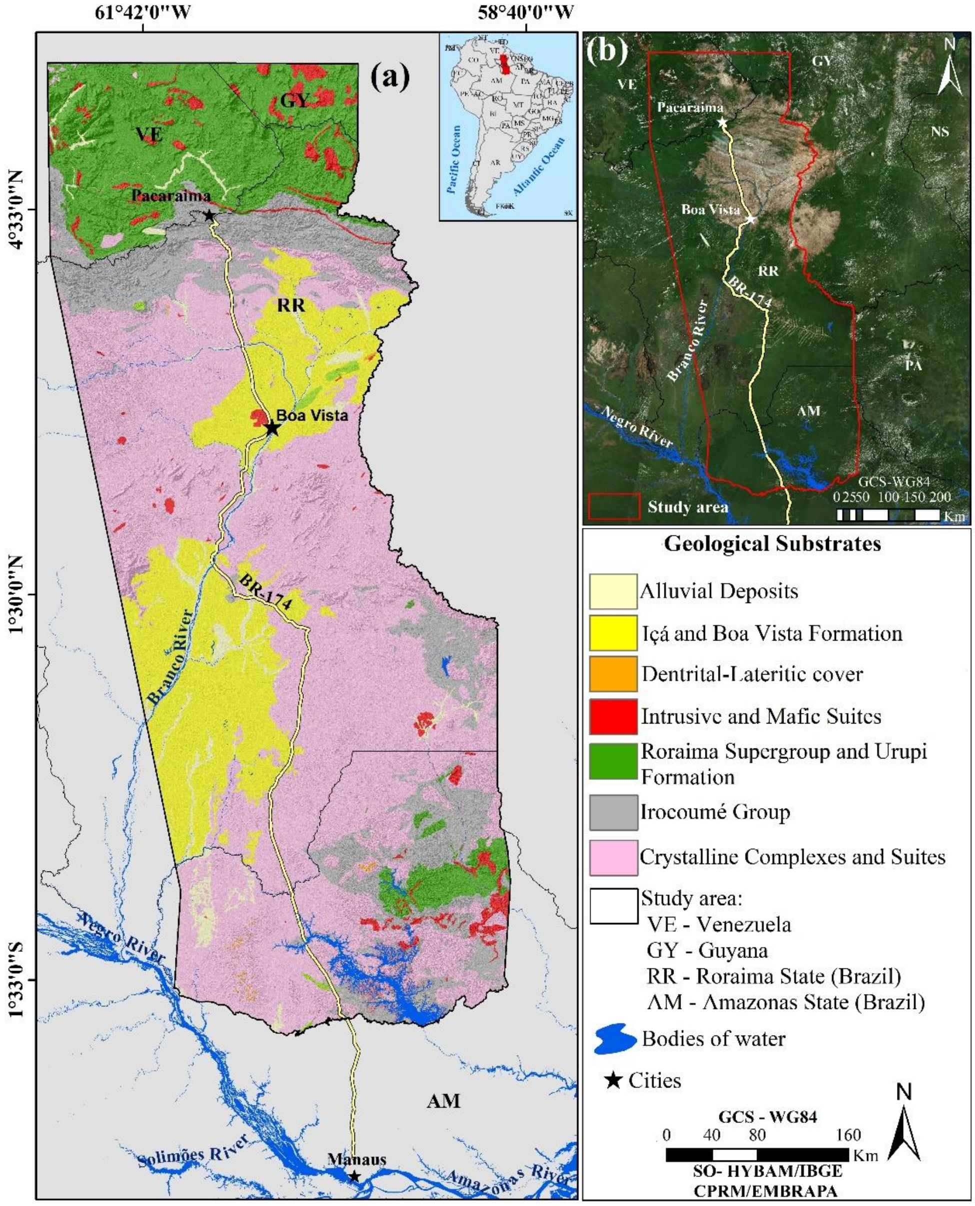

Figure 1. Location of the study area; a) Simplified map of geological substrates; b) geographical situation.

The study area integrates the following morphostructural geological units: Mesoproterozoic terrains of the Guiana Shield (Uatumã-Anauá Domain), in the central-eastern and northern parts of the study area, represented by 1.1) intrusive basic rocks of the Iricoumé Group (rhyolites, dacites and andesites); 1.2) rocks of the crystalline complexes and intrusive suites (granodiorites and monzogranites of the Água Branca Intrusive Suite; gneisses and migmatites of the Jauaperi Complex; syenogranites and monzogranites of the Mapuera Intrusive Suite; diabase basalts and dikes of the Seringa Formation); 1.3) quartz-sandstones of the Urupi Formation and quartz-sandstones and arkoses of the Roraima Supergroup (Canaima and Guaiquinima Formations) (CPRM, 2006; HASUI, 2012; USGS, 1997); 2) an extensive Pleistocene sedimentary cover, which was deposited on the Paleo and Mesoproterozoic rocky substrate, comprising the NW part of the Solimões sedimentary basin, in the central-western sector of the study area (Içá and Boa Vista Formations). Detrital-lateritic and Eocene–Oligocene covers cap remnants of tabular reliefs on the oldest rocks, while Holocene alluvial deposits are found along the current drainage network, throughout the study area.

2. Materials and Methods

The technical procedures were developed according to the steps shown in the flowchart in Figure 2.

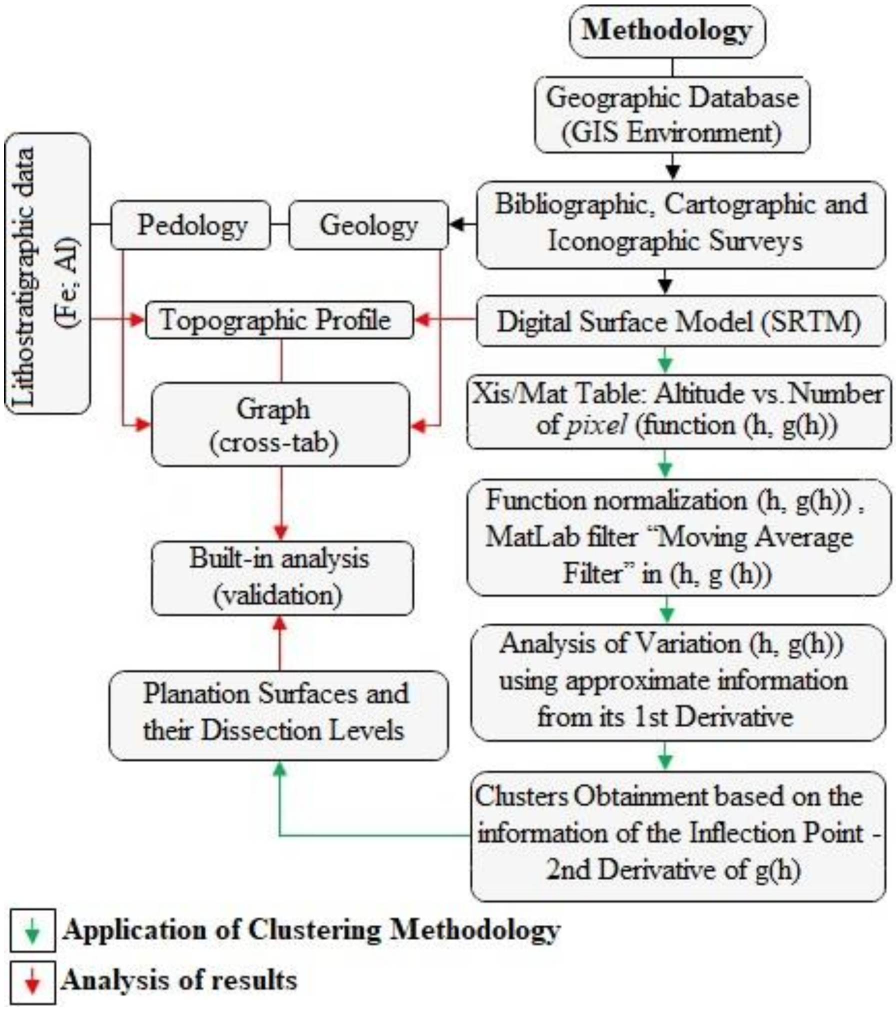

Figure 2. Figure 4 - Methodological flowchart

The initial stage of the research consisted on the survey of bibliographic, cartographic and iconographic information regarding the study area. The first piece of information included the thematic maps of pedology and geology, in a 1: 1,000,000 scale, from the RADAMBRASIL project (SA.20-Manaus, NA.20-Boa Vista, NA.21-Tumucumaque and NB-21-Roraima) (BRASIL, 1977), added to data from the geodiversity maps of the states of Amazon (2009) and Roraima (2011), with a 1:800,000 publication scale. For the bordering countries, the thematic geologic maps of Venezuela, with a 1:500,000 publication scale (USGS, 2006) and the geologic map of the Caribbean region (Guiana), with a 1:2,500,000 publication scale (USGS, 1980), were used.

Stratigraphic and lithographic data of mineral resources and soil profile description from the states of Amazonas and Roraima were used, made available by the Mineral Resources Research Company (CPRM) Geobank, by Brazilian Institute of Geography and Statistics (IBGE) and by Brazilian Agricultural Research Corporation (EMBRAPA), with a total of 228 soil profiles, filtered up to the second categorical level. 54 profiles that contained detrital-lateritic covers and laterites were selected (Fe and Al), plus 4 stratigraphic lithographic data of ferrous metals (Fe) and three samples of bauxite metals (Al). The information concerning the roads and drainage network were used from the 1:100,000 scale map, from SO-HYBAM - Geodynamical, hydrological and biogeochemical control of erosion/alteration and material transport in the Amazon, Orinoco and Congo basins.

The iconographic materials consisted of images of the digital elevation model using SRTM data available on the Alaska Satellite Facility (ASF) website, upsampling to 30 m for a pixel size of 12.5 m with orthometric altitude (geoid model EGM96), converted to geometric altitude (ellipsoidal). As the number of scenes used to fill the study area was high (approximately 130 images), they will not be described here.

For validation and analysis of the results, topographic profiles were also built to analyze all mapped compartments together with cross-tabulation graphs with the distribution of soil types, geological substrates and soil profile.

2.1 Application of the Clustering Methodology for the Central-North region of AM

The used mapping methodology is detailed in Mantovani and Bueno (2022). It enables the determination, in a semi-automated way, of the clusters representative of planation surfaces and the altitude ranges of the reliefs resulting from the dissection of these surfaces. The frequency of pixels by altitude for the studied area yielded a nonlinear function: (g(h)), where g (number of pixels) is a function of h (altitude), as illustrated in Figure 3.

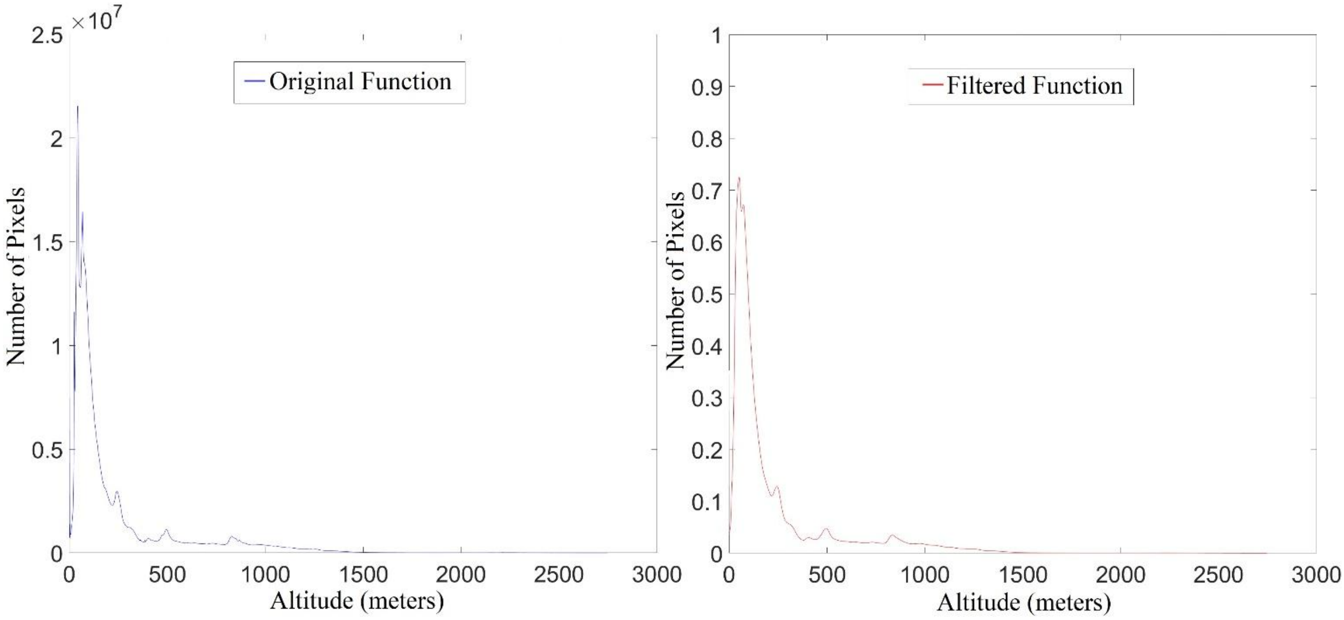

Figure 3. Number of pixels vs. normalized altitude provided by the algorithm for the study area (original function and filtered function).

The mapping method is based on the unsupervised classification of the frequency of pixels for each elevation value of an area. It considers that high pixel frequencies (peaks in the graph) indicate remnants of planation surfaces and that segments with low pixel frequencies (altimetrically below a peak or between peaks) are associated with dissected reliefs of the planation surface located immediately above. Thus, in the proposed method, each pixel is necessarily attributed to some planation surface, belonging to either the preserved parts of this surface or its dissected parts (MANTOVANI AND BUENO, 2022).

A mosaic was built with scenes of the SRTM sensor. The *FillSinks* algorithm was applied to fill spurious depressions, assigning new values to pixels with anomalies, based on information from the nearest neighbors (Wang; Liu, 2006). The generated DEM mosaic was composed of two columns (Altitude/*Pixel*), with 2,728 lines. Elevation ranged from 0 to 2,745 m with an average of 238 m. Later, the attribute table with altitude vs. pixel details was exported into an "xlsx" (EXCEL) file, to be converted into a "MAT" file for reading in the MatLab program.

The main steps for applying the clustering algorithm were:

1. Reading the database of the study area: Table (xlsx) of altitude by the number of pixels. This database composes the original function with various acquisition interferences;
2. Parameter setting, sampling window size W, regarding the database;
3. Normalizing the altitude function by the number of pixels, and filtering using the moving average filter to eliminate small variations in signal measurement and acquisition, obtaining the function $g(h)$. Filtering this function, there is an offset in the axis of the abscissas of a value equal to half of the window $(\frac{W}{2})$ between the function originally defined by the database and the filtered function. The displacement in the altitudes value is eliminated in this step and the functions, original and filtered, are put into phase.
4. Placing the filtered signal function $g(h)$ in the same altitude reference as the original function;
5. Determining orthogonal distance functions $d_1(h)$ and $d_2(h)$, dividing the curve of the function $g(h)$ in segments of lengths equal to the size of the window *W,* to get the function $d_1(h)$ and half the size of the window $(\frac{W}{2})$, to obtain the function $d_2(h)$;
6. Acquiring the function $d(h) = d_1(h) + d_2(h)$. The $d(h)$ Function indirectly represents the first derivative of $g(h)$, and allows to determine the concavity of the function $g(h)$;
7. Carrying out the initial grouping A_i^I; scanning the function $d(h)$. From the starting point H_0 of the domain of $d(h)$, a scan is made in the ascending direction of the domain of $d(h)$ until finding its first zero, the H_1 point, thus defining the first *Cluster* $A_1^I$with altitudes that comprise the interval $\Omega_1 = [H_0, H_1]$. The second *Cluster* is obtained from H_1 until finding the next zero of $d(h)$, the point H_2, defining the second *Cluster* A_2^I with altitudes that comprise the range $\Omega_2 = [H_1, H_2]$. This procedure is carried out until finding the last valid altitude value and thus obtain the last *Cluster*.
8. Performing fine-tuning of the initial grouping intervals:
   - Obtaining the function equivalent to the derivative of the function $d(h)$ to determine the points in its domain in which it is maximum and the inflection points (sign changes). The *Clusters* are defined by sets of heights, *h*, between two inflection points of $g(h)$.
   - In the first *Cluster*, A_1^I, from H_0, finding the first point of zero, $H_1^{'}$, the function $d^{'}(h)$, which is the value in which $d(h)$ is maximum (or minimum). From $H_1^{'}$, continue scanning in the domain of $d^{'}(h)$ until finding a maximum (or minimum) point, which corresponds to the limit of the *Cluster* A_1^I. The new *Cluster* is then redefined as being A_1 with the new range $\Omega_1 = \left[H_0, H_1^{'}\right]$. In the event that $d(h) > 0$, an adjustment occurs by reducing the interval Ω_1, and the points of the domain between $H_1^{'}$ and H_1 become part of the *Cluster* A_2. Proceeding with the adjustment procedure, we determine the next *Cluster* where $d(h) > 0$ and the point where its maximum occurs, $d^{'}(H_2^{'}) = 0$. *Cluster* A_2 is reconstituted as the altitudes of the set $\Omega_2 = \left[H_1^{'}, H_2^{'}\right]$. In the case of *Cluster* A_i^I, in which $d(h) < 0$, an adjustment of the interval occurs by increasing its number of points.

According to Mantovani and Bueno (2022), the only parameter that needs to be calibrated in the proposed algorithm is the size of the window, *W*, (in meters). Considering that the database gathered for study areas in the Central-North Region of the Amazon was obtained in the same way as the database for the area located in the north of Minas Gerais, adopted for the elaboration and validation of the algorithm proposed in Mantovani and Bueno (2022), with the same test conditions (noise and precision), the W=27 window was also used for applying the methodology in the Central-North region of the Amazon.

3. Results

The graph in Figure 4 shows the results obtained by clustering through the algorithm used. Each concavity of the graph represents a different geometric signature in the configuration of planation surfaces, but does not provide any information about its spatial distributions (as it is not a linear function as a function of distance, being randomly distributed throughout the study area) (Mantovani and Bueno, 2022). The highest concentrations of pixels indicate possible preserved planation surfaces.

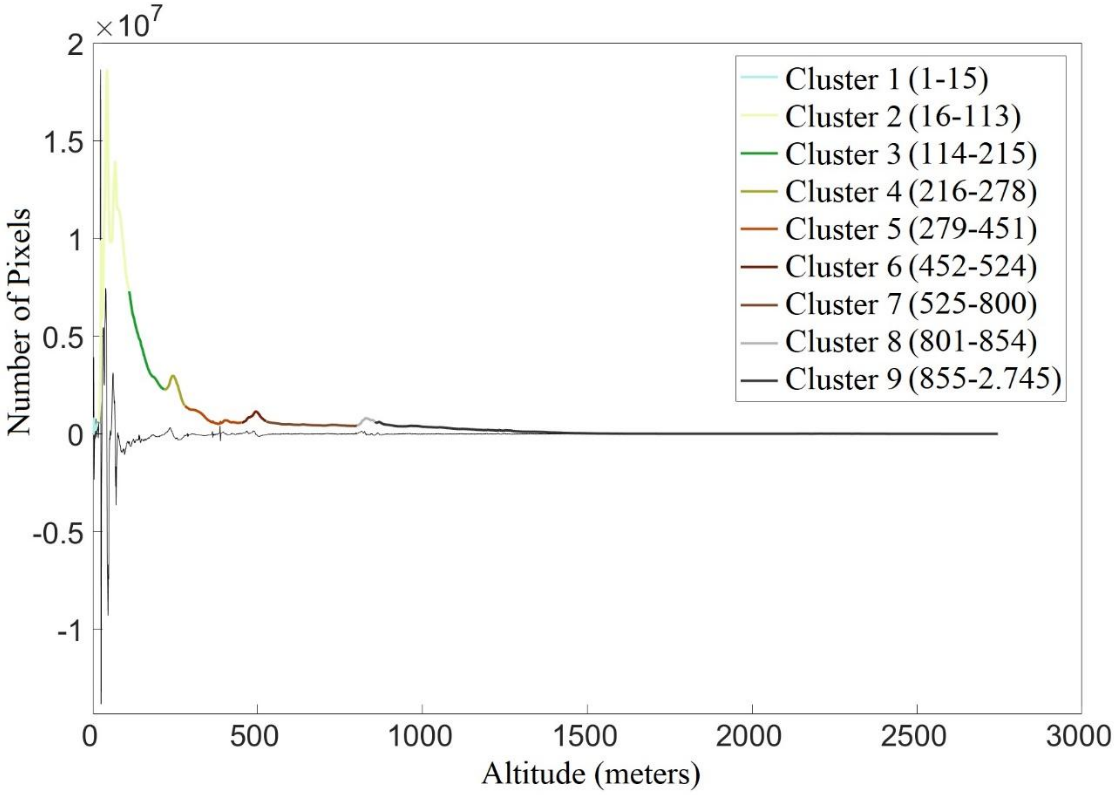

Figure 4. Clusters in the Center-North region of the Amazon.

The graph in Figure 4 shows that Clusters "C2," "C4," "C6," and "C8" correspond to the highest frequency peaks. Although Cluster "C5" represents also a peak, the clustering algorithm did not consider this small variation, because the size specified for the window "W" means that small variations of the function are not captured by the clustering algorithm, to obtain the representation of the area as a whole. This prevents the formation of clusters which may result from sampling errors and precision of the methodology for obtaining the data (MANTOVANI and BUENO, 2022).

Cluster "C2" has the highest pixel concentration, but does not correspond to the area of greatest spatial coverage; on the other hand, it is the flattest surface of the study area. Cluster "C4" corresponds to the second most preserved planation surface, followed by Clusters "C6" and "C8," which show the same behavior. Clusters "C1," "C3," "C5," "C7," and "C9" are obtained considering the change in the function behavior, based on the analysis of its inflection points and its concavity. To determine these points and the concavity, information from the signals of the first and second derivatives was used, which made it possible to verify that the g(h) function presented a smoother behavior for these altitudes, that is, it presents a variation in the number of pixels at different altitude ranges, which can be attributed to the dissected part of the surfaces (MANTOVANI and BUENO, 2022). Based on the results obtained in the Figure 4, the methodology applied delimited to the nine clustering areas, comprising the following altimetric ranges: Cluster 1: 1–15 m; Cluster 2: 16–113 m; Cluster 3: 114–215 m; Cluster 4: 216–278 m, Cluster 5: 279–451 m; Cluster 6: 452–524 m; Cluster 7: 525–800 m; Cluster 8: 801–854 m, and Cluster 9: 855–2741 m (Figure 5).

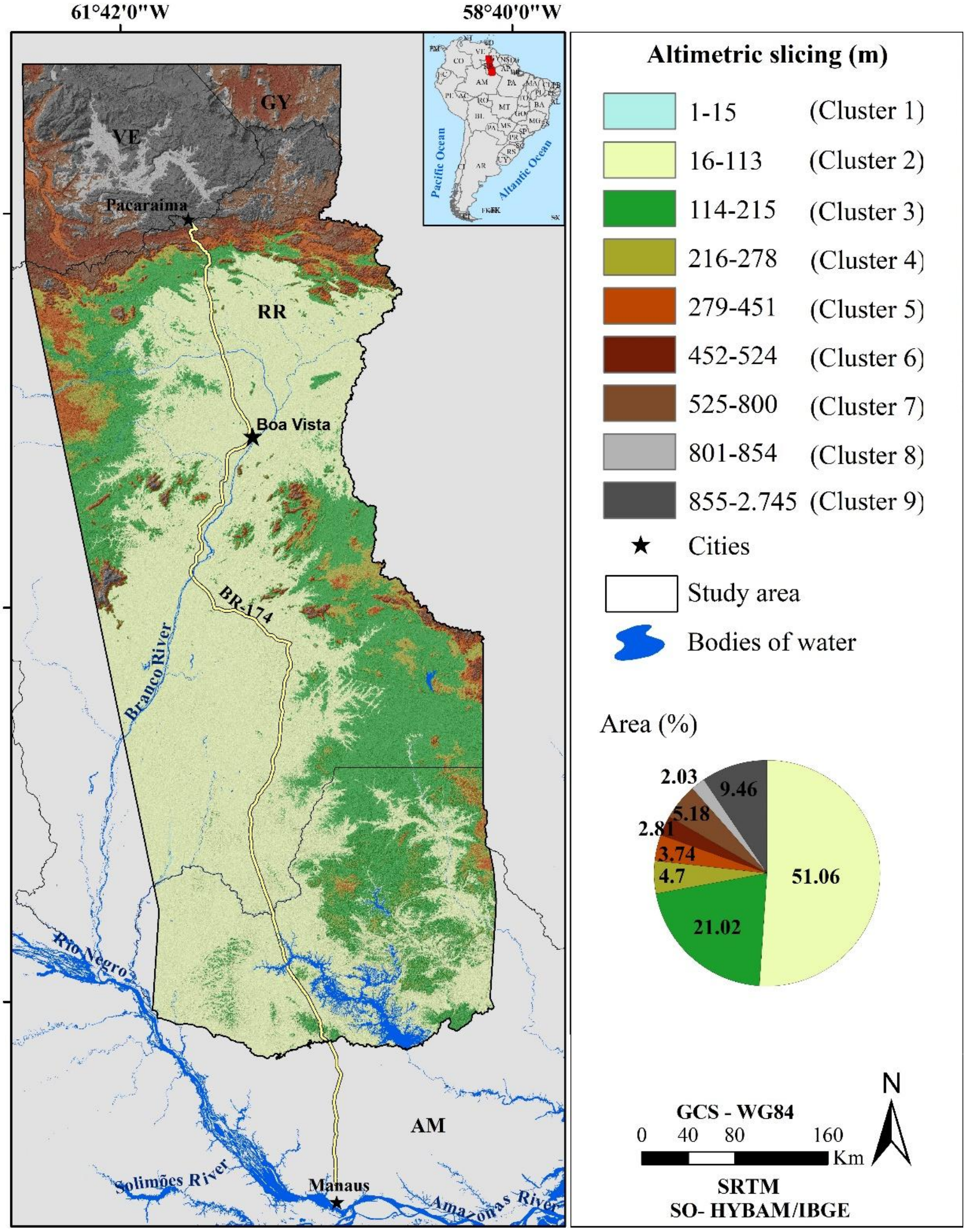

Figure 5. Altimetric slicing based on the clusters determined by the algorithm.

After identifying the clusters and extracting the corresponding altitudes for each identified planation surface, the altimetric intervals between them were considered areas resulting from the dissection of the immediate upper surface (MANTOVANI and BUENO, 2022).

"Clusters 1 and 2" were considered components of the same planation surface (Surface 5), the lowest and the most recent, "Cluster 1" being representative of the dissected area of that surface and, "Cluster 2," representative of its preserved flat area. "Cluster 3" was considered the dissected area of Surface 4 and "Cluster 4" was considered the preserved flat area of that surface. "Cluster 5" was considered the dissected area of Surface 3 and "Cluster 6" its remaining flats. "Cluster 7," following the same logic, corresponds to the dissected area of Surface 2 and, "Cluster 8," the preserved flat area of this surface. Surface 1, the highest, has only dissected reliefs ("Cluster 9") and there are no preserved relicts of its flattened relief in the study area. Thus, the configuration of the planation surfaces' map presents five surfaces, with Surface 5 being considered the youngest, and Surface 1, the oldest (Figure 5; Figure 6).

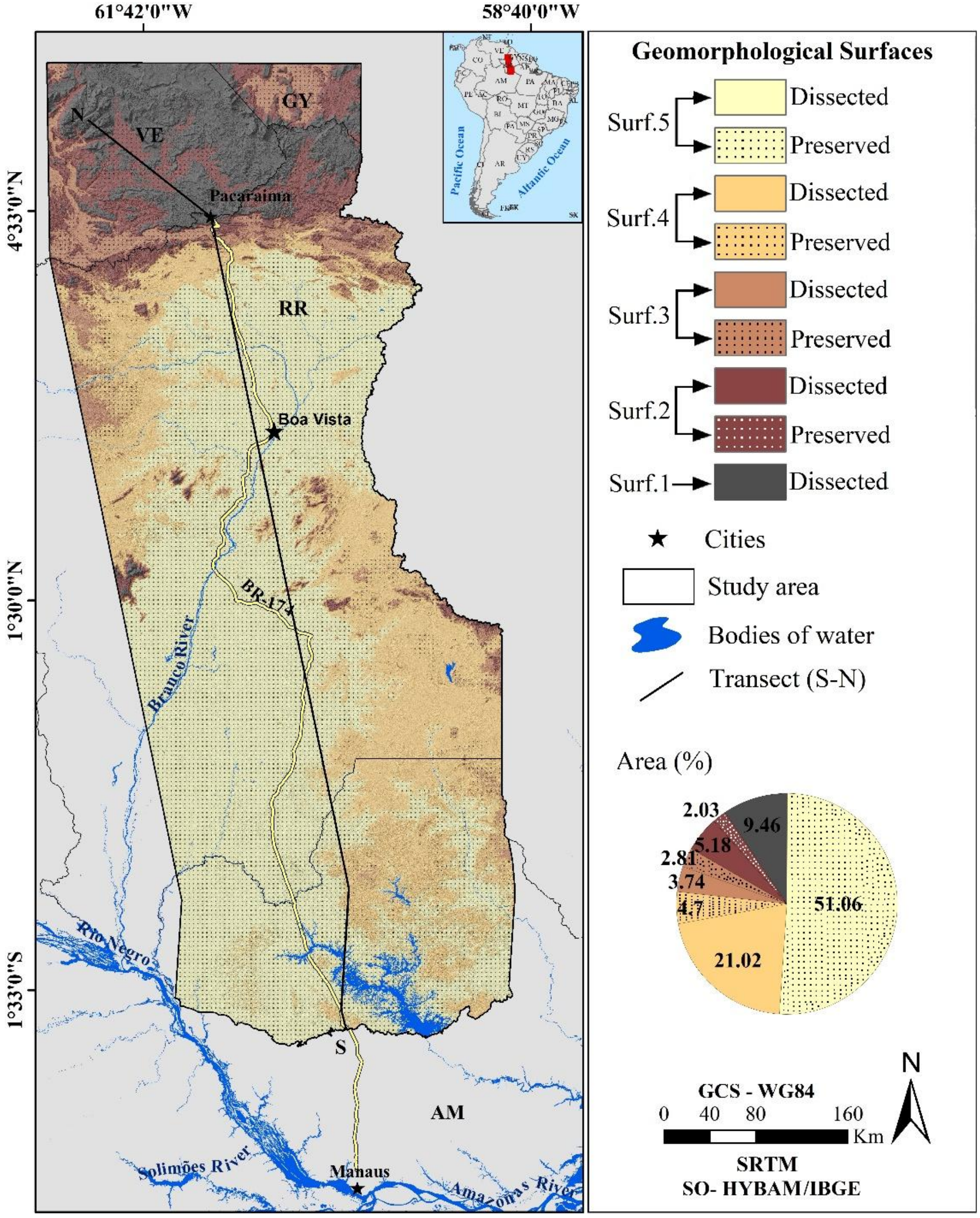

Figure 5. Map of planation surfaces (preserved flat reliefs and their levels of dissection).

The highest altitude class, located between 855 and 2,745 m, was considered to be composed of dissected reliefs of the ancient Gondwana surface, located in the northern end of the mapped area, essentially in Venezuelan territory, in addition to appearing at scattered points in central-west of the area, always over the Guiana Shield. No planation remnants of this surface were found in the mapped area. Briceño and Schubert (1990) and Rabassa (2014), based on Schubert et al., (1986) and Clapperton (1993), divide this altimetric band into two surfaces: a summit area, between 2000 and 2900 m, called *Ayuán-Tepui* (Venezuela), and other further down, between 900 and 1200 m, called Kamarata-Pakaraima (Venezuela) or Gondwana (Brazil). For the area studied here, the algorithm automatically identified only one surface. In a map that represented a compilation of the spatial distribution of more than 50 points of information on surface formations and levels of planation in the Guianas, Suriname, Venezuela and northern Brazil, Bardossy and Aleva (1990) indicate a point called *Pakaraima peak* (2040 m), present in the studied area, and associate it with the summit level. These authors correlate this summit surface to the Gondwana surface. Bardossy and Aleva (1990) consider the Gondwana surface as Mesozoic formation; whereas Prasad (1983) as Mesozoic or earlier. King (1962) classifies it as a Cretaceous or older formation. In this research, reliefs between 875 and 2785 m were considered as dissected remnants of a single surface (Gondwana). Note that the altimetric range observed within the clusters associated with each planation surface cannot be attributed solely to the dissection process, since the surfaces commonly have an original altimetric decay in some direction (Braun, 1971), and the northern region of the Amazon was known to be affected by pulses of Neotectonic activity (Costa et al., 1996). These authors identified two main Neotectonic pulses, one from the Miocene, which would have affected the plateaus with mature laterites, commonly associated with the South American Surface (Costa, 1991) and another from the Pleistocene, which also affected the surfaces with immature laterites (Costa et al., 1996).

The second class in altitude (525–854 m) was considered to correspond to the residual flattened and dissected levels of the Post-Gondwana surface. It occurs in a clearly embedded way in the dissected remnants of the Gondwana Surface, in Venezuelan territory, on the edges of northern highlands of the mapped area, as staggered levels above the lower altitude surfaces, and as sparse areas in the middle of the lower altitude surfaces, in the central part of the mapped area, always in the Guiana Shield (Figures 9 and 10). The Post-Gondwana surface, proposed by King (1956; 1962), has not been identified in the Guiana Shield by Prasad (1983), Bardossy and Aleva (1990), and Rabassa (2014), although Rossetti (2004) has found a surface (called S1), elaborated in the upper Mesozoic and, therefore, older than the South American surface, in the northeastern part of the Brazilian Amazon. We chose to discriminate this surface because it constitutes a clear level of planation, distinct from both the dissected reliefs of higher altitude (Gondwana) and the lower flattening surface (South American), whose identity is well known in the literature due to its degree of flattening, its great spatial coverage and the characteristics of its surface formations. The first and second classes in altitude, described above, fall within the relief unit called the Amazonas-Orinoco Divider Plateau by Dantas and Maia (2010).

The third class (279–524 m) appears on the map embedded in the upper surface (Post-Gondwana); at the northern highland edges of the mapped area, as staggered plateaus below the upper surface and above the lower elevation surfaces, and as isolated or more continuous areas throughout the Guiana Shield (Figures 10 and 11). Bardossy and Aleva (1990) identified the South American Surface in Brazil in Serra do Navio (350 m) and in Tartarugal Mountains (200 m), both in Amapá, and consider this surface as correlative to the Main bauxitic level, in Suriname. These authors mapped a representative point of this level that is located in the central-eastern part of the area of the present study (at approximately 2° 30'N and 60°W), in the Guiana Shield. Costa (1991) considers the tops of the hills in the Pitinga region (southern center of the area of this study, at approximately 280 m altitude) as belonging to the South American surface. According to this author, the Pitinga hills, as well as other mining sites such as Trombetas and Paragominas, have a mature, thick lateritic cover, with a supergene concentration of Al and

Fe, which would have been formed over periods of up to 30 Ma, during the Eocene-Oligocene. This flattening surface fits into the relief unit called the Residual Plateau of the North of the Amazon, in Dantas and Maia's proposal (2010), formed by hills with tops of up to 400 m in altitude.

Prasad (1983 cited by ALEVA, 1979) considers the Eocene-Oligocene weathering event as the most intense in South America, responsible for the elaboration of the thickest laterite profiles. Aleva (1994) proposes the "main laterite-bauxite level" would have settled in the Guiana Shield between 25 and 50 Ma ago. Rossetti (2004), in turn, indicates the interval between 27 and 63 Ma ago for the formation of lateritic and bauxitic materials associated with the South American surface. Rabassa (2014) indicates Eocene epoch for the surface formations of the South American surface, although the author attributes altitudes between 600 and 700 m to it. Vasconcelos et al. (1994) associated the laterite tops of the Carajás region (around 600 m) with the South American surface and found ages greater than 60 Ma (dating by ^{40}Air/^{39}Ar) for newly formed Mn oxides, indicating that the weathering associated with this surface may have started in the Cretaceous.

The fourth altitude class (114 – 278 m) covers a great space in the mapped area, being located continuously in the central-eastern and central-northwestern parts. This surface was associated in this study with the Early Velhas surface by Bardossy and Aleva (1990), which was called "Velhas I" here. These surveyors identify on their map an occurrence of this surface in the domains of the area of our study, located on the Guiana Shield, approximately 2°N and 60°W. According to these authors, this surface would have been established between the Oligocene and the Upper Miocene and would be associated with the Foot Hill Level, in Suriname. Aleva (1994), however, proposes that this last level was established 10 Ma ago. Rossetti (2014) places this surface between 15 and 23 Ma, to the NE of the Brazilian Amazon. Costa (1991) considers that reliefs associated with more recent surfaces than the South American surface present only immature laterite profiles.

The fifth and last altitude class (1 – 113 m) appears preferentially in the central, southwestern and southern sectors of the mapped area. It occupies, in lateral continuity, both large areas of the Guiana Shield and more recent unconsolidated sediments of the Içá and Boa Vista Formations. In Figure 3 Cluster 2 (flattened remnants of this surface) has two maximums. This suggests the presence of two levels, which may have two explanations: the influence of neotectonics in the region, already observed by Franco et al. (1975), Costa et al. (1996), and Rosseti et al. (2014), implying differential movement of blocks and tipping over; the fact that this flattened level is formed from the genetic point of view by two surfaces, although in lateral continuity: a surface resulting from geomorphological flattening, like the others, and a surface resulting from sedimentary deposition—sediments still unconsolidated, Quarternary, from the Içá and Boa Vista Formations (CPRM, 2006).

This surface was associated in our study with the Late Velhas surface by Bardossy and Aleva (1), which was called "Velhas II" here. These authors indicate on their map a point occurrence of the Late Velhas surface with the contact between the Içá Formation and the Guiana Shield, at approximately 3°30'S and 60°30'W, associating it with the Pediplain Level identified in Suriname. They also propose that this surface would have been formed between 20 and 2 Ma. Rossetti (2004) identifies this surface in the NE of the Brazilian Amazon and attributes it an age between 10 and 5 Ma. Allard et al. (2018) dated kaolinite and goethite minerals sampled in duricrusts on the flat tops of the hills of the Guiana Shield, north of São Gabriel da Cachoeira and Santa Isabel do Rio Negro, at altitudes between 60 and 90 m. Ages between 0.9 and 12.7 Ma were obtained.

Although suggested by several authors (e.g., Theveniaut and Freyssinet, 2002, for Amapá, between 5 and 50 m of altitude, Holocene; Rabassa, 2014, for the Guiana Shield, between 0 and 50 m altitude, Holocene; Rosseti, 2004, for the NE of the Brazilian Amazon, Pliocene–Pleistocene), in this work no identified surface was associated with the Paraguaçu surface. Following the proposals by King (1956) and Bardossy and Aleva (1990), it is considered that the Paraguaçu surface is associated with the valleys of current drainage network, having been encompassed here by the unit represented by dissected areas of the Velhas II surface (Late Velha) (Figure 3, Cluster 1).

Figures 7 and 8 illustrate the topographic profile drawn from South to North (S-N) and the map with the reconstitution of the proposed surfaces, covering all mapped compartments.

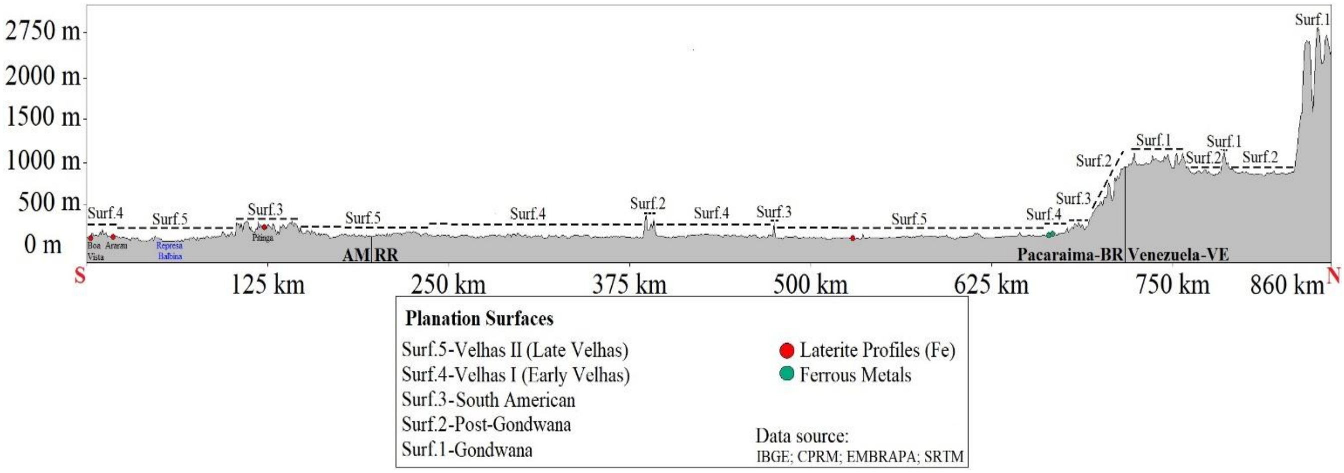

Figure 7. Topographic profile (South-North).

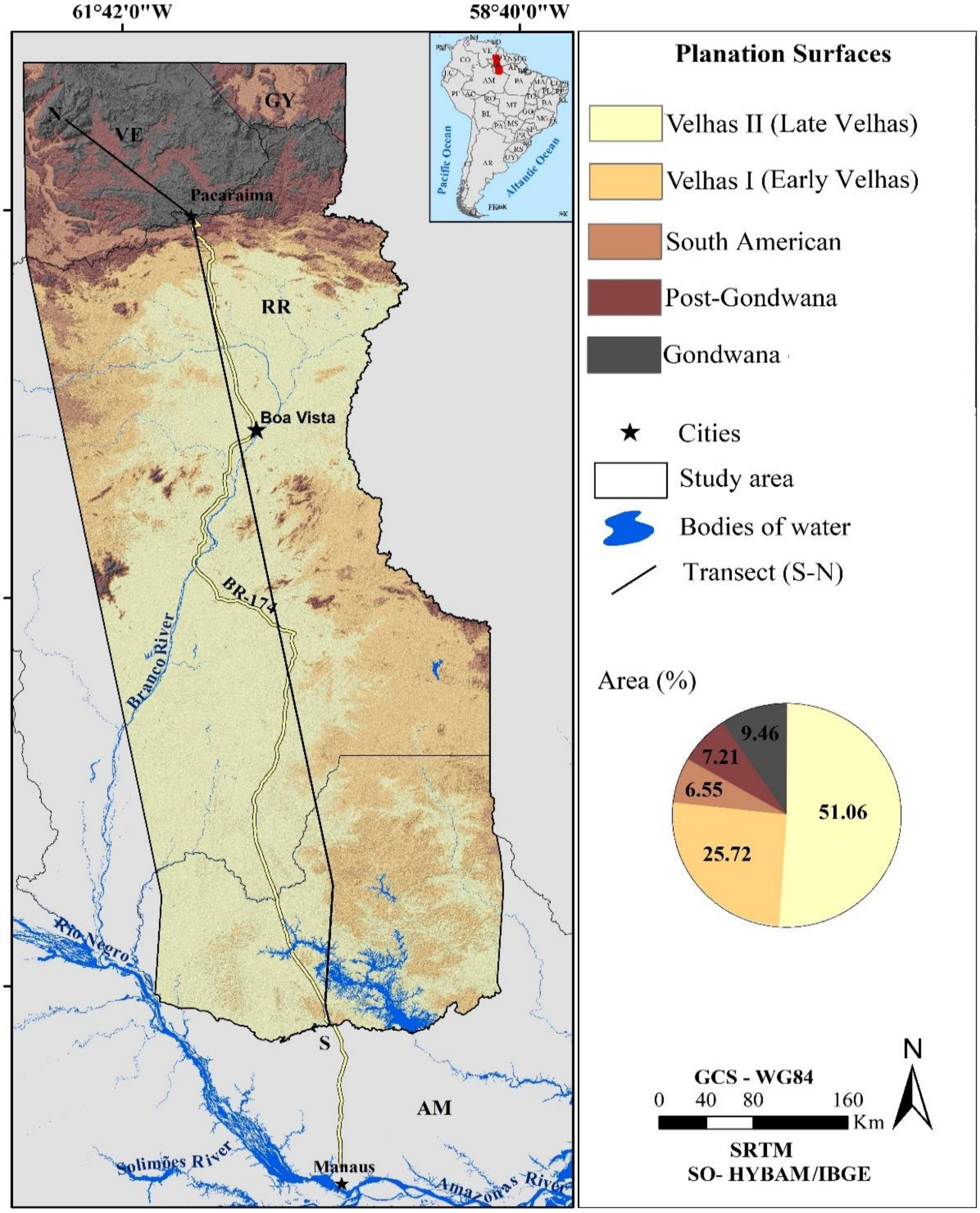

Figure 8. Map of reconstitution of planation surfaces.

Figure 9 shows the distribution of the main types of soils and occurrences of Fe and Al ores in the study area (IBGE, 2006; CPRM, 2009; 2011), while Figures 10 and 11 present graphs with the distribution of soil types and the identified planation surfaces, respectively. It is observed that in surfaces 1, 2 and 3 (Gondwana, Post-Gondwana and South American) the *Neossolos Litólicos* (Lithic Leptosols) prevail. It was interpreted here that the presence of these soils on the two highest surfaces is due to erosion of previously existing surface formations, leaving, in most cases, the rocks of the Guiana Shield exposed or covered by young and shallow soils (DANTAS and MAIA, 2010). The bauxitic laterite materials are distributed in the Guiana Shield, in the extreme north, almost on the border with Venezuela, on reliefs associated with South American and Post-Gondwana surfaces. These are mature lateritic profiles (COSTA, 1991), with higher relative concentrations of metals of economic interest.

On surface 3 (South American) the *Neossolos Litólicos* (Lithic Leptosols) are also the dominant soil. However, on this surface, records of *Neossolos Litólicos* (Lithic Leptosol) were mainly associated with the presence of poorly developed soils on duricrusts (mature laterites, according to Costa, 1991). Aleva (1994) and Bigarella et al. (1996) present examples of profiles that originally had their lateritic crusts covered by thick soils and that, after truncation by erosion, now have the hardened material exposed on the surface. The tops of the Serra de Carajás (PA), also considered representative of the South American surface (VASCONCELOS et al., 2002), are capped by iron crusts and mapped by CPRM (2009; 2011) as being covered by *Neossolos Litólicos* (Lithic Leptosol), in association with *Argissolos* (Acrisols) and *Cambissolos* (Cambisols) or as areas of rock outcrops. As in Carajás, mature lateritic profiles are found in the domains of this surface in the studied area (COSTA, 1991), with occurrences of aluminous and ferrous metals of economic interest.

At the dissected level of this planation surface (Surface 3 – Figure 10), of hill relief, *Neossolos Litólicos* (Lithic Leptosol) still predominate, but *Argissolos Vermelhos* (Red Acrisols) and *Latossolos Vermelhos* (Red Ferralsols) become more representative than in surfaces 1 and 2. The genesis of these surface formations (*Argissolos Vermelhos* and *Latossolos Vermelhos*) may be associated with the process of geochemical dismantling of hardened lateritic materials, as proposed Tardy (1993) for iron crusts when subjected to humid forest environments, under "half-orange" reliefs. The red color of these soils is indicative that well-draining conditions prevail in these raised reliefs.

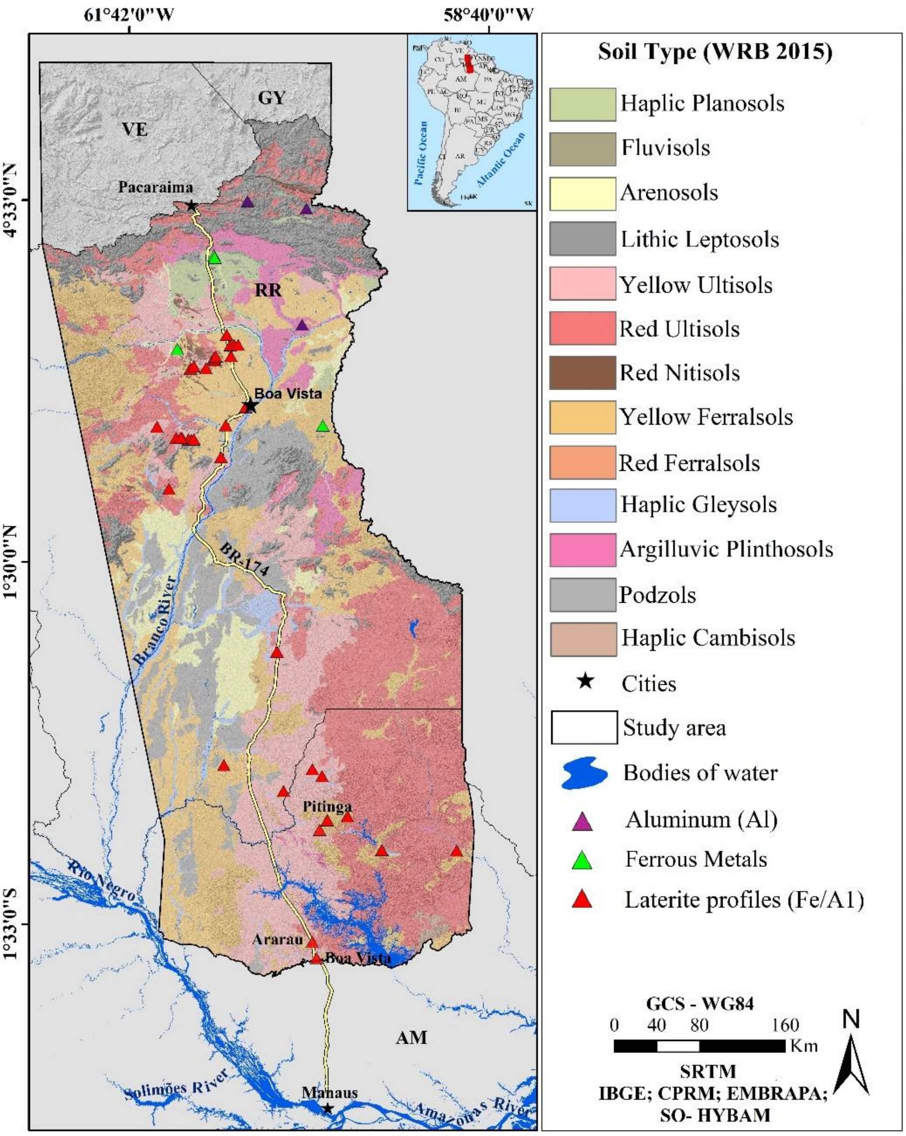

Figure 9. Pedological map and occurrence of Fe and Al ores in the Brazilian portion of the study area.

On surface 4 (Velhas I – Early Velhas) the *Neossolos Litólicos* (Lithic Leptosol) decrease in area, occupying about 20% of flat reliefs and about 7% of dissected reliefs. Considering that on this surface the laterites are immature (COSTA, 1991), it is possible that these *Neossolos* are related to the occurrence of poorly developed ferruginous crusts (regionally called *piçarreiras*) or to rocky outcrops on the edges of flat tops or slopes. The dominant soils in the flat remnants of this surface are *Argissolos* (Acrisols) and *Latossolos* (Ferralsols), both occupying 38% of the area, always red, due to more favorable drainage conditions of higher positions at the relief. In the dissected areas of this surface, *Argissolos Vermelhos* (Red Acrisols*)* dominate over *Latossolos* (Ferralsols). This is compatible with more undulating reliefs, in which the lateral drainage component becomes more important than the vertical one (VIEIRA and SANTOS, 1987). However, the increase in percentages of *Argissolos Amarelos* (Yellow Acrisols), *Latossolos Amarelos* (Yellow Ferralsols) and *Plintossolos* (Plinthosols) indicates less efficient drainage conditions, even in the dissected areas of this surface.

Surface 5 (Velhas II - Late Velhas) is the one with the greatest heterogeneity of soils, especially in its preserved flat levels. *Latossolos Amarelos* (Yellow Ferralsols) predominate, followed by *Argissolos Amarelos* (Yellow Ferralsols), *Espodossolos* (Podzols), *Argissolos Vermelhos* (red Acrisols), *Latossolos Amarelos* (Red Ferralsols), *Neossolos Quartzarênicos* (Arenosols) and *Gleissolos* (Gleysols) (Figure 10). In Figure 11 (available soil profiles) (CPRM, EMBRAPA, IBGE), this order is modified, but the heterogeneity of soils is explicit. Soils with more yellowish hues (*Latossolos* and *Argissolos*), with paler, grayish or dark colors (*Neossolos Quartzarênicos, Espodossolos, Gleissolos*), and with Fe segregation (*Plintossolos*) indicate that moderately and imperfectly drained environments occur in large areas of flat remnants of this surface. Mineral occurrences are limited to immature (Costa, 1991) ferruginous (*piçarreiras*) lateritic profiles, such as those studied and dated by Allard et al., (2018), at 60 and 90 m altitude, in the municipalities of Santa Isabel do Rio Negro and São Gabriel da Cachoeira (Amazonas State), on the Guiana Shield. In the dissected part of this planation surface, along the valleys of the current drainage network (slopes, terraces and floodplains), *Latossolos Amarelos* (Yellow Ferralsols) predominate (55%), followed by *Gleissolos* (Gleysols) (12%) and *Neossolos Flúvicos* (Fluvisols) (4%).

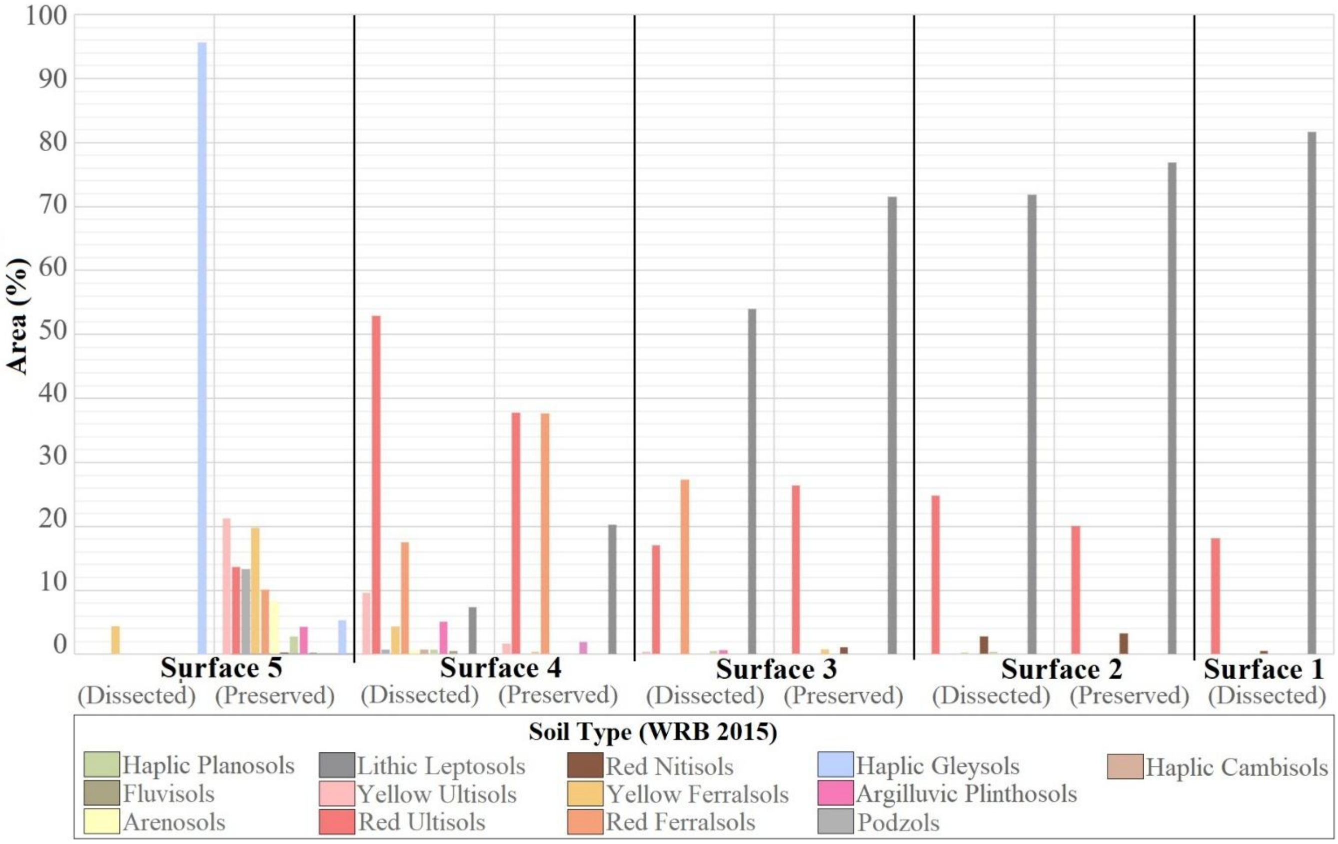

Figure 10. Graph of distribution of soil types on planation surfaces (preserved and dissected).

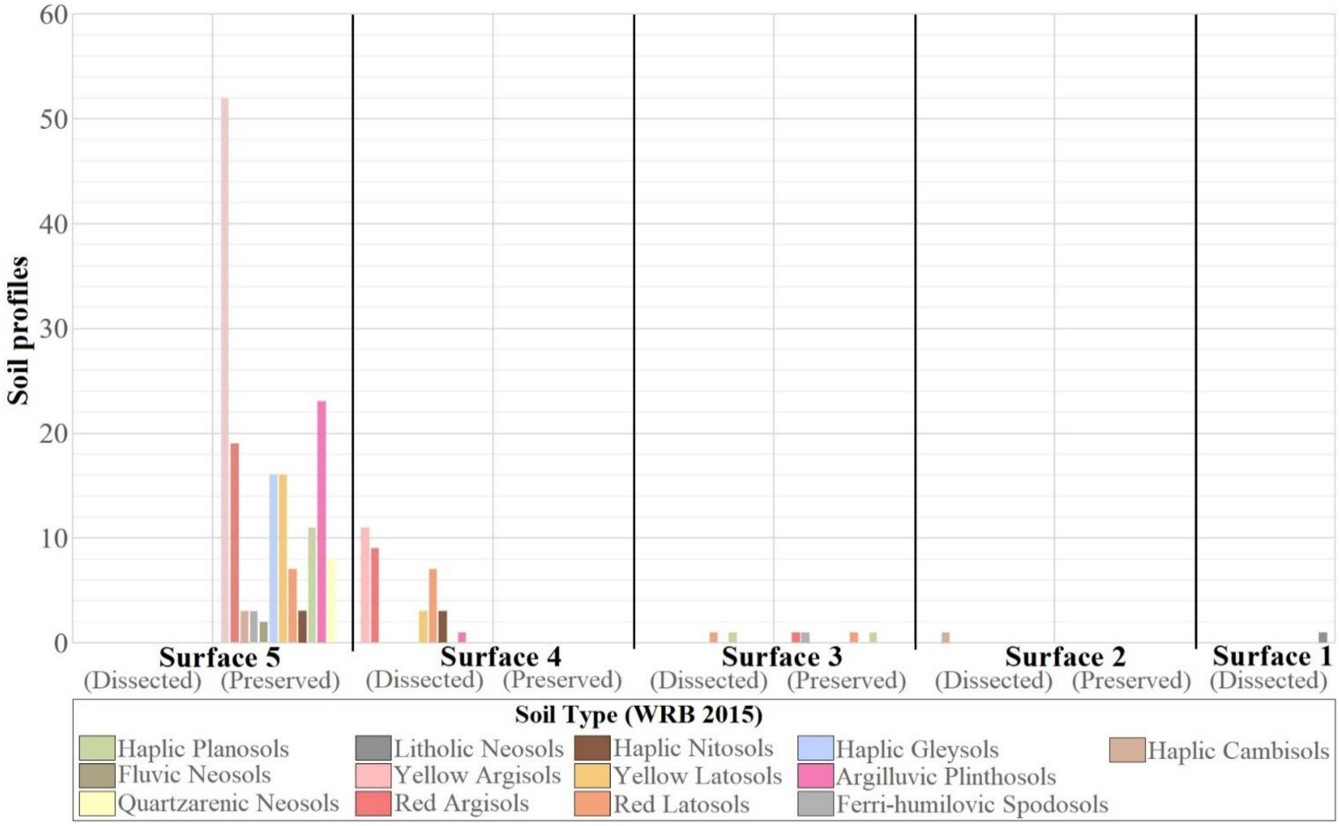

Figure 11. Graph of distribution of soil types on planation surfaces (preserved and dissected).

Surfaces 1 and 2 (Gondwana and Post-Gondwana) and the remaining flat areas of Surface 3 (South American) have quartzites, sandstones and arkoses of the Roraima Supergroup and the Urupi Formation as their geological substrate. It is verified, therefore, that higher planation surfaces are supported by rocks with greater resistance to erosion. The dissected areas of surface 3 (South American) have as substrate granites and gneisses of the crystalline basement, as well as dacites, rhyolites and andesites of the Iricoumé and Surumu Groups, which are placed in the Roraima Supergroup. Surface 4 (Velhas I – Early Velhas) was elaborated predominantly on these same groups of rocks in the Guiana Shield. This geological substrate also predominates in dissected areas of this surface. Surface 5 (Velhas II – Late Velhas) has as substrate both the Guiana Shield and the Içá and Boa Vista Formations. Considering that the final planation phase of the Velhas II cycle is considered Pliocene (BARDOSSY and ALEVA, 1990; ROSSETTI, 2004), the altimetric leveling of this surface has two genetic pathways: in areas where the geological substrate are the rocks of the Guiana Shield, the genesis of the planation level was of erosive nature, possibly by etchplanation (DANTAS and MAIA, 2010), resulting in the truncation of different lithologies, as occurred for older surfaces. For areas whose substrate is the Içá and Boa Vista Formations, the altimetric leveling reflects a fluvial-lacustrine and megafan (ROSSETI et al., 2016) sedimentation covering the surface previously leveled by erosion, as proposed by Campbell et al. (2006) for the Madre de Dios Formation, correlative to the Içá Formation in Western Amazonia. Therefore, although it configures an approximately flat surface as a whole, only part of Surface 5—the part elaborated by truncation of the geological substrate by erosion—should be considered conceptually a planation surface.

The connection between planation surfaces and lithological groups presented in Graph 3 is comparable to that found by Schubert and Huber (1990, cited by OLLIER, 2000) in his study in Venezuela: the highest planation surfaces are supported by meta-sedimentary rocks of the Roraima Group; the intermediate planation surface has as its substrate the igneous-metamorphic rocks of the crystalline basement and the lower altitude surfaces have continental sedimentary geological formations and alluvial sediments as substrate. Figure 12 shows the percentage each geological substrate occupies in the area of each planation surface identified and mapped.

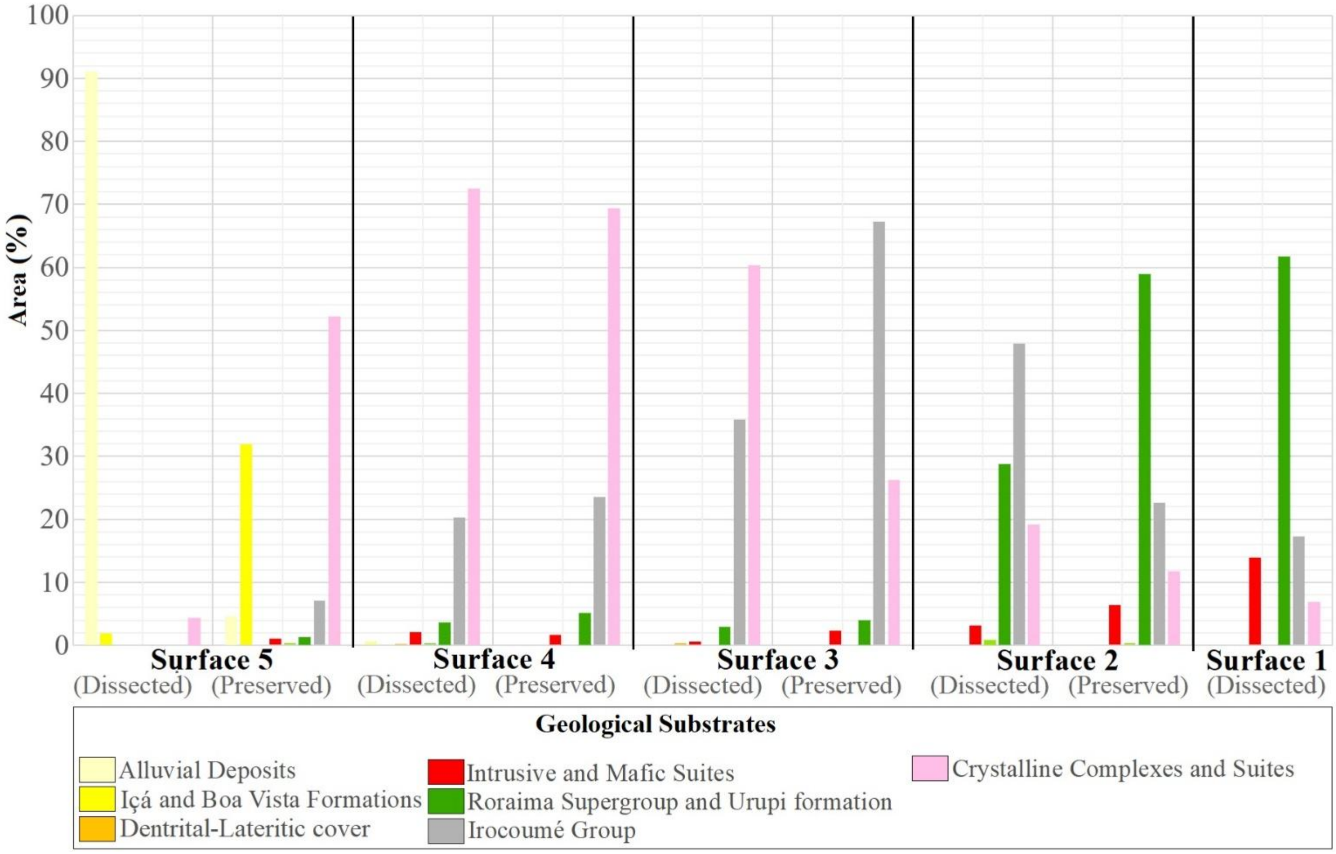

Figure 12. Graph of distribution of soil types on planation surfaces (preserved and dissected).

4. Discussion

From studies and applied methodology, five planation surfaces were identified on the Guiana Shield, in the strip that extends from the highlands of the border between Brazil, Venezuela and Guiana to the contact with rocks of the sedimentary basin of the Amazon. These surfaces were named here according to King (1956) and Bardossy and Aleva (1990): a summit surface, called the Gondwana surface (KING, 1956), from 855 to 2,745 m; a second surface (525 to 854 m), called Post-Gondwana (KING, 1956); a third surface, from 279 to 524 m, called South American (KING, 1956); a fourth surface, from 114 to 278 m, called Velhas I (Early Velhas, according to Bardossy and Aleva, 1990), and a fifth surface, called Velhas II (Late Velhas), according to Bardossy and Aleva, 1990). For each surface, flattened areas, remnants, and dissected areas were mapped.

Spatial distribution of planation surfaces showed a good correlation with spatial distribution of surface formations for the same area. In the first three surfaces, young soils predominate, whose presence was attributed to erosion of surface formations and rock exposure, in the case of the two upper surfaces, and to truncation of profiles by erosion and exposure of mature ferruginous crusts (COSTA, 1991), in the case of the South American Surface. Deeper soils gradually increase in spatial representativeness from the summit surface to the South American surface, with Ultisols predominating. On the South American surface, supergene concentrations of metals of economic interest are recorded, which reflects its extensive period of weathering under humid climate conditions. The two lower surfaces present greater soil diversity, due to the increase in flattened areas under more deficient drainage conditions (Spodosols, Plintosols, Gleisols, Planosols), in addition to Oxisols and Ultisols, which are dominant. But these soils, because they develop from younger substrates, are less thick.

Likewise, there was a significant correlation between planation surfaces and geological substrate. The two highest surfaces (Gondwana and Post-Gondwana) are supported by quartzites and sandstones, which may explain their permanence at high altitudes due to greater resistance to erosion. The South American and Velhas I surfaces were formed on granites and gneisses of the crystalline basement. However, on the South American Surface, lateritic profiles are thicker, with laterites, which hinders erosion and contributes to permanence of flat residual areas. On the most recent surface, Velhas II, the geological substrate is composed both of Guiana Shield's rocks and of unconsolidated sediments of the Içá and Boa Vista Formations and alluvium.

5. Conclusions

The structure, spatial distribution and geological substrates (rocks, surface formations) of landscapes of the Brazilian Amazon remain poorly understood, despite the scenario of growing pressure for occupation and exploitation of the region's natural resources. The development of works that aim to research physical and geographical characteristics of the Amazon region is extremely complex. In addition to territorial extension and the difficult access (lack of roads, high cost of fieldwork, often adverse climatic conditions, etc.), there is a great heterogeneity regarding natural landscapes, represented by the diversity of types of vegetation cover, which is mainly influenced by different types of surface formations, under different hydrological conditions. On the other hand, there has been an important development of remote sensing devices and geoprocessing techniques in recent years. Associated with basic mathematical concepts, it was possible to propose a map of planation surfaces and their levels of dissection in the north-central Amazon, validated through information of surface formations and their materials, and associating these surfaces with ages attributed to them by reviewed literature.

It was verified, therefore, that the methodology used for mapping presented results consistent with planation surfaces and their altimetric ranges found in the literature. These outcomes may help in understanding the organization of reliefs and in the knowledge of distribution of surface formations and rock types in the region. Furthermore, the hypothesis that there is a significant relationship between the distribution of planation surfaces and the distribution of soil types and occurrence of supergene ores was confirmed. The coupling of these products with geochronology data of surface formations and rocks associated with these surfaces would provide more precise information about the genesis of past and current landscapes of the Amazon. It was verified, therefore, that the mapping proposal presented coherent and unprecedented results on the distribution of planation surfaces in the Amazon.

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Author contribution: José Roberto A. Mantovani: Survey, structuring of the geographic database, processing of geographic information, as well as the development, implementation and validation of the methodology proposed in the study, through geoprocessing and digital cartography, creation of maps and figures, data analysis, software development and textual review. Guilherme Taitson Bueno: Structural evaluation and systematization of the text and comparison of the methodology with others available in the specialized literature, was also responsible for the methodological conception of the software development, evaluation of the results and general review of the text and figures.

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