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Research Article

Mountains of the intertropical passive margins and their cartographic representation: methodological proposal in different litostructural arrangements

As montanhas das margens passivas intertropicais e a sua representação cartográfica: proposta metodológica em diferentes arranjos litoestruturais

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Abstract: The core hypothesis of this article considers that methodological approaches related to geomorphological cartography must seek standardization based on landscape types. Thus, a methodological proposal for geomorphological cartography in mountainous landscapes is presented, with demonstrations in compartments structured in three distinct lithostructural bases located in the context of Serra da Mantiqueira: nepheline-syenites, gneiss-granites and quartzites. The results showed a similar geomorphological organization for the different compartments, admitting the same methodological approach and the adoption of a unified legend, since the geomorphic facts found were convergent, despite the differences in the geological bases between the areas. It is postulated that the methodological approach presented can be applied to different geomorphological contexts located in the large escarpments of the intertropical passive margins, thus making the universalization of interpretative and technical procedures compatible with the also universal character of this landscapes.

Keywords: Tropical mountains; Great escarpments; Geomorphological cartography.

Resumo: A hipótese nuclear do presente artigo considera que as abordagens metodológicas tangentes à cartografia geomorfológica devem buscar uma estandardização a partir de tipos de paisagem. Assim considerado, apresenta-se uma proposta metodológica para a cartografia geomorfológica em paisagens montanhosas, com demonstrações em compartimentos estruturados em três bases litoestruturais distintas localizadas no contexto da Serra da Mantiqueira, a saber: nefelina-sienitos, gnaisse-granitos e quartzitos. Os resultados apontaram uma organização geomorfológica similar para os diferentes compartimentos, admitindo os mesmos caminhos metodológicos e a adoção de uma legenda unificada, uma vez que os fatos geomórficos encontrados foram convergentes, malgrados as diferenças nas bases geológicas entre as áreas. Postula-se que a abordagem metodológica apresentada pode ser aplicada diferentes contextos geomorfológicos localizados nos grandes escarpamentos das margens passivas intertropicais, compatibilizando assim a universalização dos procedimentos interpretativos e técnicos com o caráter também universal das aludidas paisagens.

Palavras-chave: Montanhas tropicais; Grandes escarpamentos; Cartografia geomorfológica.

1. Introduction

The most characteristic geomorphological features of the passive margins of the intertropical belts are the occurrence of large escarpments located in the coastal and peri-coastal strips. The presence of these prominent geomorphological structures has been explained by theoretical models such as Walther Penck's Primärrumpf

(1888-1923) and, more recently, by the assumptions inherent in the thermal and isostatic uplift model (SUMMERFIELD, 1991; GILCHRIST; SUMMERFIELD, 1994; BIERMAN; MONTGOMERY, 2014). Such features are characterized by morphologies of escarpments, terraces and reshaped hills, with a tendency for deep dissection, significantly steep slopes and considerable local and regional altimetric amplitudes. Significant extensions of the Brazilian and African Atlantic margins present geomorphological systems with the aforementioned characteristics.

In Africa, the great escarpments occur from Angola, south of the Congo River depression, and cross the territory of Namibia to the western part of South Africa. In this significant latitudinal projection, the mountain ranges intercept hot and humid, desert and temperate zones, providing forests along the Angolan territory, schrubs in the southern part of the continent and sparse vegetation in the desert belts of Namibia that become even more sparse on the leeward slopes, where regional altitudes exceed 2000 meters.

In the context of the Brazilian Atlantic margin, the great escarpments occur in almost the entire southeast region and in part of the south region (figure 1). The steep alignments are linked to the structure concerning the continental rift of southeastern Brazil (RICCOMINI, 1989), and their zone of influence extends approximately 300 km inland, a strip that establishes diffuse contact between the large escarpments and the partially flattened intracratonic plateaus. The region of the great escarpments of southeastern Brazil presents a complex tectono-erosive regime whose specificities do not fit within the scope of this exposition, but which, in general, associates a strong denudational imperative responsible for the retraction of the escarpments, accompanied by river captures (CHEREM et al. 2013; REZENDE et al. 2013; SALGADO et al. 2018) and post-Miocene neotectonic effects responsible for the tilting and uplift of blocks, by strong river incision, by the reshaping of divides and faceting of the escarpments, among other geomorphic processes. Such findings have been demonstrated in a series of studies (SAADI, 1991; RIBEIRO, 1996; SANTOS, 1999; GONTIJO, 1999; SILVA; MELLO, 2011; MARQUES NETO, 2012; SILVA, 2023).

In this genetic-evolutionary scenario, the Precambrian Atlantic shield is exhumed and exposed at altitudes exceeding 2,000 meters in the Serra do Mar and 2,700 meters in the Serra da Mantiqueira, the second orographic step of the Brazilian Atlantic Plateau. In Africa, the altitude of the escarpments tends to increase in the north-south direction, oscillating between 1,000 and 1,200 meters in the central-northern portion of Angola, located in the intertropical belt, and progressively increasing in the peri-desert areas of the south, which are in turn influenced by the Benguela current. Next, it demands the desert belts of Namibia, where the residual surfaces exceed 2000 meters in altitude, in an altimetric distribution with a strong climatic connotation.

In Brazil, the great escarpments are entirely located in humid climate systems, being subject to intense geochemical denudation, and yet, they are found in altimetric bands similar to similar African reliefs, even being comparable to the desert belts protected from the intense denudational processes tangential to tropicality. Such evidence suggests a tectonic influence acting significantly in Brazil, also verified in the African context by authors such as Marton et al. (2000), Macgregor (2010) and Rosante (2013).

Despite the evolutionary differences given by climatic and/or tectono-structural control observed between these intercontinental geomorphological systems with the same genetic link, they share important morphogenetic, morphological, morphometric, morphostructural and morphochronological specificities. The steep reliefs were generated in the bulge of the continental fission, leaving such morphologies on both continents largely based on the same Proterozoic structures. This greater unity inherited from the breakup of Gondwana in morphographic, structural and geochronological terms converges directly with the methodological interests of geomorphological cartography, historically involved with the apparently paradoxical need to standardize the representation for such distinct geomorphological systems arranged throughout the globe.

The discussion proposed here recognizes the geomorphological specificities of tropical mountains present on passive continental margins, as well as the implications of such specificities for geomorphological cartography. Based on these premises, this article assumes the objective, based on examples from the Brazilian territory, of presenting a proposal for geomorphological cartography in mountainous landscapes of passive margins with demonstrations for different geological structures, reconciling the methodological assumptions tangent to geomorphological cartography and the specificities inherent to large escarpments. The interpretations and associated cartographic schemes were given in the following morphostructural arrangements distributed in the tropical mountains of southeastern Brazil (figure 1): (1) reliefs in alkaline intrusions (nepheline-syenites), given by the Itatiaia massif (MG\RJ\SP); (2) reliefs in quartzite mountain ranges, represented by the Ibitipoca Mountain Range (MG); (3) gneissic-granite reliefs, represented by the structure known regionally as Papagaio Mountain Range (MG).

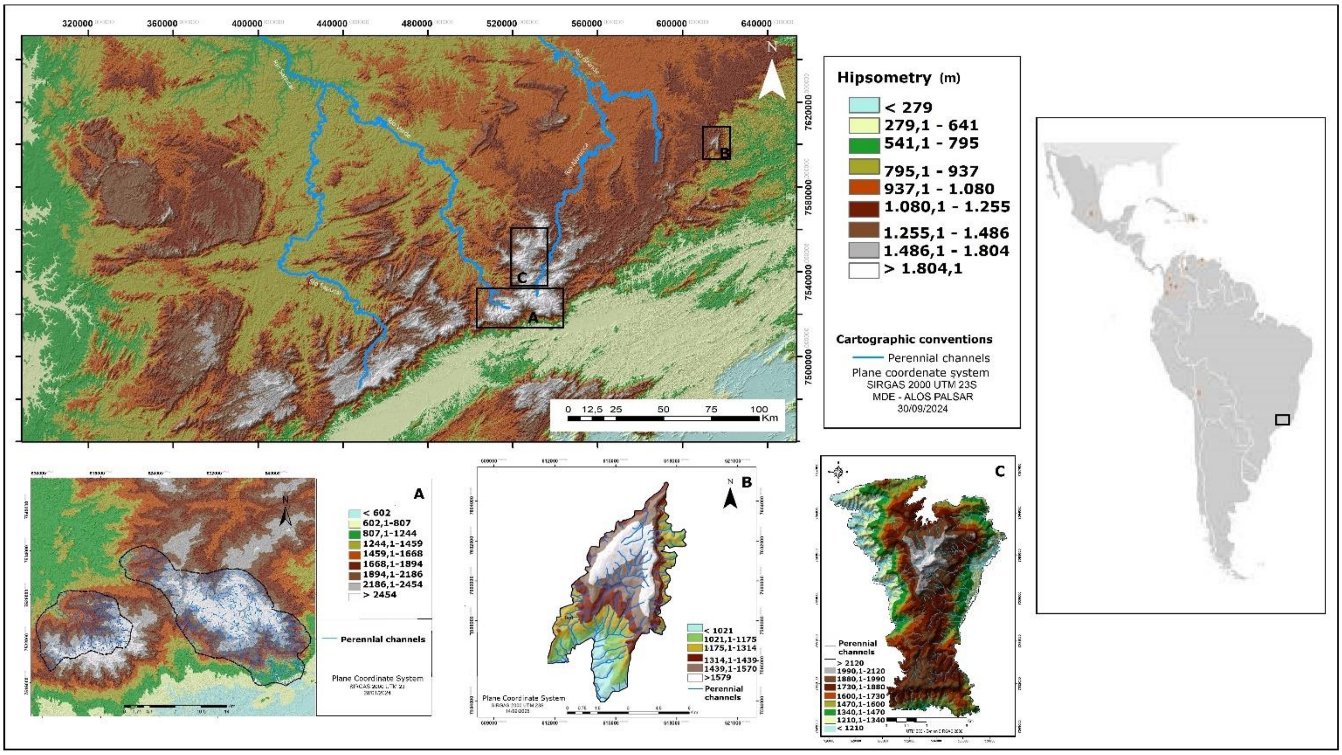

Figure 1. Location of the studied compartments in the regional context. (A) Itatiaia alkaline massif (Passa Quatro massif delimited to the west). (B) Ibitipoca mountain range. (C) Papagaio mountain range.

2. Study area

The mountainous reliefs of passive margins are usually low to medium-height mountains, with amplitudes ranging from just over 300 meters in relation to the reference base levels to contexts with elevation differences exceeding 2,000 meters, such as the orographic roofs of the Southern Mantiqueira in relation to the Paraíba do Sul Valley, the Serra do Caparaó in relation to the adjacent intermontane landscapes, and sectors of the Serra do Mar towards the Atlantic base level. We consider that these geomorphological systems, normally elevated above 2,000 meters above sea level, define altitudes that can be classified as extreme by the altimetric standards of intertropical passive margins.

In Southeast Brazil, the Precambrian structural windows raised in plateaus and mountain ranges hinder, with the exception of the most expressive grabens, a broad Cenozoic sedimentary trapping. It is known that the main area of contribution is the tectonic trench dissected by the Paraíba do Sul River, which imprisons sequences of interior Cenozoic sedimentary basins (RICCOMINI, 1989). On the other hand, the proximity of the escarpments to the oceanic base level has promoted a strong retraction of the escarpments from erosive inlets and retreats that differ regionally due to the distinct regional tectono-structural controls, characterized by copious processes of river capture and expansion of coastal hydrographic basins, as observed by Cherem et al. (2013). The sedimentary contribution in the marine environment has also been considerable during the Cenozoic, forming sequences of platform basins. This creates geodynamic environments of a subsiding nature that catalyze the process of flexural isostatic uplift of the adjacent coastal margin, a relief evolution model typically found on passive margins (SUMMERFIELD, 1991), which results in the generation of large escarpments that tend to retract. On the Brazilian Atlantic margin, it is worth highlighting that a significant morphotectonic imperative increases the set of forces acting on regional geomorphogenesis, affected by the neotectonic diastrophic effects triggered from the Middle Miocene with an initial phase of rift reactivation (HASUI, 1990; SILVA; MELLO, 2011) and sustained by different stress fields operating during the Quaternary.

The successive reactivations operated in geomorphological systems of tectonic genesis have generated profound tectono-erosive implications, which unfold on different scales. Regionally, a geomorphological organization is projected formed by stepped regional base levels that largely mark the main plateau levels of southeastern Brazil (MARQUES NETO, 2020). In the scalar integrities of detail and semi-detail, the relations of continuity and rupture are defined from knickpoints and base levels of local expression, which are staggered in the tropical mountains of southeastern Brazil in smaller blocks that trap sedimentation alveoli at different topographic levels within a plateau level of regional expression. Such ruptures are clearly distinguishable by the decrease and increase in the distance between the contour lines, and also due to textural changes in satellite images. These specificities articulate the regional and local scales in similar geomorphic facts, given by the staggering and unevenness distributed in strong laterality. Naturally, this organization has implications for geomorphological cartography.

3. Materials and Methods

3.1. General bases

Considering the set of tropical mountains as a geomorphological unit of well-defined universality prompts the development of methodological strategies capable of aligning the general framework of geomorphological cartography with the singularities of mountainous landscapes, and which at the same time encompass, to a considerable extent, regional variations without compromising the general standard of cartographic procedures.

Verstappen (1983) argues that the communication of information on the geomorphological map should prioritize simplicity to emphasize the most essential geomorphic facts and the generalization or omission of less important information, and that part of what is intended to be communicated may be contained in the legend and not on the map itself. The author also proposes that the geomorphological information to be estimated can be grouped based on a hierarchical order of importance, namely: (1) Morphographic/morphogenetic information; (2) Morphochronological information; (3) Lithological and unconsolidated material data; (4) Morphological and structural data; (5) Slope characteristics (slope, length); (5) Other morphometric data (relief amplitude, elevation).

In the case of passive margin mountains, it is first necessary to differentiate their genesis (tectonic, structural, volcanic), and subsequently the different geomorphological compartments, their relative or absolute chronology and the morphodynamic processes that operate on the surface coverings.

With regard to the materials used, the schemes relied on planialtimetric bases generated by the Brazilian Institute of Geography and Statistics (IBGE), TM-Landsat-8 images (bands 5, 4 and 3) and SRTM (Shuttle Radar Topography Mission) radar products made available by the USGS – United States Geological Service (https://earthexplorer.usgs.gov/). The work was complemented by field campaigns to recognize the compartments, describe the geoforms, georeference specific points, in addition to collecting samples of surface coverings for chemical and granulometry analyses.

3.2. Morphogenesis and morphography

The relief of large cratonic edge escarpments, such as the Brazilian Atlantic coast, is characterized by very pronounced scaling, which is observed both on a regional scale and in geoforms that can be integrated on a detailed scale. Regionally, the aforementioned scaling is differentiated based on regional base levels linked to different plateau levels (MARQUES NETO, 2020). On a local, detailed and semi-detailed scale, it is necessary to identify the local base levels and the main knickpoints contained in the area to be mapped, using planialtimetric bases to verify changes in the spacing pattern between the curves and the textural behaviors of the different geomorphological units.

In this proposal, the different geomorphological compartments were identified based on slope ruptures, normally linked to local or even regional base levels, which define different erosional and depositional organizations distributed throughout the different compartments. The differentiation of the morphologies assigned to each compartment was based on morphometric data (slope and dissection depth) and the interpretation of remote sensing products (radar and satellite images) to capture different shape patterns from the identified textural responses. The intermediate result is a stepped topomorphological compartmentalization, which shows the spatiality of the mountainous relief from the different altimetric levels, establishing a pattern strongly adhering to the topographic staircase aspect inherent to this type of geomorphological organization, forming sequential levels that descend from the somital surfaces and project down to the local and regional base levels.

The geomorphological compartmentalization was performed based on the different genetic types (residual, denudational and aggradational), organized in the legend according to sections that nest the different topographic levels, showing the direction of mass and energy flows in two projections. The option of organizing the legend according to the levels instead of the modeled ones is justified by the evolutionary and dynamic processes that differ according to the stepped blocks, since different base levels grant relative erosional and depositional autonomy to each compartment. Although tropical mountains are characterized by strong lateral connections in high-energy relief, such geomorphological organizations are also marked by recurrent ruptures that differentiate compartments with their own typicities. Furthermore, such areas are tectonically deformed, with recurring unevenness of chronocorrelated surfaces, making it safer to treat the chronology of the forms according to the different staggered levels, especially when working only with relative dates, minimizing the insufficiencies of the merely altimetric criterion and seeking adhesions with the geomorphological organizations that the abrupt ruptures differentiate.

3.3. Morphodynamics

It is imperative that geomorphological cartography in mountainous regions be able to estimate the high energy of the relief that characterizes these areas. In this sense, the genetic types were represented by color families, which in turn group together different dynamic-functional compartments of the landscape, namely: (1) eluvial zones of progressive pedogenesis (residual types), corresponding to the tops preserved at different topographic levels; (2) transeluvial to transaccumulative erosion zones (denudadional types), concerning the dissected slopes; (3) accumulative zones (aggradational types), given by the plains, alveoli and ramp complexes. The delimitation of zones according to the dominant processes is strongly dependent on the scale, and there may be accumulative enclaves in erosion zones, for example, that cannot be represented at regional and semi-detail scales and are only observable at detailed scales.

Additionally, granulometric and chemical analyses were performed on samples of surface coverings in the different dynamic-functional compartments (eluvial, transeluvial, transaccumulative and accumulative). Although the textural elements and their respective geochemical signatures were not directly incorporated into the maps and the unified legend, they were of great value in understanding the physical-chemical variations in the surface structure of the landscape according to the substrate, which has both physiographic and morphodynamic implications.

The limitations concerning the representation of morphodynamic information on a semi-detailed scale can also be compensated by the use of symbols aimed at representing geomorphic facts that denote processes, to be inserted into the map based on field georeferencing or detection in satellite images.

3.4. Morphochronology

Chronological information is often one of the main bottlenecks in geomorphological cartography, which normally uses relative dating. Absolute geochronological techniques for dating geomorphological surfaces are very costly, and dating of sedimentary material by Optically Stimulated Luminescence (OSL) and Carbon-14 only captures aggradational genetic types of Quaternary, essentially Neoquaternary, age.

The present proposal presents a relative chronology that can be read both in the vertical and horizontal planes of the legend, an organization that is also suitable for absolute chronological data. By vertical reading, the relative age of the relief decreases from the oldest preserved somital surfaces to the lowest geomorphological level, linked to the lowest and most intensely dissected base level. The age of the aggradational models also decreases in the same direction, sequencing the high-mountain plains confined in the preserved topographic domes, the colluvial ramps of the reshaped slopes and the active fluvial plains at the lowest base levels. The decrease in relative age is also verified horizontally within the different levels, where the residual Paleogene orographic roofs partly preserved by duricrosts, the dissected Neogene slopes, and the Quaternary aggradation models are staggered, in a connectivity that occurs between the levels and is repeated within the specific levels.

3.5. Legend organization

In this proposal, a unified legend was organized for the maps, structured according to a vertical and horizontal ordering. The information arranged vertically refers to the altitudinal successions of the relief forms and their dominant slopes within the three genetic types identified (residual, denudational and aggradational), where level 1 comprises the highest sectors, level 2 the intermediate extensions and level 3 the lowest compartments. The horizontal projection of the legend, in turn, shows the relative chronologies of the models and the different dynamic-functional compartments (eluvial, transeluvial, transaccumulative and accumulative), aggregating information that is repeated in the different levels arranged vertically according to the well-marked knickpoints. Distinctly, in the legend structure the vertical and horizontal variations intersect and allow a reading in these two planes, integrating morphological levels and flow directions.

In addition, recurrent geomorphic facts in tropical mountains with passive margins were incorporated through the use of symbols, one of the most recurrent graphic resources in geomorphological cartography. Although the legend presented a unified collection of symbols, such a graphic resource can be quite flexible and vary according to the existing geomorphological features and the priority given to their representation.

4. Results

4.1. General aspects: tropical mountains as a geomorphological unit

The cartographic productions conceived give rise to important discussions and comparisons about the geomorphological organizations and landscape structure in tropical mountains with passive margins. Such reliefs present a sequential compartmentalization of the somital surfaces up to the slope breaks in the mountain foothills that, in general, have three fundamental units in the following sequence: residual models preserved from dissection in the form of narrow or locally flattened tops and interfluves; dissection models in scarps and reshaped terraces filled or not by colluvium ramps; aggradational models in the form of plains associated or not with terraces, positioned at different morphological levels. Some variations can be verified, with the presence of high-mountain hills or even convex morphologies at the base of the mountains generated by the dissection of steps and terraces and the reshaping of these geoforms into embedded hills. However, the pattern remains even in the face of lithological variability and the different regional base levels to which such models are associated.

The tropical mountains of the Brazilian Atlantic margin have a tectonic genesis linked to the uplift of the coastal margin synchronous with the opening of the South Atlantic, generating large escarpments (RIBEIRO, 1996; ZALAN; OLIVEIRA, 2005). Despite the retreat of some mountain fronts with migration of knickpoints to the interior of the continent, many structures are preserved close to the base level (MARQUES NETO, 2017). Successive reactivations have reshaped escarpments and generated high-mountain valleys disconnected from the regional base levels. Thus, the residual, denudational and aggradational morphologies tend to replicate themselves at different levels of the mountainous relief, generating geomorphological organizations controlled by the local base levels that form along the topographic staircases.

The general standard that is established makes it possible to edit a single legend for all mapped geomorphological contexts, which can be expanded or reduced according to the number of units and the levels of detail/generalization defined by the scale used. The use of a single legend was debated and defended by Gustavsson and Kolstrup (2006) and Gustavsson et al. (2009), who used the zoom feature to show the geomorphological reality at different scales, inserting or removing symbols according to the level of detail/generalization.

4.2. Syenitic mountainous reliefs

Alkaline intrusions from the Cretaceous-Paleocene intercepted the Proterozoic rocks in the context of the tectonic reactivation that occurred during the deformational efforts linked to the separation of the African and South American plates, in the context of the continental rift system of southeastern Brazil (RICCOMINI, 1989; CHIESSI, 2004; ZALAN and OLIVEIRA, 2005). The tropical mountains of passive margin are arranged in the form of large escarpments on the continental margin, generated by the reactivation of older structures, which results in a structuring of more or less aligned reliefs that on the Brazilian Atlantic margin assume a general NE-SW orientation. Among the geotectonic effects linked to the syn-rift and post-rift phases are the epirogenetic compensations that caused the uplift of the Brazilian coastal margin and the formation of mountainous reliefs, basaltic-tholeiitic and anorogenic volcanism, in addition to alkaline intrusions in batholiths of various sizes, among which the most expressive is the alkaline massif of Itatiaia.

Some specificities differentiate the relief linked to such intrusive foci in relation to the rest of the set of large escarpments of Southeast Brazil, both in the orographic step of the Serra do Mar and in the Serra da Mantiqueira. A genetic specificity is highlighted, since these structures have their genesis linked to alkaline intrusions, and not to uplifts related to the reactivation of faults. The particular genesis of these structures also has repercussions on morphological specificities, given by a more circular geometry that differs from the large alignments of elongated ridges. Naturally, morphometric singularities are given by greater local and regional elevations and amplitudes, even though the slope patterns are similar to the general set of large escarpments. This elevation pattern, which assumes extreme levels within the passive margins, is also due to a morphostructural specificity given by nepheline-syenites, lithotypes that are more resistant to denudation processes compared to the gneiss-granitic-migmatitic set that is the regional majority.

The energy of the relief concerning the alkaline intrusions is quite exacerbated, and, although it is similar to the set of large escarpments, thick bands of colluvial deposits around the intrusive bodies indicate more intense reworking, with a profusion of mass movements and granulometric inversions indicating rapid transport of the regolith. The most pronounced amplitudes, therefore, define a morphodynamic specificity highlighted by the intensification of gravitational processes in the slope domain, with the formation of ramps containing correlative deposits, which in the regional context have accumulated mainly in the valley bottoms. In the domain of the somital surfaces of the syenitic reliefs, in turn, geocryogenic processes occur that are significantly more intense in relation to the context of the highlands of Southeast Brazil, as demonstrated by Modenesi-Gauttieri and Nunes (1998), without significant implications in the generation of geomorphic facts, at least in the current climatic context. Downstream, in the dissected portions of the landscape, gravitational processes intensify; on the summit surfaces, defined in the residual genetic types, the effects of the tropical highland climate intensify. The Itatiaia massif (figure 2) is part of an orographic set of tectonic genesis, linked to the reactivation of Proterozoic crustal structures (CHIESSI, 2004). Morphrochronologically, therefore, the alkaline batholiths align with the set of steep ridges of the Serra da Mantiqueira, supported by prevalent Cenozoic tectonics and significant neotectonic contributions (SANTOS, 1999; MORALES, 2005; MARQUES NETO, 2012).

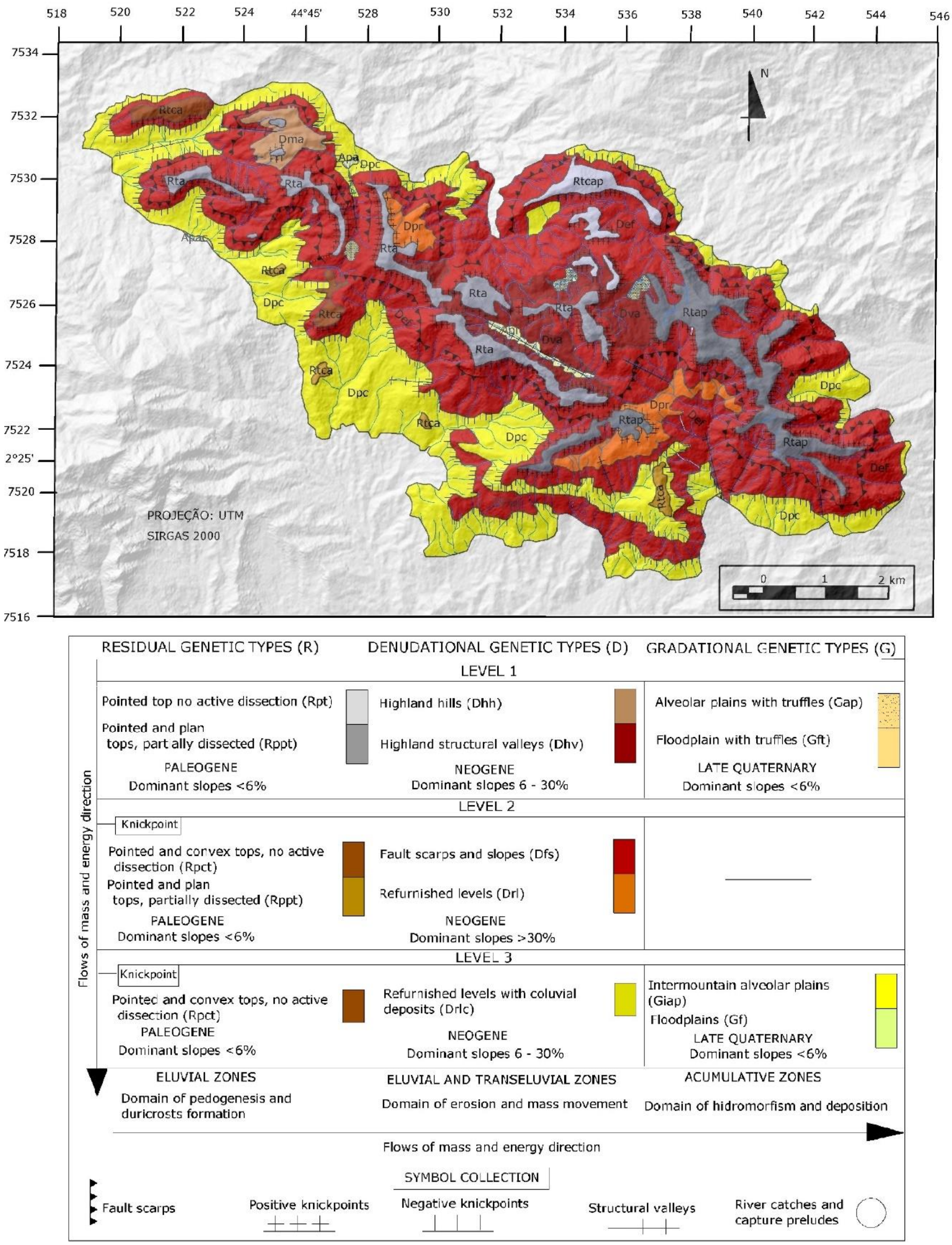

Figure 2. Geomorphological map of the Itatiaia alkaline massif.

4.3. Quartzite mountainous reliefs

In the Brazilian crystalline shield, quartzite reliefs are normally linked to structural control and differential erosion, with elevated ridges sustained due to the greater resistance of quartzites to chemical attack (REZENDE, 2018). Structures such as the Serra do Espinhaço and a profuse set of orographic alignments in central-eastern Brazil are reliefs marked out in quartzites. Within the rift margin closest to the coastal façade, where reactivations have been more intense, quartzites are accessory lithotypes and have a coarse appearance, which distinguishes them from the plane-parallel bedding pattern with gentle dips found in the relatively common low-grade metasedimentary contexts along the edges of the São Francisco Craton. The structure related to the Serra do Ibitipoca (figure 3) is marked by coarse and saccharoidal quartzites (ROCHA, 2013), indicating a reactivation genesis, and not exactly a metamorphism in sedimentary covers of folded cratonic edges during events related to the Brasiliano Cycle. Its limits are defined by the occurrence of quartzites that dominate the ridges that rise at the NE end of the southern branch of the Serra da Mantiqueira.

Although the syenitic intrusions define elevated surfaces, it is undeniable that the quartzites support quite resilient geosystems, with precarious transformation and, consequently, a superficial regolith structure rich in primary minerals interspersed with rocky outcrops where rocky fields thrive. The first topographic level defines locally flattened extensions and valleys whose evolution has chemical dissolution as an important component, with the formation of karst morphologies recorded by the occurrence of caves, closed depressions and pipes that can be mapped on a detailed scale. As in the syenitic relief, the scarps define the functional connectivity with the second level through pronounced erosional unconformities in the contact between the quartzites and the dominant gneissic and schist lithotypes in the lower valleys and adjacent intermontane surfaces.

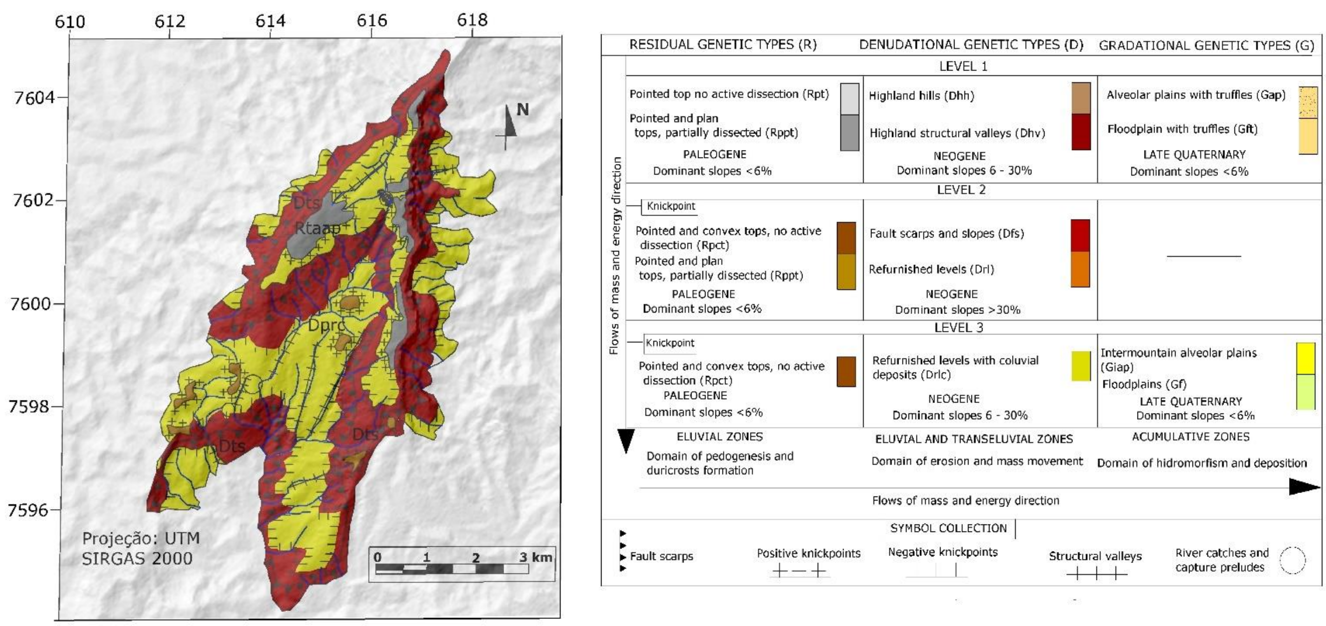

Figura 3. Geomorphological map of the Ibitipoca mountain range.

4.4. Gneiss-granitic mountainous reliefs

The tectonic reactivation that affected the Brazilian Atlantic façade, as highlighted, affected various lithotypes, including gneiss-granitic rocks, quite common in the context of the Serra da Mantiqueira. Serra do Papagaio is also part of the so-called upper step (SAADI, 1991) or Upper Mantiqueira Geosystem (MARQUES NETO, 2020), and the morphotectonic character of the geomorphological system in question maintains Precambrian orthogneisses and late-tectonic granitic intrusions of Cambro-Ordovician age on the somital surfaces. In the structure in question, the morphotectonic features are quite conspicuous and diverse: fault scarps, pronounced vertical incision, hanging valleys disjointed from the local base levels, copious trapezoidal facets, misalignment of interfluvial lines, shutter ridges linked to neotectonic strike-slip faults, among others.

The geomorphological organization of the Serra do Papagaio closely resembles the structures previously presented, with a predominance of steep slope geoforms characterized by steep slopes (figure 4), as occurs in the Serra do Ibitipoca and in the alkaline massif of Itatiaia. However, in the structure in question the spatial expression of the scarps is more significant, involving the entire mountainous compartment from the slope ruptures with their narrow somital surfaces. The steep buttresses of the Serra do Papagaio intercept the entire level 2, from the tops to the bottoms, on both the eastern and western slopes, two opposing flanks that overlap in the predominantly N-S alignment defined in the interfluvial line. On both sides, there is a drainage pattern that is parallel to subparallel in the direction of the foliations. On the northern and southern ends, the parallelism is maintained, but the dissection is more functional and the slopes, therefore, are more reshaped and with slightly gentler slopes.

Despite the exacerbated energy of the local relief, a morphodynamic pattern typical of the mountains of the humid tropics, the transmissive capacity of the Serra do Papagaio is significant, and there is therefore little sediment storage in the confined valleys and restricted plains. The aggradational geoforms are restricted to the occurrence of small summit alveoli that are confined between two steep levels that generate ruptures in the continuous connectivity that transfers matter and energy in the system. The transaccumulative zones, therefore, are negligible, being restricted to a continuous sector in the northeastern part of the structure. Thus, the colluvial packages are comparatively restricted to the two structures presented above, dominating the transfer of regolith to the lower domains of the stepped levels of the Serra da Mantiqueira, in the inner rear of the large escarpments.

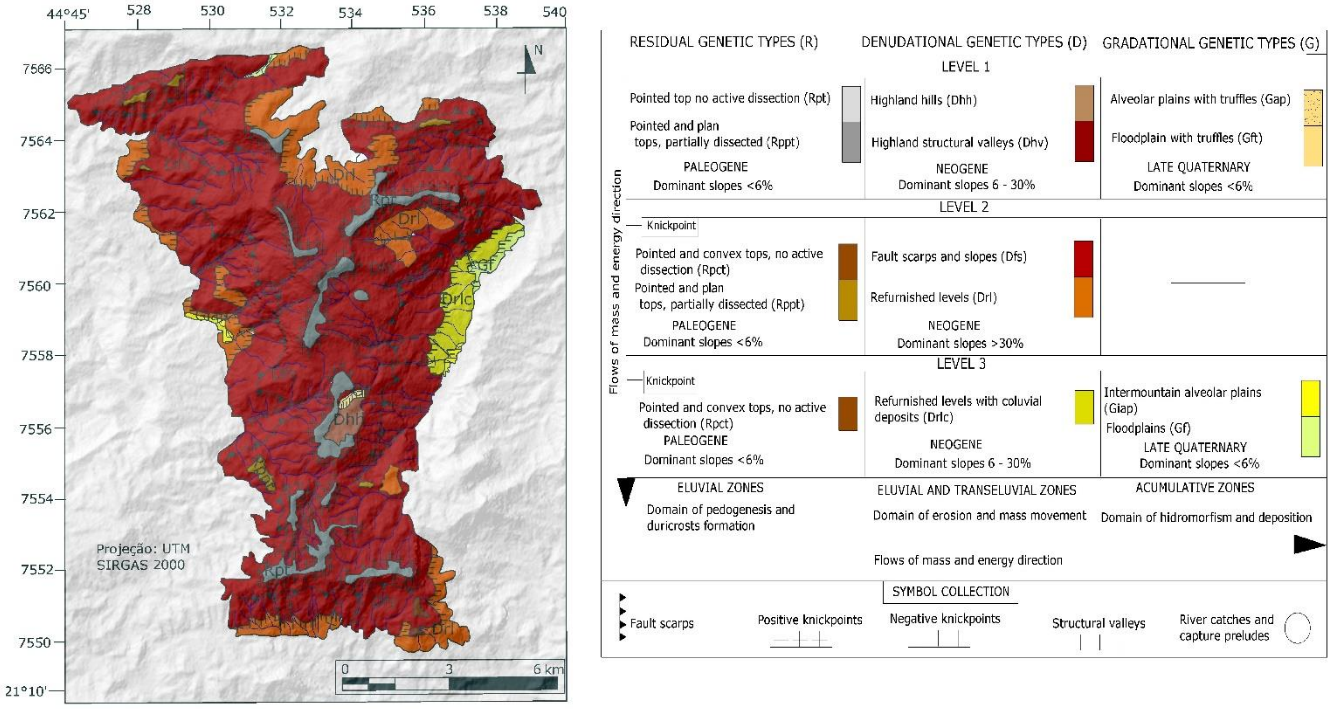

Figure 4. Geomorphological map of the Papagaio mountain range.

5. Discussion

The areas compared by the applications demonstrated here evoke a universality for mountainous geomorphological systems with passive margins, and this universality coexists with the particularities inherent to each of the areas studied, which differ from each other in terms of their general characteristics. Both the universal and the particular elements were highlighted in this proposal for the geomorphological mapping of the types of landscape in question.

The geological differentiation between the three areas compared was a premise, with the geomorphological organizations found being the products of evolutions processed on each of the lithostructural bases: nepheline-syenites, quartzites and gneisses/granites. The convergent evolutionary aspects align with the universal elements concerning tropical mountains, and the divergent evolutions define their particularities.

The main geomorphological convergence between the areas refers to the arrangement in levels proposed by the legend, linked in turn to a macro-compartmentalization characterized by a topographic staircase that has plateau levels flanked and interposed by inter-plateau depressions of both erosive and tectonic genesis. Controlled by well-marked regional base levels, the plateau levels of Eastern Brazil contain mountainous structures that, like the regional landscapes, preserve traces of tectono-erosive organizations linked to different tectonic contexts, resulting in a compartmentalization defined in topomorphological levels that tend towards the pattern revealed in the legend: residual somital surfaces, fault scarps or fault-inherited scarps, and levels reshaped in the form of terraces, ramps, hills, and local interfluves (figure 5). This configuration is convergent, and has already been recognized in other studies focused on the geomorphological systems of the Brazilian passive margin (MARQUES NETO, 2017; MARQUES NETO, 2021), defining fundamental morphological patterns of tropical mountains and their great escarpments.

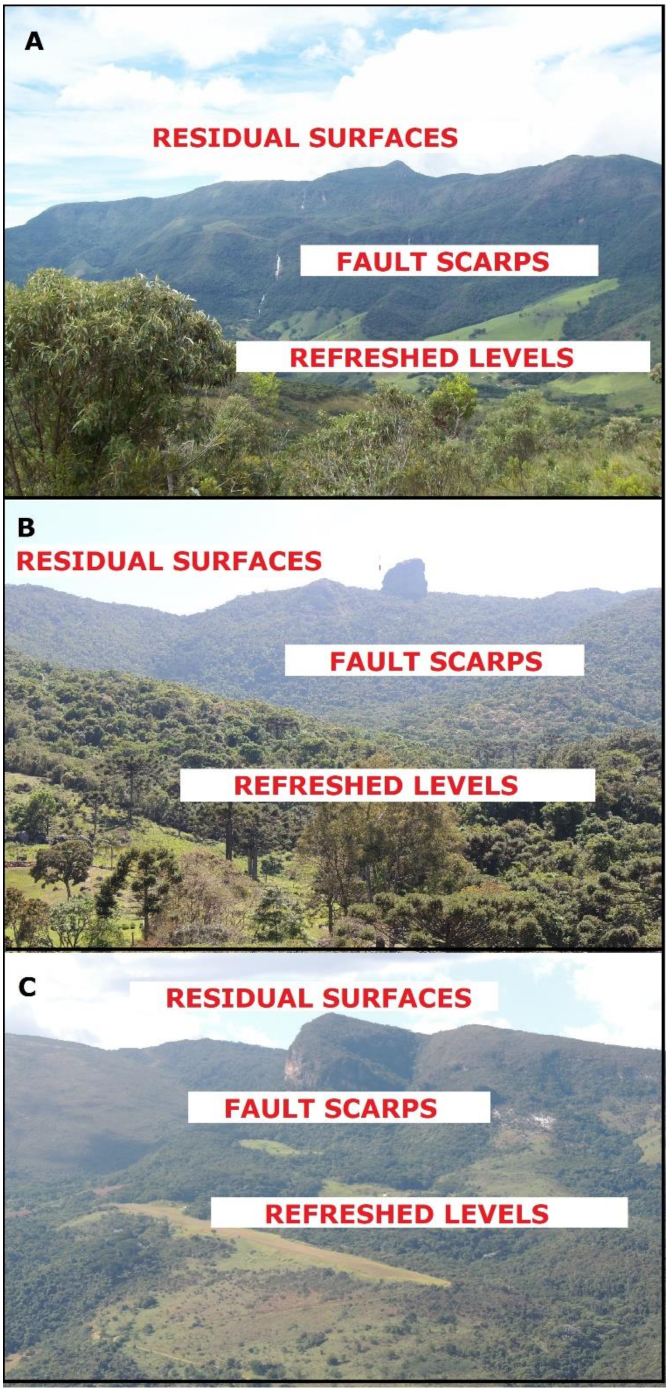

Figure 5. Geomorphological frameworks of the tropical mountains of the Southeast rift margin with well-marked scaling. A) Serra do Papagaio compartment. B) Itatiaia massif compartment. C) Serra do Ibitipoca compartment.

It is also important to emphasize that the pattern mentioned here is repeated at different scales, as shown in the profiles in Figure 6, successive zooms that concatenate the regional context of the compartments analyzed with local configurations. In all views, the geomorphological reality denotes the scaling of blocks in connectivity separated by local base levels, suggesting that the methodological organization presented here can be carried out at different scales. In the field of geosciences, the zoom method is part of the holistic-systemic approaches (FÁVERA, 2001) and can be used both at scales that capture geomorphological organizations, as well as for stratigraphic tracts down to the microscopic scale. In this sense, the legend can also be zoomed in according to the detail of the information contained in the map, as discussed by authors such as Gustavsson and Kolstrup (2006), Otto, Gustavsson and Geihausen (2011) and Jong et al. (2021).

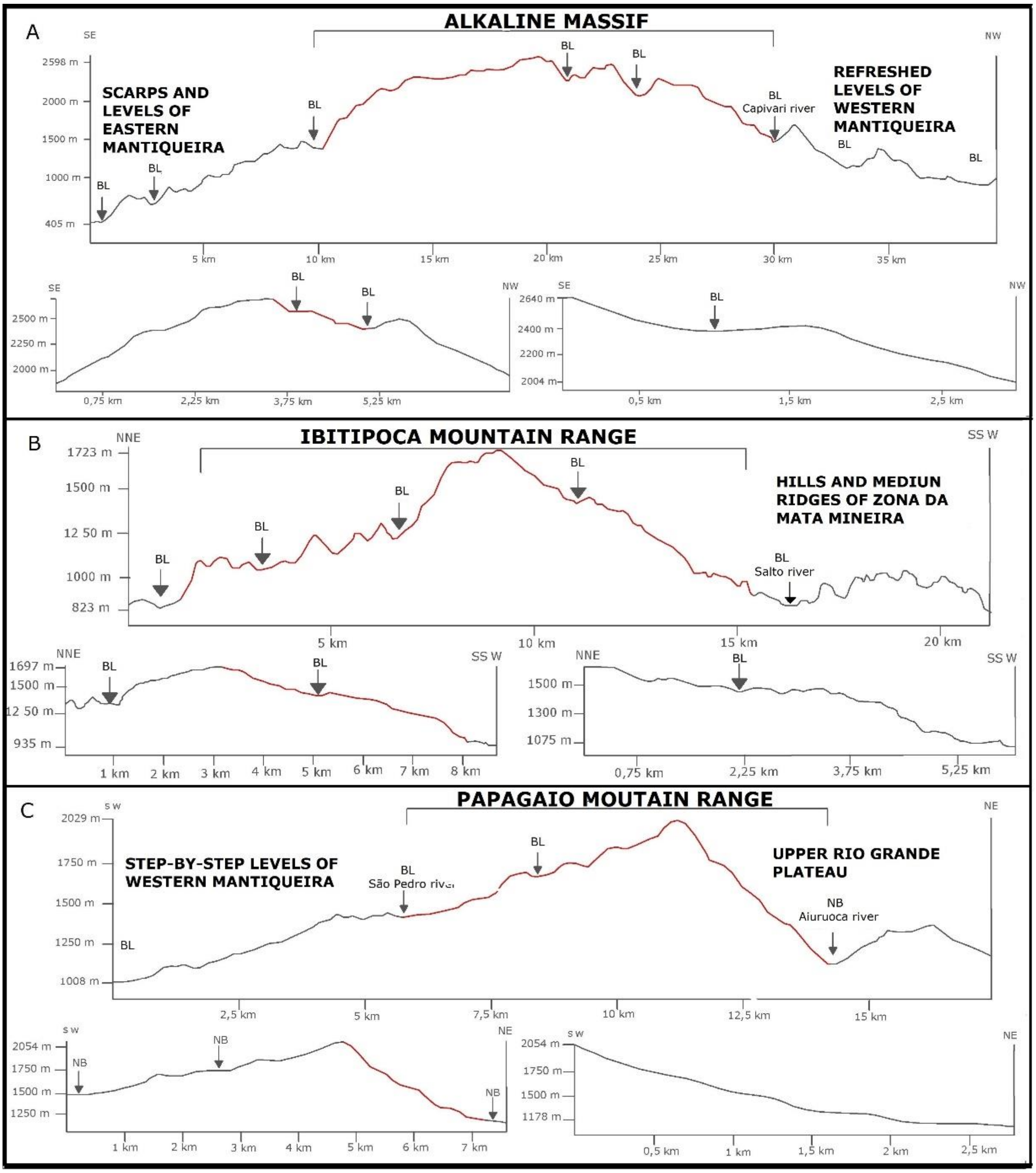

Figura 6. Topographic profiles of the analyzed areas organized in zooms from regional to local. In red, the line corresponding to the most detailed zoom of the subsequent profile. A) Itatiaia Massif; B) Ibitipoca Mountain Range; C) Papagaio Mountain Range. NB – Base levels

In these escarpments, the residual patterns are closely related to the formation of aluminic duricrosts, a supergene process that is absolutely universal in the intertropical belts and is one of the most typical geochemical signatures of hot and humid tropicality. Such formations were recorded in syenitic intrusions (SÍGOLO, 1997; MARQUES NETO, 2012) and other structures linked to the southeastern rift, such as the Poços de Caldas volcanic massif (LEONARDI; LADEIRA; SANTOS, 2010), Serra do Caparaó (SILVA; OLIVEIRA; SOUZA FILHO, 2019) and diverse geomorphological organizations (VALENTON; MELFI, 1988; CARMO, 2004). In general, such formations are relatively dated to the Paleogene, attesting to the high atmospheric CO2 rates of the Eocene. In the Serra de Ibitipoca, although some laterization in quartzites has been detected in the field, it is considered that the support of elevated somital surfaces is essentially due to the resistance of quartzites to chemical attack.

In addition to the role of duricrosts and differential erosion, Neogene tectonics has also been responsible for the uplift of blocks and maintenance of horsts generated during reactivations tangent to the Southeast rift system (MORALES, 2005; ZALAN and OLIVEIRA, 2005). Although the three structures compared here present evidence of neotectonic activity in the relief and drainage, it is in the Serra do Papagaio where such facts are most abundant in the landscape, as has already been demonstrated in previous studies (SANTOS, 1999).

The mountains of tectonic and/or structural genesis support interfluvial surfaces of varying dimensions, alternating sharper sectors and flatter extensions. In general, these summit levels project onto steeply sloping scarps, a morphology that is also omnipresent in tropical mountains. The well-marked laterality between the summit surfaces and the steeply sloping dissection models allows for a standard cartographic representation, with the transition from one compartment to the other clearly marked by a slope break represented by a linear symbol that encompasses all preserved summits. In general, the attenuation of slopes and their rearrangement into steps is a regional pattern that allows for marking with the same linear graphic resource, but inverted.

The unification of the legend, as discussed, was concerned with highlighting the temporal-spatial laterality of the mountains studied. Contacts between the different geomorphological units contained in tropical mountains tend to be established through well-marked knickpoints, as well as these with the lower intermontane surfaces. This configuration has repercussions on the arrangement of the aggradational morphologies, since it implies local base levels that imprison different altimetric levels of Quaternary deposits. This defines a chronology in which the oldest sedimentary archives (neopleistocene) are found in the high-mountain hanging valleys and river terraces, and the most recent in the active plains of the lower levels (Holocene). A relative chronological sequence of Quaternary deposits is also consistent along the levels and laterally within the levels themselves.

The morphogenetic, morphological and morphochronological aspects were adjusted to the recent and current morphodynamic processes based on the symbolized representations. In this sense, the symbols have a transversal function and more flexible use, crossing different morphological and chronological levels of the relief and conditioned by the geometry of the slopes, the fracturing pattern and the climate. Such controls are universal in tropical mountains, landscape types that are unified by their steep morphologies, significant densities of lines of weakness to which dense drainage networks are linked, as well as by the high rainfall volumes throughout the year, increased by orographic rains. Such convergences end up defining symbols to represent the current controls and the associated processes that normally tend to replicate themselves copiously in the mountains of the Brazilian passive margin: fault scarps, structural valleys, captures, focus of mass movements, etc.

5. Conclusions

The search for spatial patterns is one of the fundamental principles of area differentiation, an inexorable route in the interpretation of particularities in their inter-scale relationships with universal landscapes. In this sense, the results show that, for the set of large escarpments with passive margins, emphatically the part that encompasses the so-called tropical mountains, there is a comprehensive geomorphological pattern that in turn demands and admits a methodological organization capable of providing an efficient representation that encompasses the general pattern and the specificities. For the more specific elements, the symbolized representation so used in different methodological systems of relief mapping is crucial, being the main resource of flexibility in unified legends.

Since the difficulty in establishing a general standard for geomorphological cartography is a historical debate, a methodological standardization according to the type of landscape has proven effective. In addition to a broader possibility of combinations and adjustments between cartographic products generated for different areas, it also allows the geomorphological organizations in question to be interpreted from a systemic perspective, referencing the relief in the landscape itself.

Considering the results obtained, the possibility of applying the same methodological approach to different compartments differentiated by distinct lithostructural bases highlights the considerable scope of this proposal for geomorphological mapping for landscapes of large escarpments with passive margins. Furthermore, once the general patterns of relief structuring are recognized based on the connectivity established between the stepped base levels, it allows for application at different scales, without impairing the established logic.

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