Journal of the Geological Survey of Brazil

Geomorphological landscape analysis for the study of surface and groundwater in a carbonate rock environment in northern Minas Gerais, Brazil

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Abstract

The relief is formed by the conjunction of processes that can be influenced to a greater or lesser extent by the morphostructure or morphosculpture, both of which act in the formation of the landscape. This work aims to, through the analysis of relief formation, provide subsidies for the studies of the run-off and the groundwater in an area of carbonate rocks in the north of Minas Gerais. The geomorphological landscape of this area is strongly influenced by morphostructural factors. Such influence is observed in the rectilinear drainage pattern of some rivers, in the presence of structural valleys, in abrupt changes in the direction of drainage net, and in scarps aligned in the same direction of joints and faults present in the area. Such structural influence is quite clear in the southern and central portions of the study area, being less significant in the northern portion, which has a much higher concentration of sinkholes than what was observed in the other areas. Considering a systemic perspective of the processes and dynamics that act on the surface and underground, this work presents these results of the formation of the geomorphological landscape so that such analysis helps in understanding the dynamics of groundwater in this area, as well as the relationship between surface waters and underground.

Article Information

Publication type: Research Papers
Received 28 December 2023
Accepted 24 April 2024
Online pub. 3 May 2024
Editor: Joana Luz

Keywords:
Geomorphological Mapping
Geomorphogenesis
Morphostructure
Karst environment
Water resources
Hydrogeology

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1. Introduction

Geomorphological landscape analysis offers valuable input for studies in various areas, since it is dedicated to understanding morphology, not only in the context of morphosculpture, but also in relation to understanding the formation of such landscapes and their main delineating processes. This effort seeks to understand which forces/ processes act hegemonically in the dynamic equilibrium advocated by Hack (1960), or in what Saadi (1998) calls “sustained disequilibrium”, which forms and modifies the shape of the earth’s surface. In many cases, morphogenetic studies, by uncovering the mechanism that forms the surface model, present a morphodynamic that, from a systemic perspective (Drew 2002), can contribute to understanding processes in other areas of the geosciences. From this perspective, the geomorphological analysis that gave rise to this article is part of a broader study by the ANA (Brazilian National Water Agency) in partnership with the Geological Survey of Brazil (SGB/CPRM) for the implementation of integrated surface and groundwater management in the São Francisco river basin: sub-basins of the Verde Grande and Carinhanha rivers (Simões and Dantas 2024, in press).

This work covers several thematic areas with the aim of advancing knowledge of hydrogeological and hydrological systems in karstic and fissure karstic aquifer domains, in order to understand their water availability and their compatibility with the current use of the resource (ANA, CPRM 2018). Therefore, this article presents the contribution of geomorphological analysis to hydrogeology studies, considering the premise that the processes that lead to the formation of the relief on the surface do not cancel each other out in their influence on dynamics, including water, that occur underground, especially in a region of carbonate rocks.

Integrated studies of groundwater and surface water, based on quantifying the water balance and the effects

ISSN: 2595-1939
https://doi.org/10.29396/jgsb.2024.v7.n2.2
Open access at https://jgsb.sgb.gov.br

of anthropogenic activity on these water resources, have become more popular as the use of water has increased to support agricultural production. Such studies to understand the limit of water resource use capacity start from the premise that groundwater and surface water dynamics do not occur in isolation, as the hydrological system interacts in different ways according to the physiographic and climatic context of each region (Sophocleous 2002). To this end, it is necessary to understand the hydrological dynamics of a given region according to certain characteristics, such as soil permeability, rock porosity, rainfall patterns and topography (Winter et al. 1998; Mesquita and Moraes 2004). In the case of karst areas, due to the complex process of karstification, knowledge of the structural elements becomes central to understanding the formation of conduits, their interconnection and their influence on the interaction between surface water and groundwater.

A study by the ANA (2018) indicates that the São Francisco River and its tributaries receive a significant amount of groundwater in their beds, which helps to keep these watercourses perennial during periods of lower rainfall. However, it is worth noting that this study does not aim to determine how the dynamics between surface water and groundwater occur in the study area, since geomorphology is only one of the variables that can reveal the organization of such dynamics. Furthermore, karst regions are so complex that understanding this interaction is one of the objectives of the project between the ANA and the Geological Survey of Brazil, mentioned above.

Groundwater studies commonly use geomorphological analysis and also reinforce the importance of this topic for analyzing aquifers, including in karst areas. However, the studies that focus on this aspect, such as Salles et al. (2018); Cruz Júnior (1998), mostly concentrate on interpreting the distribution of relief features, such as dolines, on a detailed scale, which is restricted to the analysis of morphosculpture and does not extend to the morphostructural elements that make up the investigation on a regional scale. Furthermore, when dealing with aspects of regional geomorphological analysis, most of the work is based on hypsometry and slope maps and satellite images (Morais 2013; Magnabosco et al. 2020), without exploring the tools for investigating the geomorphogenetic processes of the landscape, especially field analysis. Regional geomorphological studies dedicated to understanding the relief and its relationship with water processes are more extensive in terms of surface water flow (Goerl et al. 2012, Monteiro and Bacellar 2014; Felippe and Magalhães Jr. 2016). Thus, there are fewer studies dedicated to understanding the role of the model and its morphostructural and morphosculptural genesis in the processes that interfere with groundwater, as well as the role of these flows in shaping the geomorphological landscape, as discussed by Gonçalves et al. (2017).

It is important to clarify that this geomorphological analysis initially had a more descriptive bias, in order to provide a map of relief patterns and the morphological description of these patterns, in terms of hypsometry and slope and the favorability of these patterns to water recharge, for the study of surface and underground water flows. However, throughout the work, the characteristics and dynamics of the formation of the relief in the study area showed some peculiarities regarding the process of formation of this landscape and its dissection dynamics. Therefore, delving deeper into these issues proved instigating not only for geomorphology and the possible explanations for the formation of this relief, but also to unravel the persistent questions about the water processes in this karst study area in carbonate rocks, especially with regard to the flow of groundwater.

Therefore, considering that the formation of relief is the result of a combination of processes (Leopold et al. 1964; Christofoletti 1980; Saadi 1998), whether of morphostructural or morphosculptural origin, there is no way to disassociate the role of such processes in the dynamics of underground water flows, which may not be central, but will certainly be an indicator of how the conditions for such flows are configured, especially in a carbonate rock environment, which is widely described as difficult to predict (Goldscheider and Drew 2007).

Given this conceptual scenario, this work is supported by the following hypotheses: (i) the dissection dynamics responsible for the formation of the geomorphological landscape is influenced by morphostructural elements, evident both in relief mapping and in the field; (ii) geomorphological mapping, considering relief patterns and the dynamics that drive such formation, can contribute to groundwater studies in carbonate rock environments.

Based on these hypotheses, the aim of this work is to demonstrate how understanding the geomorphological landscape and its formation processes can contribute to hydrogeological studies in karst formed in carbonate rocks in northern Minas Gerais.

2. Study area

The study area covers portions of the following municipalities in northern Minas Gerais: Montes Claros, Coração de Jesus, Claro dos Poções, Brasília de Minas, Capitão Enéas, Patis, São João da Ponte, Varzelândia, Verdelândia, Jaíba, São João do Pacuí and Mirabela (Figures 1A and B). This area is part of the Verde Grande river basin, extending to areas bordered by the São Lamberto, Pacuí and Riachão rivers, direct tributaries of the São Francisco river (Figures 1A and 1B). Figure 1B shows the large number of river basins that make up the study area. This area is predominantly underlain by carbonate and pelitic rocks of the Bambuí Group (Figure 1C), especially the limestones and metarhythmites of the Lagoa do Jacaré Formation; the siltstones and argillites of the Serra de Santa Helena Formation, as well as these same rocks of the Serra da Saudade Formation. All these geological formations are Neoproterozoic in age and represent a platform cover of low-grade metasedimentary rocks that lie on the São Francisco Craton. On top of the Bambuí Group rocks, the Cretaceous ortoquartzite sandstones of the Areado Group were deposited and, more recently, during the Neogene, the Eluvial-Colluvial Covers were generated (Iglesias and Uhlein 2009).

The development of the geomorphological landscape in karst environments is directly associated with the process of chemical dissolution of these rocks (Stokes et al. 2010; Rodet 2014). The peculiar genesis of these regions makes the study of relief forms more complex, since surface modeling is also the result of a long process of the formation of subsurface water conduits, generating relief forms such as dolines, uvalas and lapiés. The formation of morphology in karst environments is marked by strong lithological and structural control, since the development of typical forms, such as dolines, is usually favored by the secondary porosity of the

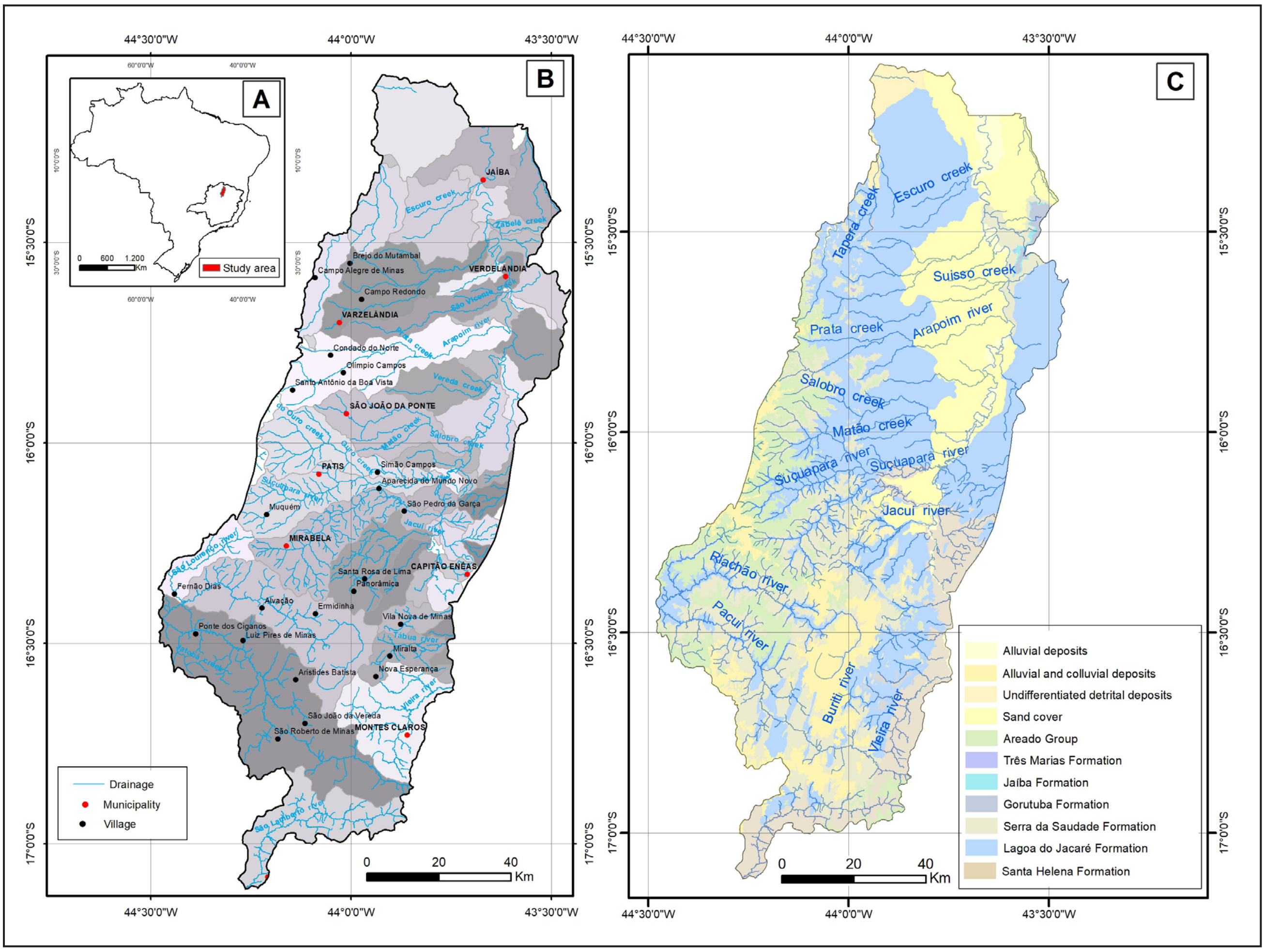

FIGURE 1. A- Location of the area in the state of Minas Gerais and in Brazil; B- Boundary of the river basins in the study area; C- Geological map of the study area (Martins and Cavalcanti 2024, in press). Vector data, such as municipalities and municipal boundaries obtained from the IBGE (Instituto Brasileiro de Geografia e Estatística) database. Hydrography basin data obtained from the ANA (Agência Nacional de Águas e Saneamento Básico) database (https://dadosabertos.ana.gov.br).

rock, such as faults, joints, and bedding planes (Ford and Williams 2007; Piló 2000) through which the gradual process of dissolution of the rock and formation of the relief occurs. This region of the state of Minas Gerais has a history of water deficits and conflicts related to the demand for water use, and the use of groundwater is frequent because, in addition to the high demand, the availability of surface water is scarce and seasonal (ANA 2013). Because it is a karst aquifer, the hydrological and hydrogeological systems are more complex since this type of lithological environment develops a series of conduits and features, which make the circulation between surface and groundwater much more complicated and multifaceted when compared to other environments. Due to these very specific characteristics, the project (ANA, CPRM 2018) which led to the results discussed in this article, extrapolated the boundaries of the Verde Grande river basin when defining the study area, extending to the western portion into areas drained by rivers belonging to other river basins.

3. Materials and methods

The analysis of the attributes of the modeling of the study area was based on the mapping of relief patterns on a scale of 1:50,000, which follows the classification of the Library of relief patterns of the Geological Survey of Brazil (SGB/CPRM) (Dantas 2016; Dantas et al. 2023), which categorizes relief forms according to their aspects of morphology of tops and slopes, amplitude (topographic variation) and slope. In order to identify and classify the relief patterns, a pre-map was produced and interpreted using products derived from the digital elevation model (DEM). The DEM used in the study contains SRTM data, used in the radiometric correction of ALOS PALSAR RTC images, pre-processed by the Alaska Satellite Facility, resampled at a resolution of 12.5 meters (ASF 2015). The following maps were produced with this EAW: slope (intervals: 0° to 3°, 3° to 5°, 5° to 10°, 10° to 30, 30° to 45° and above 45°); hypsometry, with seven class intervals; contour lines, with equidistances of 5 and 20 meters; shaded relief, with artificial lighting azimuth of 315° and slope of 45°. In addition to these products, the interpretation of the relief patterns made use of satellite images available in Arcgis 10.7 from: Esri, DigitalGlobe, GeoEUE, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

In the study area, the preferred morphostructural lineaments were photo-interpreted at a scale of 1: 50,000 on the digital terrain model, considering the ridges and straight valleys, using images with NE and NW azimuths. Once the lineaments had been analyzed, a lineament density map was drawn up using the Line Density tool in Arcgis 10.7 software, which, by generating a raster, calculates the density of lineaments in the vicinity of each output raster cell, the density being calculated in units of length per unit area, in this case km/km^2. The density maps produced in this work used a radius of 2,000 meters to calculate density. This map will show the concentration of preferential lineaments in the study area, helping to assess the relationship between the morphological landscape and the structure.

The pre-field relief pattern map was checked in three field campaigns that took place in 2019: January 29 to February 6, May 28 to June 6, and November 19 to 29. During this field work, in addition to checking the relief mapping, the characteristics of the relief were recorded, in terms of its morphology and structural aspects, geomorphological processes and also the configuration of the drainage net and its most striking attributes. In the final stage, the information from the relief pattern mapping was redefined in the office. An analysis of the formation of the area's geomorphological landscape was carried out, taking into account the geomorphological map and the density map of the study area's preferred lineaments, as well as the evidence of the relief features observed in the field. This analysis produced a combined assessment of the maps of the area, the drainage patterns, together with the information on these same elements observed and recorded in the field work.

4. Results

The geomorphological map (Figure 2C) classifies the relief according to its morphological and morphometric characteristics, with emphasis on slope and altitude variation. Some points will be highlighted throughout the discussion to exemplify the geomorphological analysis of the area. These points are marked on the geomorphology (Figure 2C) and lineament density (Figure 5) maps, as well as on the topographic profiles (Figures 4) with the following numbers: 1- Upper course of the Vieira river basin; 2- Santa Rosa structural valley, near the river of the same name; 3- Cruz stream, a tributary of the Ouro stream; 4- doline area near Jaíba.

The northern sector of the area has the lowest altitudes,

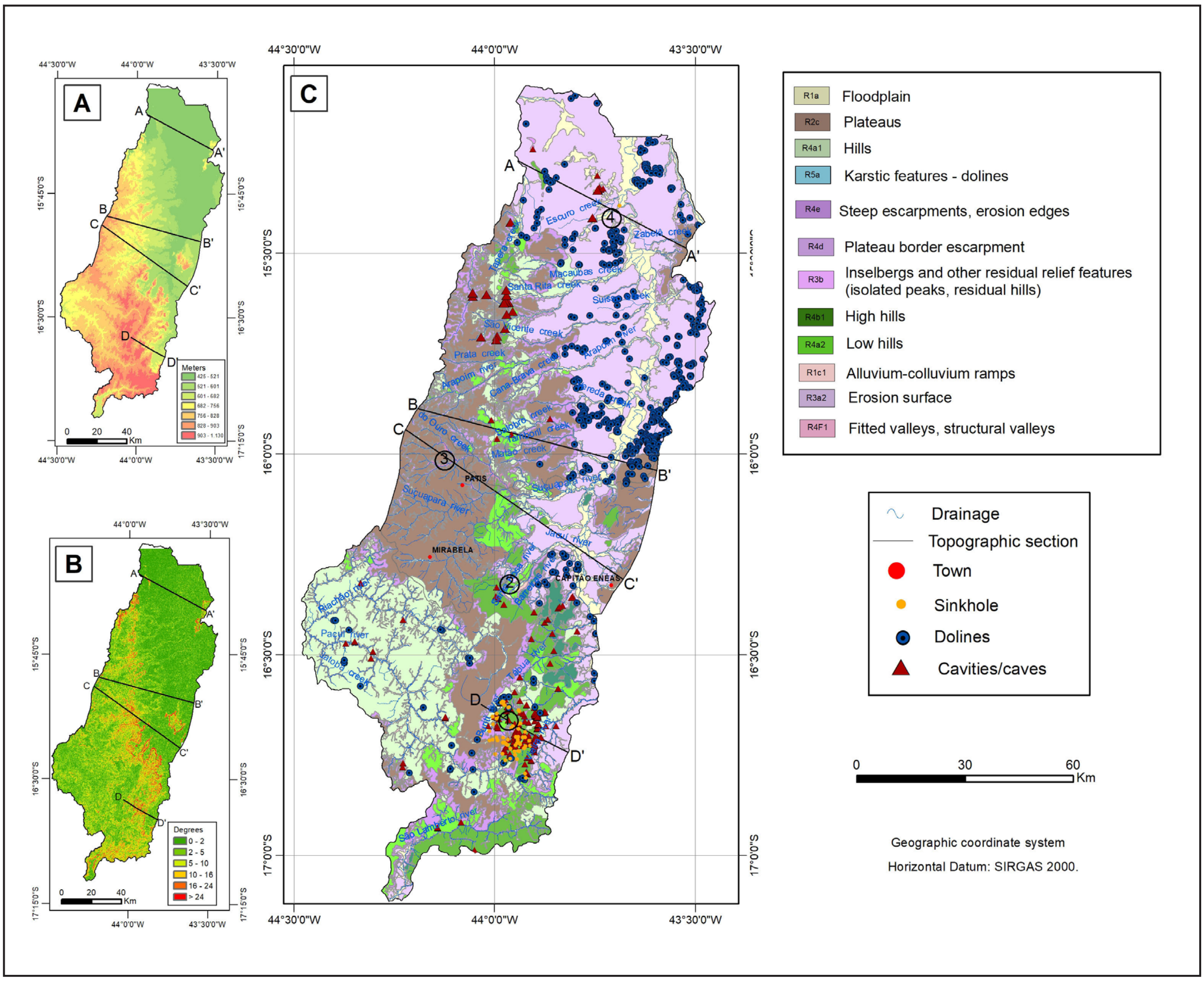

FIGURE 2. A-Hypsometric map of the study area; B: Slope map of the study area; C: Geomorphological map of the study area, classified according to the Library of relief patterns (Dantas 2016; Dantas et al. 2023). The numbers 1 to 4 represent the location of points that are discussed throughout the text in this paper. Vector data obtained from the IBGE (Instituto Brasileiro de Geografia e Estatística) database. Geomorphology data according to Simões and Dantas (2024, in press).

varying between 425 and 521 meters (Figure 2A), which progressively increase in a westerly/southwesterly direction, approaching the interfluvium with the basins of watercourses that are tributaries of the São Francisco River. The highest altitude in the study area, around 950 meters, is to the southeast of the area, at the watershed of the São Lamberto, Pacuí and Vieira river basins (Figure 2A).

Much of the area is marked by low slopes, ranging from 0° to 10° due to the widespread predominance of erosion surfaces and plateaus (Figure 2B), except for some specific sectors, generally consisting of steep steps: to the south, in the São Lamberto river basin; near Montes Claros (Figure 3A), at the headwaters of the Vieira river basin, in the upper reaches of the Verde Grande river tributaries (Figure 3B), along the eastern edge of the study area, the Buriti, Tábua, Barreiras and Santa Rosa rivers (Figure 3C); in the central part of the area, in the middle course of the Suçuapara river basin; extending northwards as a strip, passing close to the municipalities of Patis, São João da Ponte and Varzelândia.

When observing the configuration of the relief throughout the study area, it is possible to highlight zones with different morphological characteristics. The relief in the northern part of the area is marked by an extensive degraded erosion surfaces (Figure 3D; Figure 4, topographic profile A-A') which occurs mainly in the eastern, northern and southeastern portions. This erosion surface is characterized by a gentle slope (Figure 2B) of no more than 5 degrees, which can be extremely flat or gently undulating. This surface, which dominates the eastern portion, is sometimes interrupted by plateaus bordered by short and steep escarpments (Figures 3 E and F), as in the vicinity of the town of Verdelândia. In the western portion of this northern sector of the area, the presence of plateaus is more recurrent, as are escarpments and erosion edges, characterizing a more undulating relief (Figure 4 topographic profiles B-B' and C-C').

As the relief in the southern portion of the study area is analyzed, there is a significant narrowing of the presence of the erosion surface to the east, occupied by hills and an extensive plateau with steep edges at the interfluvium between the Vieira, Pacuí and Riachão river basins (Figure 3A; Figure 4, topographic profile D-D'). This gradual change along the study area, in a north-south direction, will be further discussed in this work in order to better understand the conditioning factors of the relief-shaping processes along this area.

4.1. Morphostructural analysis

Some types of relief on the geomorphological map (Figure 2C) suggest a structural influence on the process of evolution of the regional relief, such as the escarpments (Figure 4, topographic profile D-D'), especially those that occur in the Vieira river basin (located with the number 1), in the southeastern portion of the area (Figure 3A), characterized by being aligned parallel and in a NNE direction, the same preferential direction as the fractures and faults in the area (Cavalcanti 2024, in press; Cavalcanti 2022). The hypsometry map (Figure 2A) shows how the eastern edge in the vicinity of the Vieira river basin presents an abrupt lowering of the relief, decreasing in altitude from around 800 meters to approximately 600 meters, forming a step, which characterizes the escarpments described above. This condition is not restricted to the Vieira river basin but extends from this basin along the eastern edge northwards to the district of Santa Rosa de Lima (located with the number 2). This lowering can be seen in the topographic profiles B-B'; C-C' and D-D' (Figure 4), with the latter showing a steeper altimetric gradient.

The configuration of the drainage network also reveals this structural influence, since it has stretches of drainage with a rectangular pattern, characteristic of areas where the geological substrate is marked by joints, fractures or faults at approximately orthogonal angles, embedded valleys (Figure 3G and H) (Stevaux and Latrubesse 2017). The places where this condition is most evident are in the southeastern and central portions of the study area, such as the upper reaches of the Ouro stream (Figure 3H). Here, not only the source of the Ouro stream (Figure 4, topographic profile C-C'), but also its tributaries, the Cruz stream (located at number 3) and the Pedra Preta stream, show an abrupt change at an angle of 90° in the course of their watercourses. These characteristics can also be seen in other drainage systems, such as those in the Vieira river basin and the Salobro river basin, but in the southern part of the study area, such structural evidence in the drainage network is scarce and punctual.

In the northernmost part, there is a more flattened landscape with a gentle slope and altitude range (Figure 4, topographic profile A-A'), with valleys that are not very dissected (located with the number 4). The drainage network in this area has a dendritic pattern with little evidence of structural control. A karst landscape made up of dolines and sinkholes dominates this region.

Looking at the density map of preferential lineaments (Figure 5C), it can be seen that in some parts of the study area there is a higher density of these lineaments, especially in the following areas: extreme south in the middle course of the São Lamberto river basin; in the southeast in the middle course of the Vieira river basin, extending in a northerly direction to the Tábua, Cana-Brava and Santa Rosa river basins; and extending in an apparently continuous manner in a northerly direction along the middle course of the Jacuí, Suçuapara, Ribeirão do Ouro; Salobro rivers. In the extreme north-northwest of the area, it extends along the upper reaches of the Arapoim river, São Vicente stream and Mutambal stream. These areas of high lineament density are very striking due to the high concentration and the prolongation, sometimes continuous, forming a band, which extends from the Vieira River near Montes Claros to the NNW sector near the town of Brejo do Mutambal. This continuity of the high density of lineaments is very expressive on the map showing the two lineament directions, NE and NW (Figure 5C). It is also important to note that this continuity of lineaments remains persistent when analyzing the maps that show the density of preferred lineaments in these areas separately, in the NE (Figure 5A) and NW (Figure 5B) directions.

It is worth mentioning that although we have several points throughout the study area that express a high concentration of lineaments, sometimes demonstrating geographic continuity, the central portion, in the Suçuapara river basin (located by number 3), stands out as it presents a very high density of lineaments in both preferred directions, NE and NW, concentrating the highest density of lineaments in the study area in this basin (Figures 5A, B and C).

This significant presence of lineaments interpreted from satellite images is confirmed by the field geology works, which report the presence of fractures and faults throughout the study

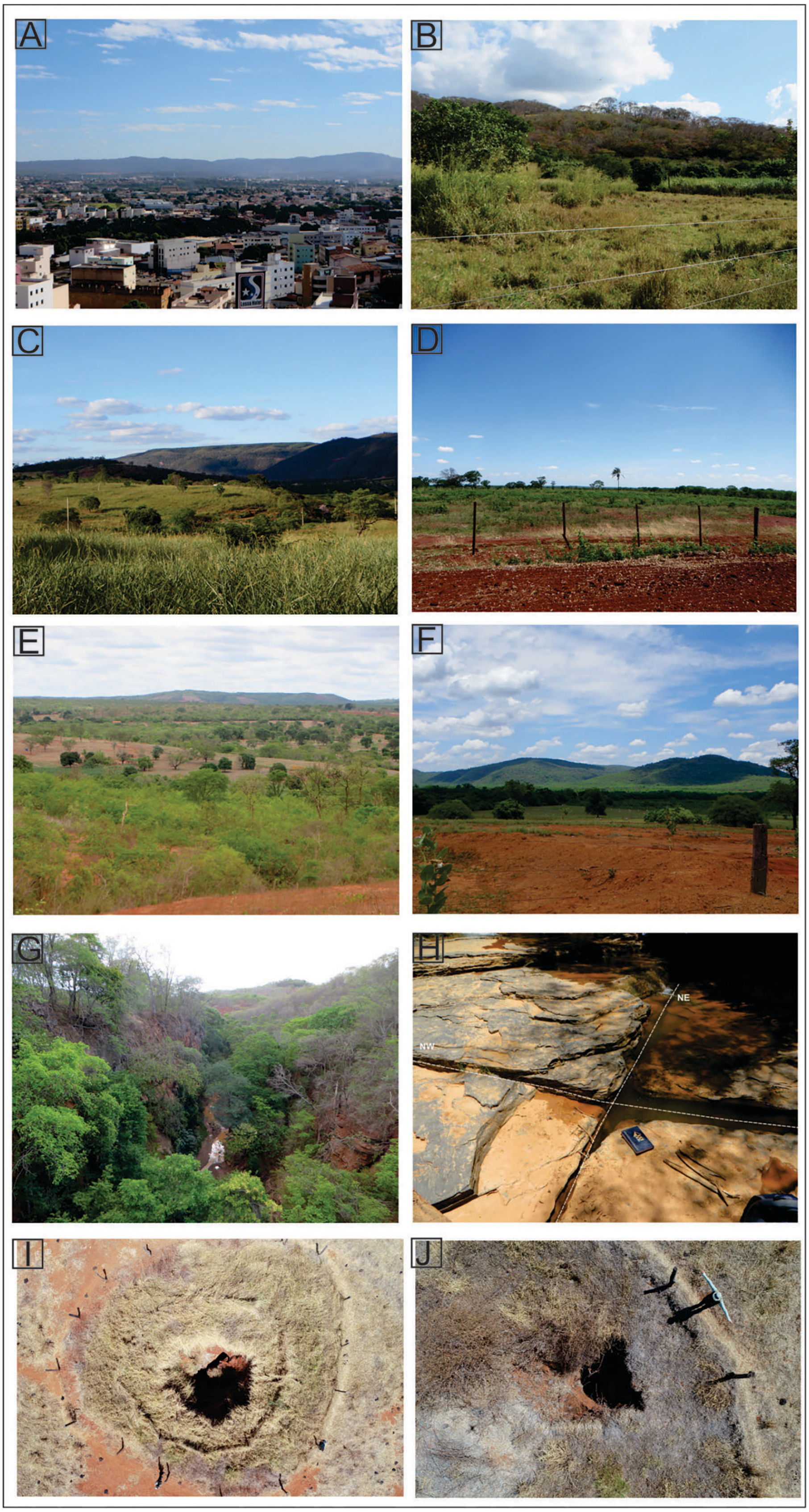

FIGURE 3. Photographs of the study area, A: Steep escarpment stretching in a NNE-SSW direction, located near the urban area of Montes Claros; B: Rio do Cedro, located in the upper reaches of the Vieira river basin; C: Hills and low mountains near the Santa Rosa de Lima river; D: Erosion surface located in the southeast of the study area; E: hills and plateau bordered by short steep steps near São João da Ponte; F: View of plateau along the Tapera River; G: Narrow structural valley in a stretch of the Arapoim River; H: Segment of the Ouro riverbed, with fractures in the NE and NW directions, represented by the white lines; I and J: Dolines photographed by RPA (Remotely Piloted Aircraft) flight, on a farm near the town of Jaíba.

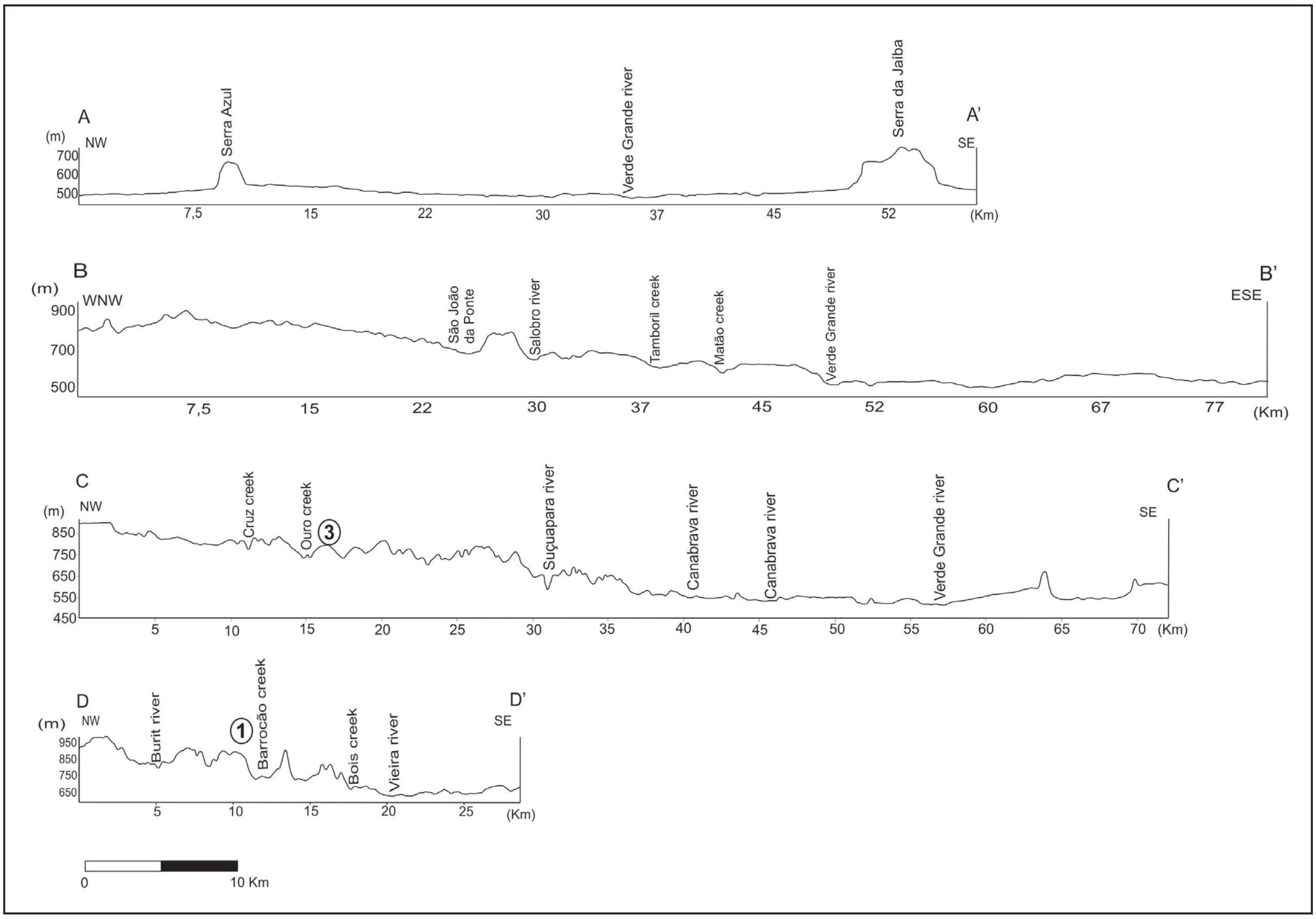

FIGURE 4. Topographic profiles of the study area, A-A': profile of the extreme northern portion of the area, near the town of Jaíba; B-B': profile in the central portion of the study area, in the town of São João da Ponte; C-C': profile in the central portion of the area, near the town of Patis; D-D': profile along the Vieira river basin, near Montes Claros. The numbers 1 and 3 represent specific points that are discussed throughout the text.

area in these same preferred directions: in the southernmost portion of the Vieira river basin in a NNE-SSW direction (Cavalcanti 2024, in press; Cavalcanti 2022); in the central area, along the Salobro river basin, NE-SW to N-S, and also NW-SE (Garcindo 2024, in press). In the northernmost portion, in the vicinity of Jaíba, it occurs preferentially in the NNE-SSW direction and secondary in WNW-ESE and E-W (Brito 2024, in press). This presence of fractures and faults, verified in the field, underlies the massive presence of structural elements in the area and is concentrated in some portions, which are configured as a strip along the area in the SE-NW direction, with some points of discontinuity.

5. Discussion

The study area presents a clear morphogenetic association between the geomorphological landscape and the structural framework present in the region. This association is more noticeable at some specific points, which will be further discussed below (areas highlighted with numbers 1, 2, 3 and 4). These points demonstrate more clearly how the dynamics of the relief dissection process is influenced by the morphostructure.

The upper course of the Vieira basin is marked by the presence of scarps stretching in the NNE direction, and structural valleys, some directed to the NW and others to the NNE, such as the Barrocão stream (1), highlighted in the topographic profile D – D' (Figure 4). In addition to this clear morphostructural evidence in the relief sculpture, the abrupt changes in the drainage courses, such as the Buriti and Tábua rivers, reinforce this influence. When observing the geomorphological map and the topographic profile D – D' (Figure 4), what is revealed is a staggered decrease in altitude in the NW-SE direction, starting from the plateau, the interfluvium between the tributaries of the São Francisco and Verde Grande basins, with approximately 950 meters of altitude to the flat surface located at 650 meters, close to the municipality of Montes Claros. Castro (2008) agrees that the region upstream of the upper course of the Vieira river, in the extensive plateau that corresponds to the interfluvium of this basin with the Riachão river, presents, at the source of the Riachão, a sudden change in direction of the bed towards the NW, indicating a strong presence of structural control. Cavalcanti (2024, in press) highlights in his report the role of structures in the circulation of groundwater through the bedding plane and through the conditioning of fractures N15°E, coincident with the fold axis, and N75°W, perpendicular to the fold axes, being related to the direction of maximum distension. According to the same author, these structures, which condition the circulation of underground water and the

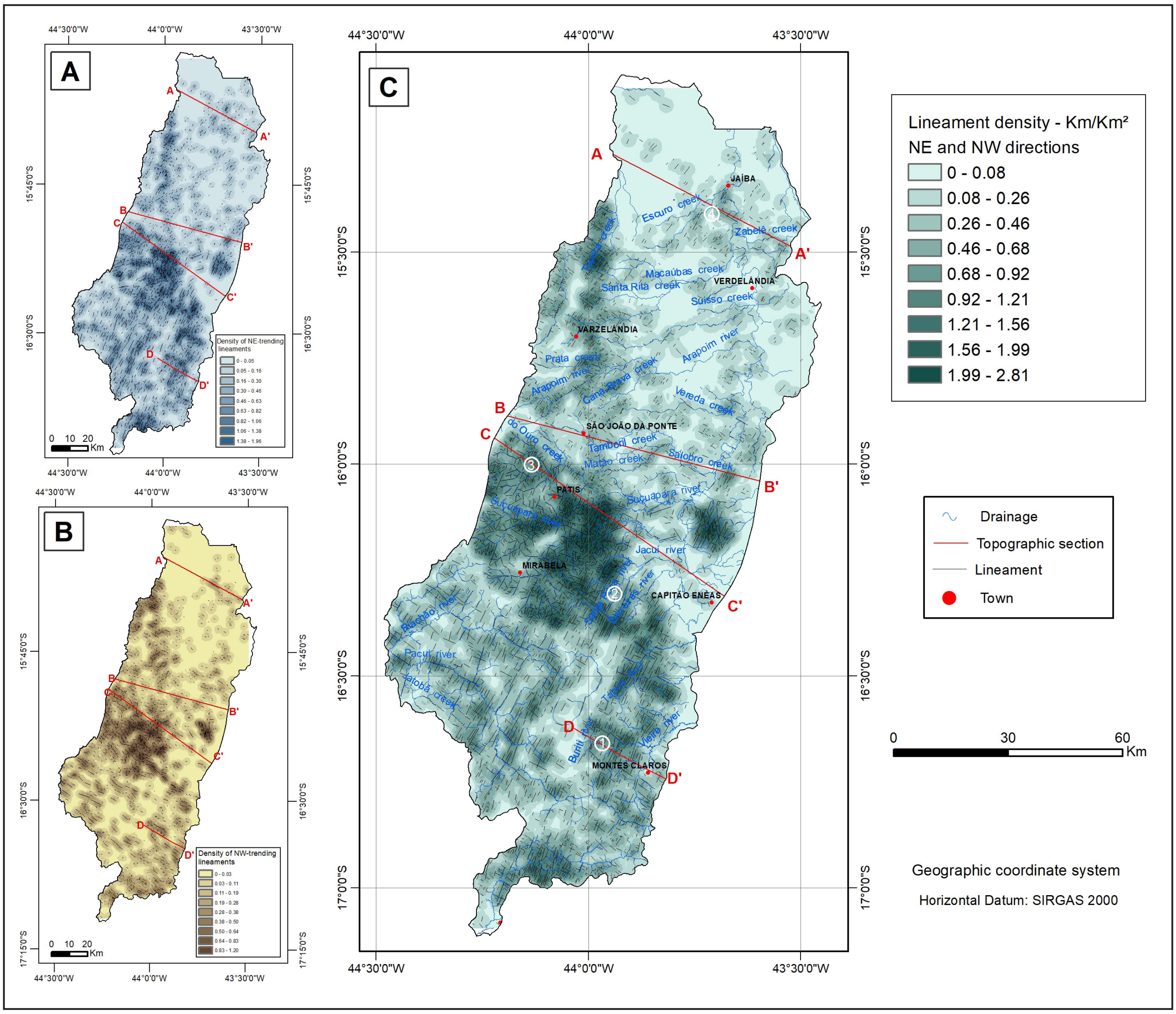

FIGURE 5. A: Lineament density map of the study area, preferred NE direction; B: Lineament density map of the study area, preferred NW direction; C: Lineament density map of the study area, combining the preferred NE and NW directions. Vector data obtained from the IBGE (Instituto Brasileiro de Geografia e Estatística) database. Geomorphology data according to Simões and Dantas (2024, in press).

formation of karst aquifers, are related to the compressive phase of the Brasiliano cycle. It must be considered, although such structures may have been reactivated during the phase of crustal distension, at the end of the Brasiliano cycle, or even in the Cretaceous during the extensional period of the opening of the Atlantic Ocean (Hasui 1990).

The structural valley of the Santa Rosa River, identified on the maps (figures 2 and 5) as number 2, is characterized by the presence of the Santa Rosa fault, which does not stand out markedly on the relief map (Figure 2C), as it is represented by the interruption of the plateau and the presence of high hills and degraded cliffs. However, in the drainage net, there is an abrupt change of direction in the Santa Rosa River itself, from NW at its headwaters to NE from the middle course. This change in direction indicates an influence of this fault, which is described by Martins (2024, in press) as a normal fault and also a strike-slip fault, with a WNW direction. According to the same author, this structure differs from the most commonly described in the region, which are fractures, axial planes, and fold axes in the NNE direction. In the lineament map (Figure 5C) that presents both preferred directions of the study area, this WNW structure is barely noticeable. However, in the map that highlights only the NW direction lineaments (Figure 5C), it is possible to observe a high density in this direction in the Santa Rosa River area.

The course of Ribeirão do Ouro (number 3 in figures 2, 4 and 5) stands out in the region for being one of the few watercourses that remains perennial during the dry period. In its middle course, it is characterized by the presence of a structural valley in the general NW-SE direction, with the presence of emergence along its course. The section of this valley represented in figure 3H is in the N-S direction, and it is possible to observe fractures in the NW-SE and NE-SW directions, which possibly favors the presence of a surge. This fact may be related to the persistence of water flow in this drainage during the dry period. The upper course of this drainage, identified with the number 3, is highlighted on the map in figure 2C, more specifically the confluence between the Ribeirão da Cruz and the Ribeirão do Ouro. In this location, the watercourses have straight drainage with a confluence marked by right angles, which demonstrates a strong structural influence on the drainage. (Bezerra et al. 2001; Maia and Bezerra 2013; Stevaux and Latrubesse 2017). The lineament density map (Figure 5C) shows that this area is contained in a region, in the central part of the study area, with the highest concentration of lineaments, in both preferred directions.

In the northernmost part of the study area, close to the municipality of Jaíba, in an area of sinkholes (Figure 3 I and J) represented by number 4 (Figures 2 and 5), there is an extensive erosion surfaces, with poorly structural valleys (Figure 2C). The topographic profile A-A' (Figure 4) illustrates this landscape characterized by altimetric homogeneity (Figure 2A). This region apparently has less structural influence, and the lineament density map (Figure 5C) shows a lower density of lineaments, with these gradually reducing density from the central portion to the northern portion. A feature that stands out in this area are the sinkholes, which are more abundant in this northern portion when compared to their presence in the southern portion and in the vicinity of Montes Claros. This more significant presence of sinkholes in this area, largely supported by carbonate rocks from the Lagoa do Jacaré Formation, apparently has no direct relationship with the morphostructure in terms of lineament intersection patterns (Carneiro and Mourão 2024, in press); however, more studies are necessary to understand the concentration of the presence of these karst features in this area.

Analyzing the dissection of the relief from a regional perspective, it is observed that in addition to the dissection front represented by the scarps, which divides the zone of plateaus and erosion surfaces, common in this type of morphological environment, there is a second dissection front, at least in part of the study area. This second dissection front occurs in a strip in the N-S direction, morphologically configured as a sequence of hills in the middle of the plateau, which extends from São João da Ponte to the north of Varzelândia. This band of more intense dissection, embedded in the plateaus, presents a high density of lineaments, both on the map (Figure 5C) of the junction of the main lineaments and on the maps (Figures 5A and 5B) that show the density of separate lineaments in the NE and NW directions. In the topographic profile B – B' (Figure 4), this greater dissection can be observed in the plateau, in the vicinity of São João da Ponte, which occurs parallel to the dissection that separates the domain of the plateaus and the erosion surface marked by the presence of the escarpment.

Thus, given what has been exposed, the leading role of structural control in the formation of relief is clear, especially in the southern and central part of the study area. This strong presence of geological structure in the geomorphological landscape is not exclusive to this area, nor even to this type of lithology, and has already been described in other regions of Brazil: Hasui (1990); Lima (2000); Bezerra et al. (2001); Hiruma et al. (2001).

6. Conclusions

This study exposes more explicitly how understanding the processes and dynamics of the formation of the geomorphological landscape offers valuable support for studies in other areas of Geosciences. The characteristics regarding the striking elements in the dissection of the surface modeling expose how the morphostructural elements are active in this region, and, probably, they are also the same for the establishment of the conduits, which understanding becomes essential in the studies of groundwater in rock environments carbonates.

The analysis of the formation of the geomorphological landscape in this area demonstrates that the morphostructural elements are more active in driving the dissection processes, especially in some areas where fractures and faults are more abundant or significant, such as plateaus, edge scarps, structural valleys, or a relief dissected into hills with a predominant trellis or rectangular drainage patterns and frequent channel inflections. It is important to characterize the reflection of morphostructural controls in the landscape. In the study area, it is evident how the structure is more influential on the dissection dynamics in the southern portion of the area, significantly reducing its influence in the northern areas, close to the municipality of Jaíba. Apparently, the Salobro river basin, in the middle part of the study area, is configured as a limit, even if gradual, of the greater influence of the structures present in the modeling of the relief, being more evident and striking in the central and southern portions of the study area. How this influence is reduced or maintained in the dynamics of groundwater, as is the case for geomorphological processes, should be further investigated. However, these findings already point to evidence and hypotheses that the structural dynamics of the area are important in conducting dissection processes and also act in a heterogeneous way throughout the study area. Such processes were certainly not limited to the formation of relief, and are influential in the configuration of the underground flow system. Therefore, geomorphological analysis provides important evidence for direct investigation and understanding of the processes that occur underground.

Acknowledgements

This work became possible due to field observations related to the geomorphology report that is part of the project "*Estudos para implementação da gestão integrada de águas superficiais e subterrâneas na bacia hidrográfica do São Francisco: sub-bacias dos rios Verde Grande e Carinhanha*", a partnership between the Geological Survey of Brazil/CPRM and the National Water Agency – ANA. The authors thank the technical coordinators, Maria Antonieta Mourão and Fernando Carneiro, and the financial coordinator, Natália Lopes. We also thank the anonymous reviewers of JGSB.

Authorship credits

Author	Study design/ Conceptualization	Investigation/Data acquisition	Data Interpretation/ Validation	Writing	Review/ Editing	Supervision/ Project administration
PMLS						
MED						

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