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Geological Field Guide of Montes Claros Karst, Minas Gerais

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Abstract

The Montes Claros Karst is located on the eastern margin of the Bambuí Basin, one of the covers of the São Francisco Craton affected by the Brasiliano Event, which deformed the limestones of the Lagoa do Jacaré Formation, creating a westward folding system and a pair of fractures F1 (NNE-SSW) and F2 (WNW-ESE). These structures control the circulation of water in the limestone massifs, leading to the development of the Montes Claros karst. The main features of the karst landscape are caves, valleys, dolines and limestone massifs. The caves are the best place to observe the main sedimentary facies of the limestones of the Lagoa do Jacaré Formation, as well as sedimentary and deformational structures. The main controls of the cave conduits are the F1 and F2 fractures. These are the same directions described on a regional and local scale, which shows us that the structural control of the exocarst is the same as that of the endocarst. This geological field guide shows in a didactic way the main facies and sedimentary structures of the limestone of the Lagoa do Jacaré Formation, the deformational structures that favoured the karst formation and the typical karst morphologies in limestone rocks.

Keywords: Karst, Speleology, Hydrogeology, Stratigraphy.

1. Introduction

The geological field guide of the Montes Claros karst has as main reference the geological map of the Vieira river basin, in the scale 1:50,000 and the paper “Neoproterozoic-Cambrian structures as a guide to the evolution of the Bambuí karst in the Vieira river basin, Montes Claros, North of Minas Gerais, Brazil (Cavalcanti 2022)” which resulted from the project "Sub-basin of the Verde Grande and Carinhanha rivers: studies for implementation of integrated management of surface and underground waters of the São Francisco river basin". This project was developed by the Geological Survey of Brazil in cooperation with the National Water Agency.

The Vieira river basin covers 579.42 km2 and is located near the boundary between the São Francisco Craton and the Araçuaí Orogen. This limit is represented, physiographically by Espinhaço Mountain Range. The basin is inserted in the domain of the Bambuí Sedimentary Basin that is represented by Serra de Santa Helena, Lagoa do Jacaré and Serra da Saudade formations, that outcrop throughout its extension. In terms of regional setting, the main structure that occurs is the thrust fault that marks the contact between the rocks of the Macaúbas and Bambuí groups. This fault is positioned east of the Vieira River basin, but its reflections are clear in almost all its extension.

The Lagoa do Jacaré Formation outcrops in the western portion, in the karstic domain, where the landscape is marked by the presence of rocky massifs that occur in the form of continuous bands and island massifs, valleys and karstic plains, dolines and a great number of caves, which can constitute springs and sinkholes. The caves are a chapter apart in the region, representing the channels (conduits) through which the underground water flows and their study is indispensable when the focus is on karstic hydrogeology. Besides the water potential, the carbonate rocks of the Bambuí Group are important sources for the production of cement and lime, and can be a source of natural gas, lead, zinc, silver, and fluorine (Misi et al. 2004, Nobre-Lopes 2002, Martinez 2007, Atman 2011, Reis 2011, Alkmim 2018).

2. Geological Setting

The Bambuí Sedimentary Basin (BSB) partially covers São Francisco Craton, occupying an area of 146,000km^2 in the states of Minas Gerais, Bahia, Goiás and Tocantins (Fig. 1). In the northern region of Minas Gerais, the basin is bounded to the east by the Araçuaí Orogen, where outcrop the Macaúbas Group rocks deposited between 750 and 667Ma (Costa & Danderfer Filho 2017, Castro et al. 2020). The Neoproterozoic deformation of the Bambuí Group represents, in this region, the result of the action of the fold-thrust belt of the Araçuaí Orogen, with tectonic transport from east to west. This deformation had a brittle-ductile character and resulted in a system of asymmetric folds verging westward and a set of fractures that control the main karst features in the region.

Figure 1: Map of the geological provinces of Brazil with the location of the São Francisco Craton, the Bambuí Basin and the location of Montes Claros city (map compiled from Schobbenhaus et al. 2022, unpublished).

According Dardenne (2000), the Bambuí sedimentary basin has a record of three sedimentary megacycles. The first megacycle is composed of pelitic-carbonate sediments of the Sete Lagoas Formation, which is a coarsening upward sequence with dark grey to black calcilutite at the base, passing to limestone and dolomite at the top. The second megacycle is composed of pelitic-carbonate sediments of the Serra de Santa Helena Formation, essentially pelitic, indicating a sudden basin subsidence, followed by Lagoa do Jacaré Formation, which is composed of dark grey limestones deposited on a platform dominated by storms and tidal currents. And, the third megacycle is formed by sandy pelitic sediments belonging to the Serra da Saudade Formation, which represent pelitic layers deposited on a sloping platform of medium depth, periodically subjected to storms, arcossian sandstones deposited on a shallow platform dominated by storm currents with easy tidal and supramarine currents of Três Marias Formation.

Currently is considered that the Bambuí Basin sediments were deposited during the Ediacaran-Cambrian time between 550 and 515Ma, over the São Francisco paleoplate that was affected by several tectonic events throughout its geological history, giving rise to Proterozoic rifts, Neoproterozoic fold thrust belts and Cretaceous rifts (Paula-Santos et al. 2015; Reis et al. 2017, Babinski et al. 2019).

In the Montes Claros region, the outcropping rocks of the Bambuí Group are represented, from base to top, by Serra de Santa Helena, Lagoa do Jacaré and Serra da Saudade formations (Fig. 2). The Lagoa do Jacaré Formation, which is the object of the geological guide, is mainly composed of limestones with interlayers of lenses/layers of siliciclastic rocks and marls. It shows faciologic variations along its whole extension, from calcarenite, calcilutites, calcirudites, intraformational breccia and conglomerates, oolitic limestones, stromatolitic limestones and intercalations of pelitic rocks (Fig. 3). Microscopically, were described: calcilutites; thin to medium laminated and banded calcarenites with layers of calcilutites and/or calcirrudites; oolitic limestones; thin to thick calcirrudites; and rare intraformational breccia layers. The records of depositional environments are marked by a large faciologic variation of limestones with predominantly thin and medium, massive, banded with calcilutites and finely laminated calcarenites. The main sedimentary structures documented were: undulating bedding; planar-parallel stratification; planar cross-stratification, trough cross-stratification and herringbone; hummocky, flazer, lenticular and wavy stratification; and horizontal stylolites.

The main ductile structure described are folds that occur in various scales and styles (Fig. 4). In general, they are open on a kilometric scale, representing synformal and antiformal structures with vergence for W to WNW (Fig. 2). The mesoscale folds are usually asymmetrical with the angle of one flank higher than the other, and may even occur when reversing it. They occur mainly in limestone massifs and can reach up to 30 m of amplitude. In outcropping scale, most folds have vergence for W to WNW, making them an important kinematic indicator of the region. The fractures are very pervasive structures in the area studied (Fig. 4). In the limestone of Lagoa do Jacaré Formation predominate four families of fractures: F1 (N10º - 30ºE), F2 (N75ºW), F3 (N40º - 75ºE) and F4 (N20º - 40ºW). The F1 joints are perpendicular to the maximum compression direction and parallel to the axial planes of the asymmetric folds, and the F2 joints are parallel to the main force direction. The F3 and F4 fractures are posterior to F1 and F2 joints (Cavalcanti 2022).

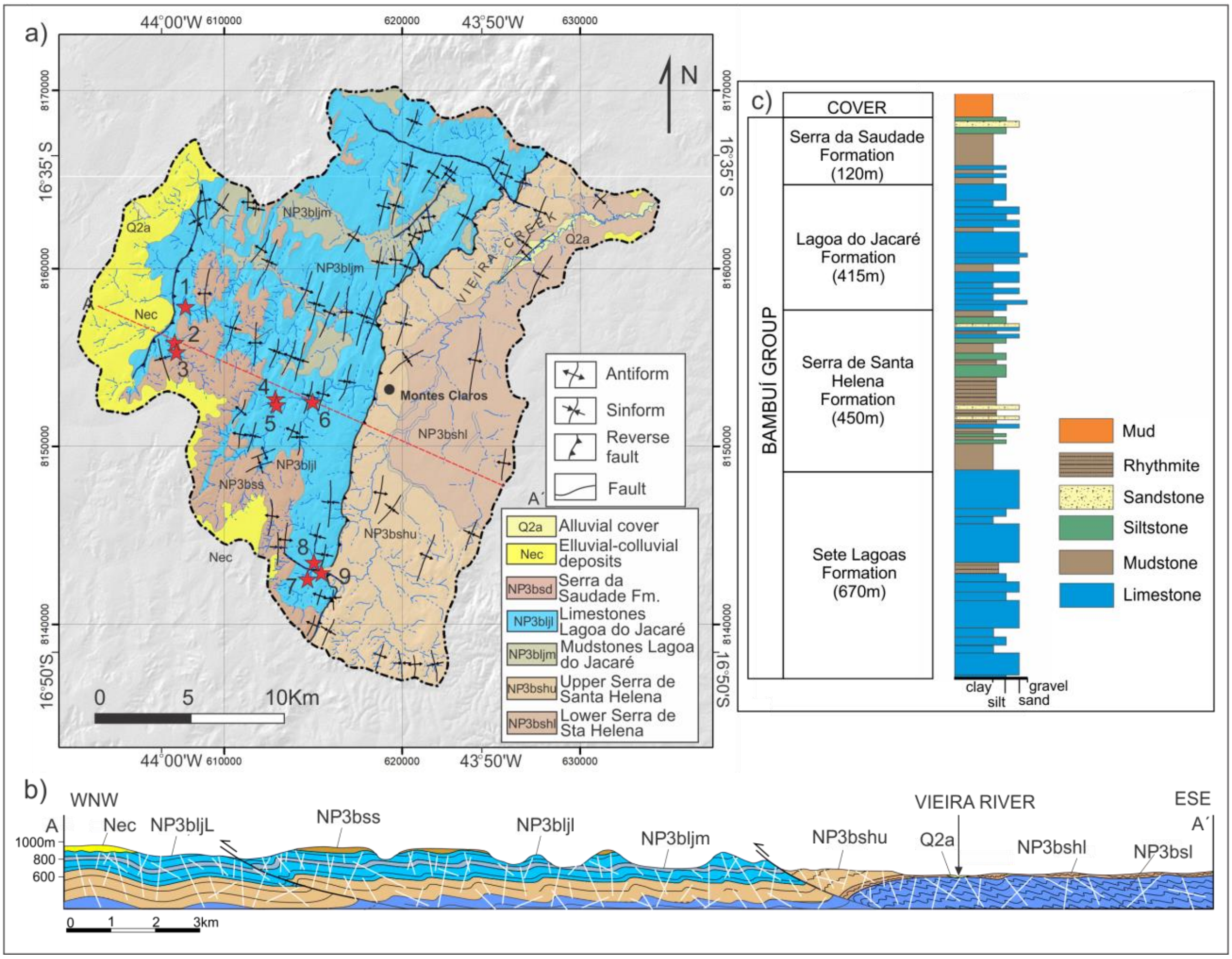


Figure 2: Vieira River basin. a) Simplified geological map with the location of the points described in the guide (map compiled from Cavalcanti 2022); b) geological profile; c) stratigraphic column. Points: (1) Lapa das Andorinhas, (2) Lapa da Claudina, (3) Lapa da Santa; (4) Lapa Grande, (5) Lapa do Boqueirão da Nascente, (6) Lapa d'Água, (7) Cachoeira Tuffs, (8) Vieira River Spring, (9) Vieira River Tuffs.

Figure 3: Main lithotypes of the Lagoa do Jacaré Formation, described in the field. a) thin to medium calcarenite with massive aspect; b) calcarenite with wavy lamination; c) banded calcarenite; d) calcarenite with calcilutite intraclasts; e) oolitic limestone; f) thin calcirrudite; g) stromatolitic limestone; h) limestone with microbial lamination.

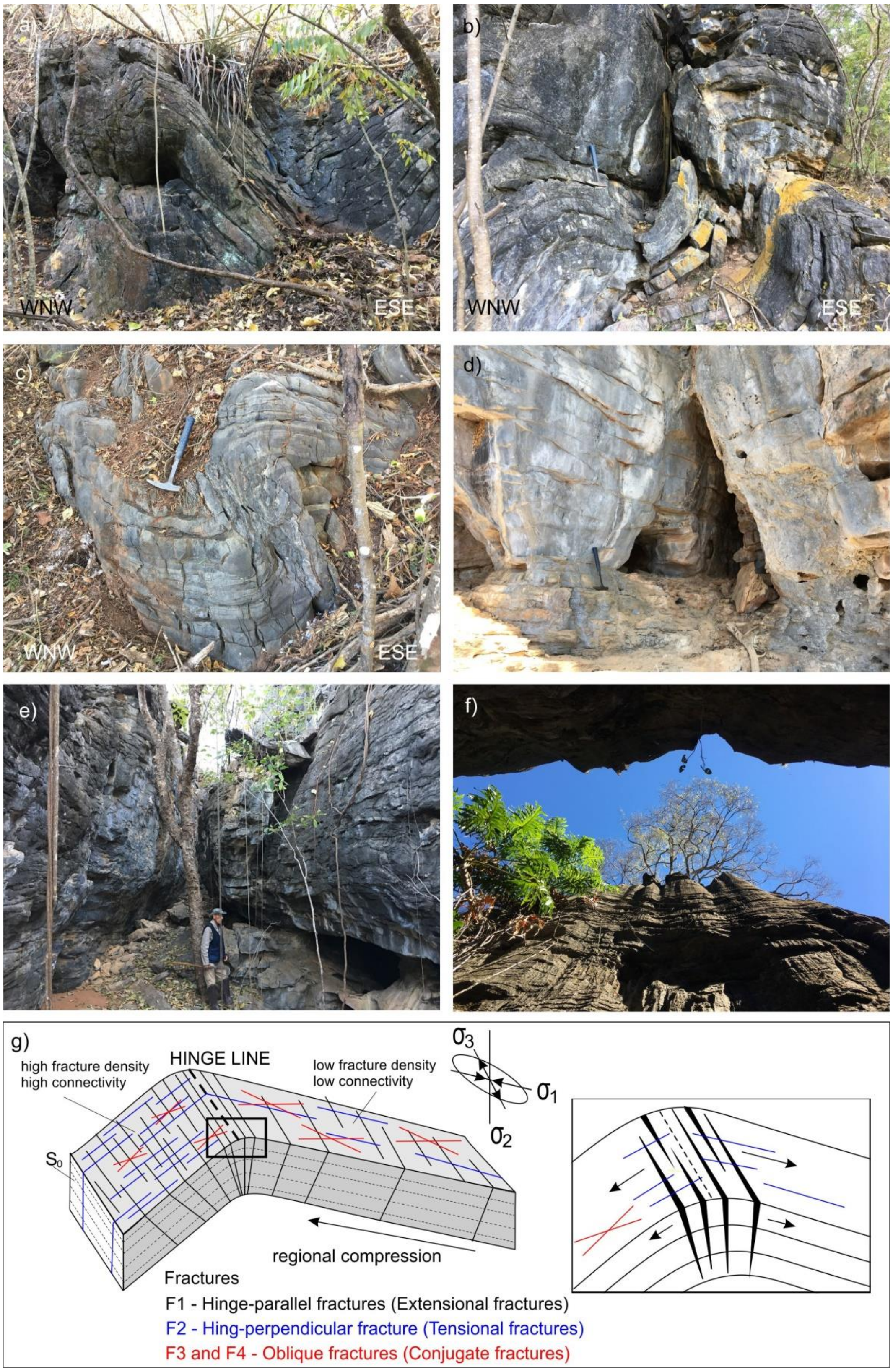


Figure 4: Pictures (a), (b) and (c) the main types of folds; pictures (d), (e) and (f) open fractures; g) joint model associated with an asymmetric fold (adapted from Price 1966, Awdal et al. 2016, Watkins et al. 2017), and in the box detail of the hinge area of the asymmetric fold (based on Jadoon et al. 2007, modified from Stearns 1968, Nelson 1979).

3. Field Trip Logistics

Montes Claros city is located to 422 km from Belo Horizonte, 694 km from Brasilia, 850 km from Rio de Janeiro, 1002 km from São Paulo and 1122 km from Salvador. The main access from Belo Horizonte is highway BR-135. It has an estimated population of 402,027 habitants and area of 3,568,941 km2. It is considered the pole of development of the northern region of Minas Gerais. It has a great infrastructure of hotels, restaurants, bars, supermarkets, and airport (Fig. 5). To make the trip you should stay in the city, where you will have access to quality services and lodging. The airport has daily flights to Belo Horizonte.

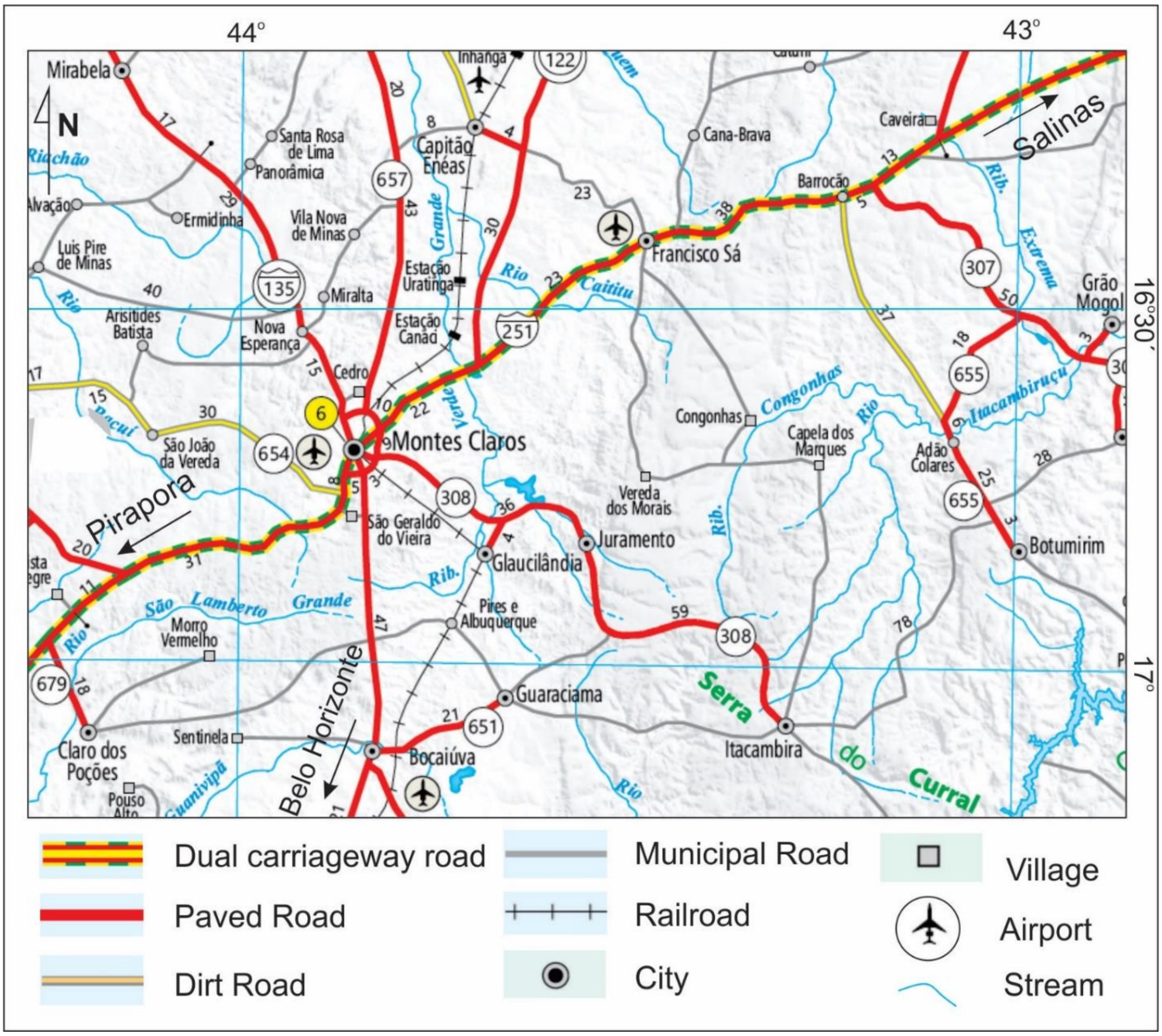


Figure 5: Montes Claros location map. Compiled from Minas Gerais road map (DER-MG, 2021). Available at: https://www.der.mg.gov.br).

4. Outcrops

The main purpose of this geological field guide is to discuss the lithostratigraphic and structural controls of the Montes Claros karst. It will be seen points with: i) main depositional facies of limestones of the Lagoa do Jacaré Formation (calcarenite, calcirudite, oolitic limestone, stromatolitic limestone and intraformational breccias); ii) structures that control the karst (folds and fractures); iii) and karst features, with main focus on the caves of Lapa Grande State Park, Montes Claros, Minas Gerais.

Table 1: Points and routes in the Montes Claros karst.

POINT	COORDENATES		ALTITUDE	DESCRIPTION	ROUTE
	NORTH	EAST			
1	8,157,837	607,814	797	Lapa das Andorinhas	ROUTE 01
2	8,155,716	607,219	825	Lapa da Claudina	
3	8,155,496	607,318	805	Lapa da Santa	
4	8,152,595	612,712	714	Lapa Grande	ROUTE 02
5	8,151,931	612,824	748	Lapa Boqueirão da Nascente	
6	8,152,541	615,043	695	Lapa d´Água	
7	8,143,113	614,940	769	Waterfall Tuffs	ROUTE 03
8	8,142,735	614,713	749	Vieira River Spring	
9	8,143,032	615,323	706	Vieira River Tuffs	

Route 01

This route is located near the Buritis do Campo Santo village, a district of Montes Claros, located in the western portion of the Lapa Grande State Park. The access to the Buritis do Campo Santo village of is by highway BR-135, leaving Montes Claros in the direction of Nova Esperança village (Fig. 6). From there it is an unpaved road for about 15km. Another way is by an unpaved road, from the street that gives access to PELG, for 13km. On this route are the caves Lapa das Andorinhas (Point 1), Lapa da Claudina (Point 2) and Lapa da Santa (Point 3). Besides the caves, along the way, the karst landscape form limestone walls, valleys and dolines. There are also several limestone outcrops of the Lagoa do Jacaré Formation which were described during the geological mapping of the region.

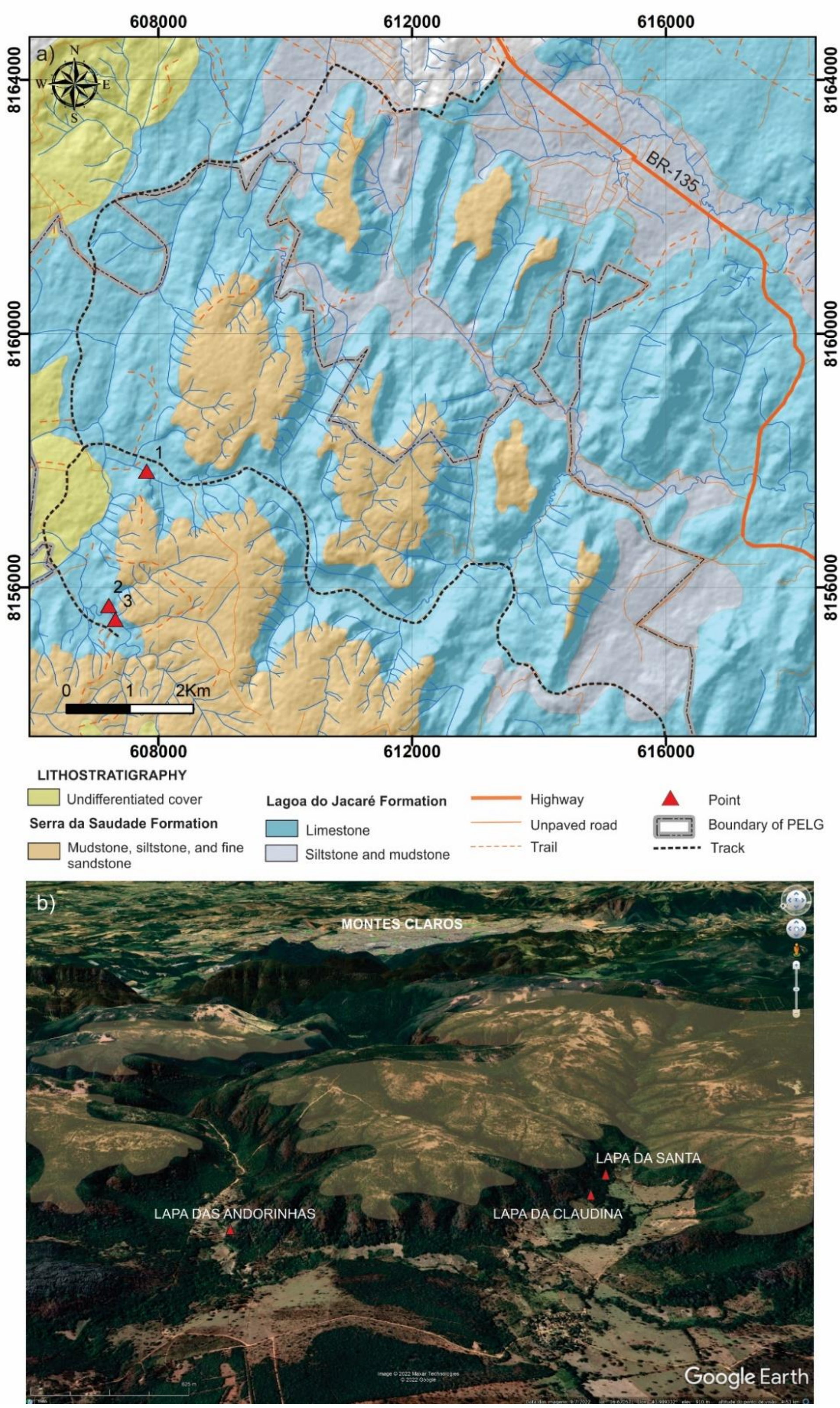


Figure 6: Route 1. a) Simplified geological map with the accesses to the points (1, 2 and 3); b) Google Earth image with the location of the points and delimitation of the Serra da Saudade Formation pelites on the top of the limestones of the Lagoa do Jacaré Formation. Points: (1) Lapa das Andorinhas; (2) Lapa da Claudina; (3) Lapa da Santa.

Point 1 - Lapa das Andorinhas

Lapa das Andorinhas is located at coordinates 607,771 E, 8,157,818 N and altitude of 800m, it has a reticulated (labyrinthine) pattern. The cave floor is horizontal and the conduits have an elongated vertical shape, narrow and very high, controlled by vertical fractures, typical of a cave that developed in a flooded water regime (Fig. 7). The underlying rocks are calcarenites (massive and laminated) and calcirrudites. The collection of sedimentary structures is formed by planar-parallel, planar cross-stratifications and herringbone of médium-sized. The reticulate development pattern of the cave is controlled by fractures (F1) and (F2) (Fig. 8).

Point 2 - Lapa da Claudina

Lapa da Claudina is located at coordinates 607,258E, 8,155,657N and altitude of 825 meters. The cave developed in calcirudite, has a great variety of primary sedimentary structures, such as planar-parallel stratification, planar cross-stratification, channeled and fishbone. Its main geomorphological features are elliptical galleries, domes, roof slopes and thin bark (Fig. 9). In structural terms it is controlled by two sets of fractures. Another feature of the cave is the presence of a high-energy deposit that is configured as an alluvial bedding deposit composed of limestone breccia immersed in a secondary carbonate matrix, over which a thin peel has developed.

The cave has two very distinct structural domains (Fig. 10). In the western domain a reticulated pattern predominates, controlled by a pair of orthogonal fractures (F1) and (F2), typical of a distensional system. On the other hand, in the east domain the cave has a dendritic pattern controlled by fractures of closed angle, fractures (F3) and (F4), where (F3) is coincident with (F1), characteristic of pairs of shear fractures. This may indicate that the cave developed in two different periods. The first phase would be phreatic or hypogene, while the second phase would be flooded water. In flooded water phase also formed a constructive period represented by the remarkable collection of speleothems in the cave. In addition, a clogging phase, marked by high-energy clastic sedimentary deposits (breccia and conglomerates) and low energy, a period when the cave remained flooded, is notable, which is represented by the clay deposits. In certain places, an erosional phase was also observed on the clastic deposits (Fig. 9).

Figure 7: a) One of the Lapa das Andorinhas entrances with pillars controlled by vertical fractures; b) conduit in the form of a warhead; c) medium sized cross stratifications; d) detail of a wall with channeled cross stratification; e) sample of calcirudite which is the main rock of the cave; f) layer of intraformational breccias in the calcarenite.

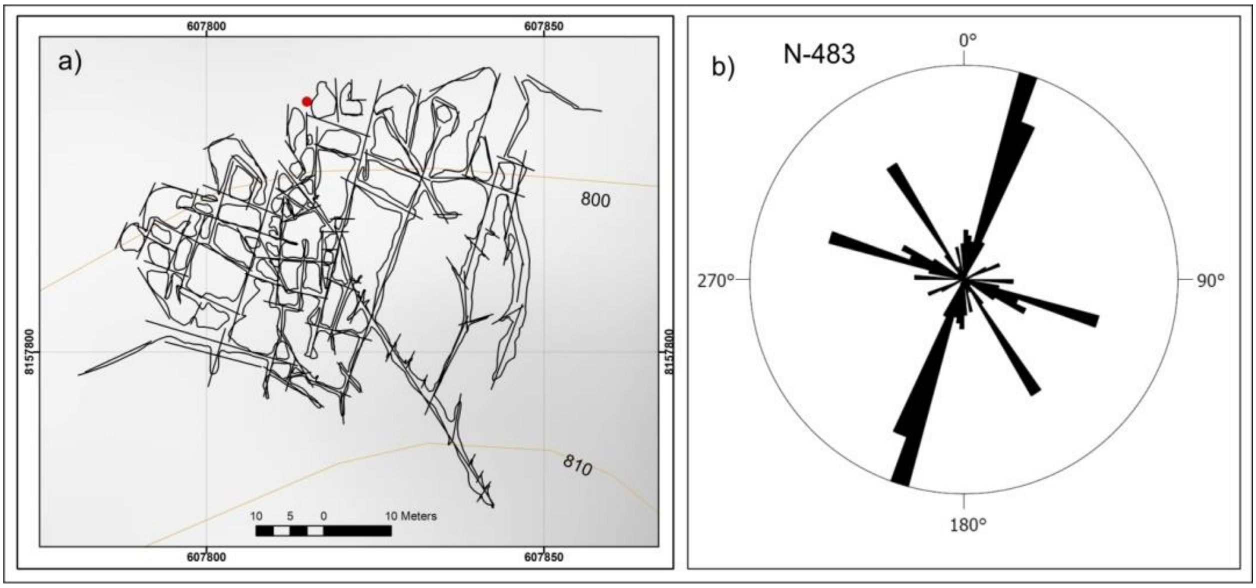


Figure 8: a) Simplified map of Lapa das Andorinhas with interpreted lineaments; the red point is located at one of the cave entrances. b) Rosette of fracture directions and lengths.

Point 3 - Lapa da Santa

Lapa da Santa is located at coordinates 607,449 E, 8,155,401 N and altitude of 810 meters and has a meandering linear development pattern. It is an intermittent spring of the Bois creek, in the region of Buriti do Campo Santo village. It is a typical cave of hypogene environment, with few speleothems and galleries with elliptical shapes containing many pendents, domes and bedforms on the ceiling (Fig. 11). Along almost the entire length of the cave there are clastic deposits (clayey and conglomeratic) marking epochs of flooding and erosion. The development of the cave appears to be controlled mainly by Fractures (F1) and (F2) (Fig. 12).

Figure 9: a) Entrance of Lapa da Claudina showing the plane of the bedding (S0) in the background and highlighting the area of photo (b); b) channeled cross stratification; c) planar cross stratification; d) horizontal stylolites in the calcirudite; e) detail of the calcirudite, the main rock of the cave; f) swarm of calcite veins; g) pendants indicating water flow under pressure and the erosion of clastic deposits revealing the flooded water phase inside the cave; h) clogging level of the cave.

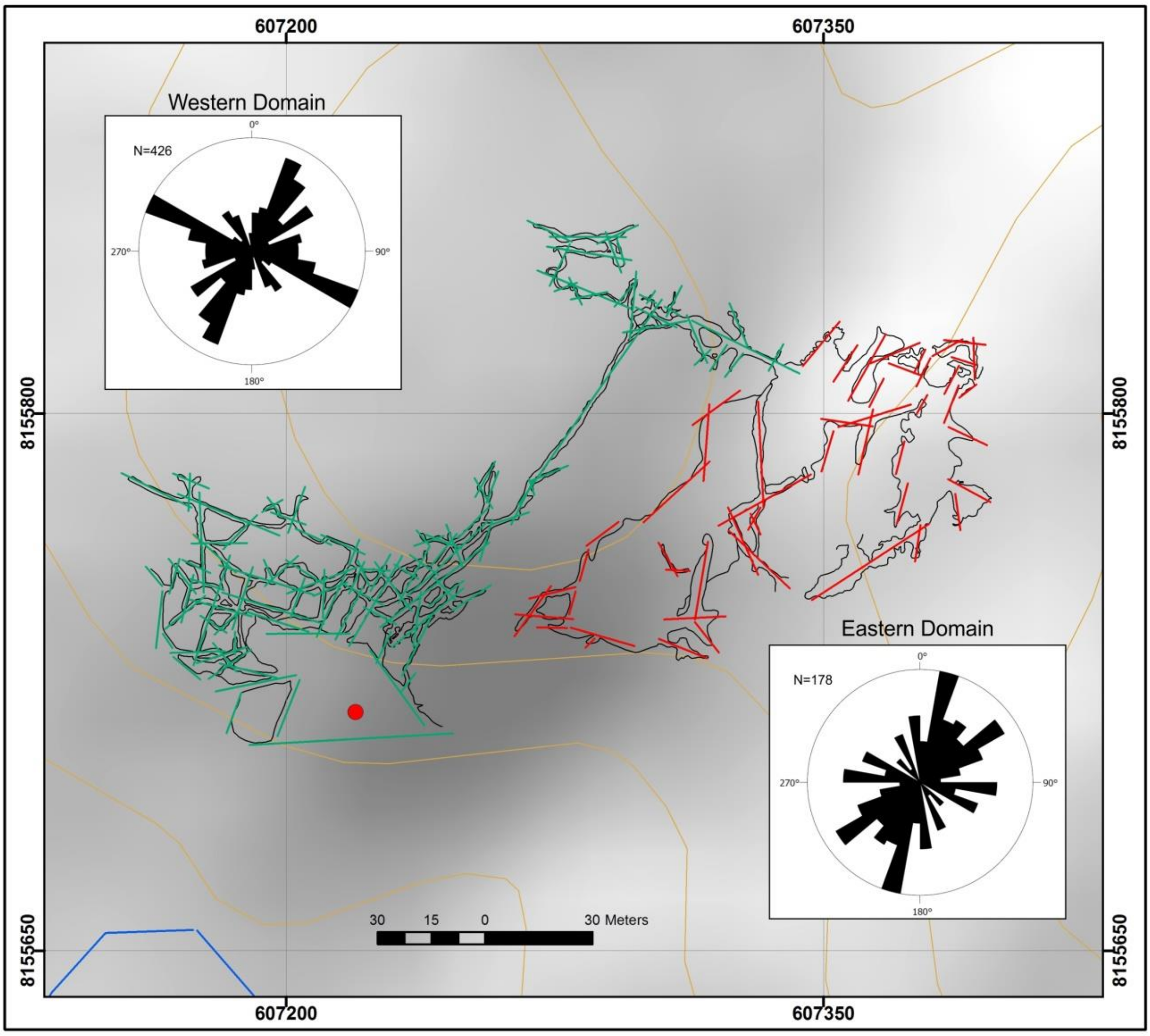
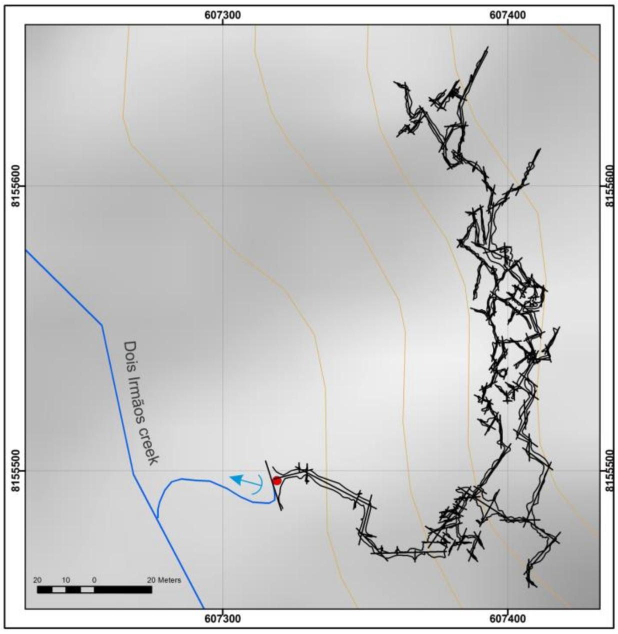


Figure 10: Structural domains of Lapa da Claudina and the rose diagrams of the frequencies of the interpreted lineament directions.

Figure 11: a) Entrance of the Lapa da Santa where the (dry) stream channel can be seen in the center and the clastic deposits on the edges; b) detail of the thin calcarenite with cross stratification; c) detail of a calcirudite layer that occurs intercalated with the thin calcarenite; d) detail of a stromatolite fragment immersed in the matrix of the thin calcarenite; e) conglomeratic fouling level; f) conduit with mud clogging level; g) roof channel shape; h) elephant foot shaped pendants.



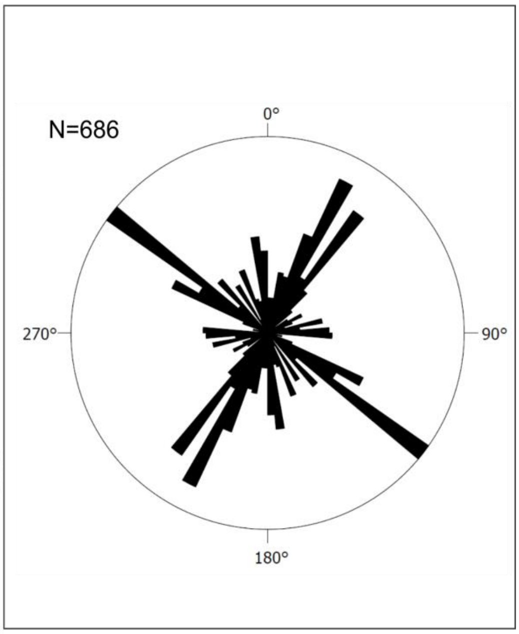


Figure 12: Simplified map of Lapa da Santa; b) rose diagram of fracture directions. The red dot is located in the cave entrance hall.

Route 02

On this route are the caves Lapa Grande, Lapa do Boqueirão da Nascente, and Lapa da d'Água, located near the Visitor Center of the Lapa Grande State Park (PELG) (Fig. 13). The access to the park's entrance is through Manoel de Souza Brasil Avenue. The PELG has several attractions, among which are the caves of this route. The highlight of the park are the giant pearls, more than 20cm in diameter (Cavalcanti et al. 2022). Other attractions are the Lapa Pintada, the Ponte de Pedra and the limestone tuffs of the Lapa Grande creek with its crystal-clear waters.

An interesting point in the PELG is the viewpoint that is located on a plateau sculpted in the rocks of the Serra da Saudade Formation. From the viewpoint one can observe the entire geology and geomorphology of the region. The main view is to the east, where you can see the foothills of the Espinhaço Mountain Range where the rocks of the Macaúbas Formation outcrop, the Montes Claros Mountain Range (or Mel Mountains) and the residual hills of the limestone of the Lagoa do Jacaré Formation, with strongly karstified limestone, forming islands in the middle of the valleys. To the west, the relief of gentle hills where the pelitic rocks of the Serra da Saudade Formation.

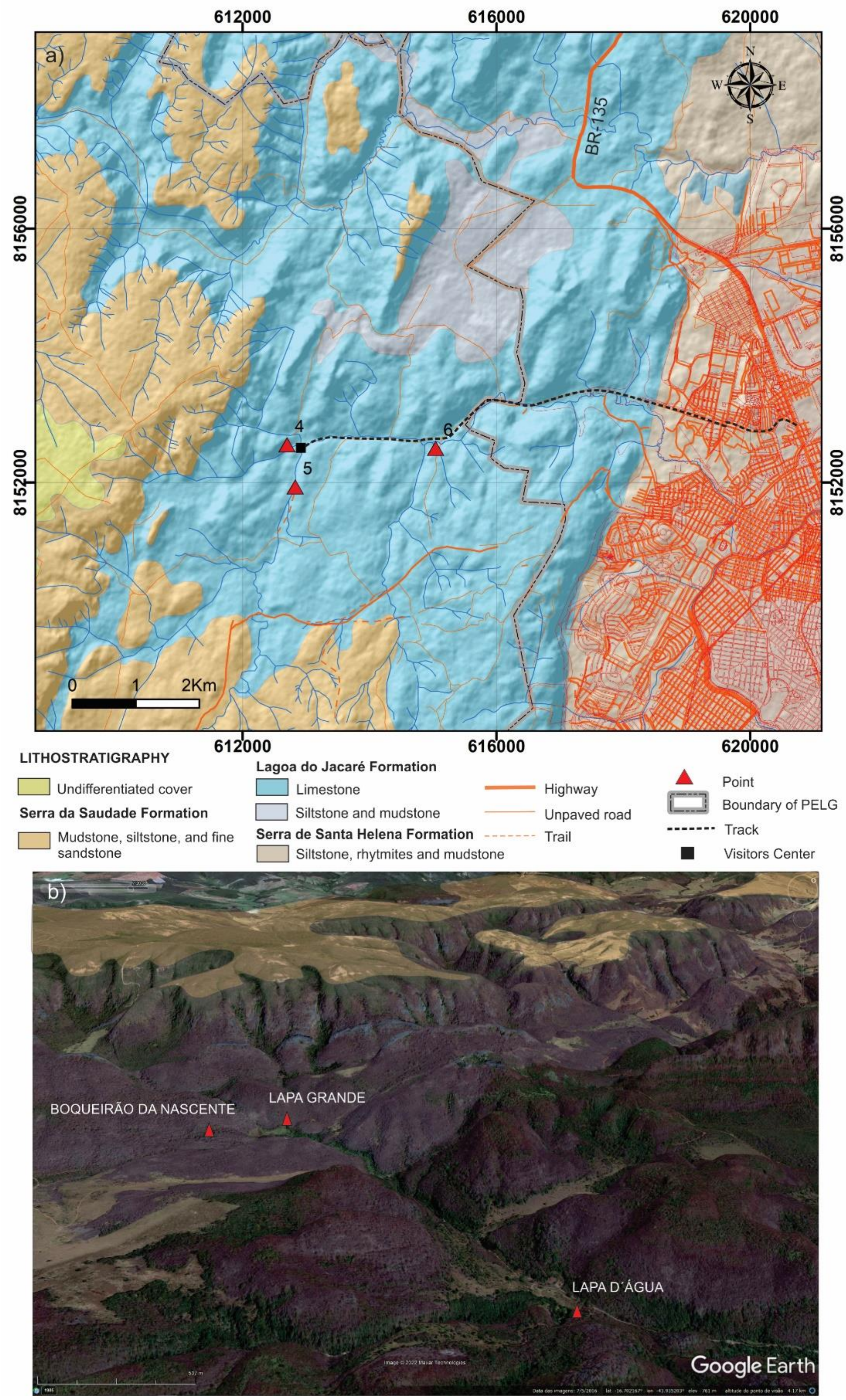


Figure 13: Route 2. a) Simplified geological map with the location of the points (4, 5 and 6); b) Google Earth image in perspective with the location of the points and delimitation of the pelitic rocks of the Serra da Saudade Formation on the top of limestones of the Lagoa do Jacaré Formation. Points: (4) Lapa Grande; (5) Lapa do Boqueirão da Nascente; (6) Lapa d´Água.

Point 4 - Lapa Grande

Lapa Grande is about 2,200 meters high and is located at coordinates 612,699 E, 8,152,595 N and altitude 710m. The rock is dark gray, fine to medium grained calcarenite, with calcilutite intercalations. The main structures described were planar-parallel and planar cross stratifications, fractures and drag folds with westward vergence with the axial plane parallel to the fracture (F1). Fractures (F2) and (F4) together with the bedding plane (S0) control the main development of the cave, but there are some galleries developed in the directions of fractures (F1) and (F3) as can be seen on the cave map and fracture rose diagram (Fig.15). The cave has a linear development pattern, with meandering and reticular galleries (Fig. 14).

Point 5 - Lapa do Boqueirão da Nascente

Lapa do Boqueirão da Nascente, its name indicates, is a spring, located within the limits of Lapa Grande State Park (Fig. 16). The Boqueirão complex has several points where it presents itself as a sinkhole and a resurgence of the Lapa Grande creek, and the underground sections are known as: Boqueirão de Cima (sinkhole), Boqueirão do Meio and Boqueirão da Nascente (resurgence), from upstream to downstream (Barbosa et al. 2015).

Lapa do Boqueirão da Nascente has a linear shape controlled mainly by the F1 fracture of NNE-SSW direction, with an approximate length of 450 meters (Fig. 17). The stream runs through the entire length of the cave on a permanent regime and flows into the Lapa Grande creek. It has three halls with areas covered by a stalagmitic floor and the most common speleothems are stalactites, stalagmites, oozings, coralloids, columns, curtains and travertines.

Figure 14: a) View of the Lapa Grande entrance, from inside to outside, showing fracture control (side walls) and bedding (the ceiling); b) view of the side wall and ceiling where the limestone exhibits drag folds with axial plane parallel to the F1 fractures (NNE-SSW); c) limestone witness block exhibiting the fracturing pattern that controls the direction of the conduits; d) calcarenite of the cave entrance; e) thin skinned on deposits of terrigenous sediments; f) fold in the calcarenite with westward vergence. Photos (d) and (e) by Eduardo Gomes.

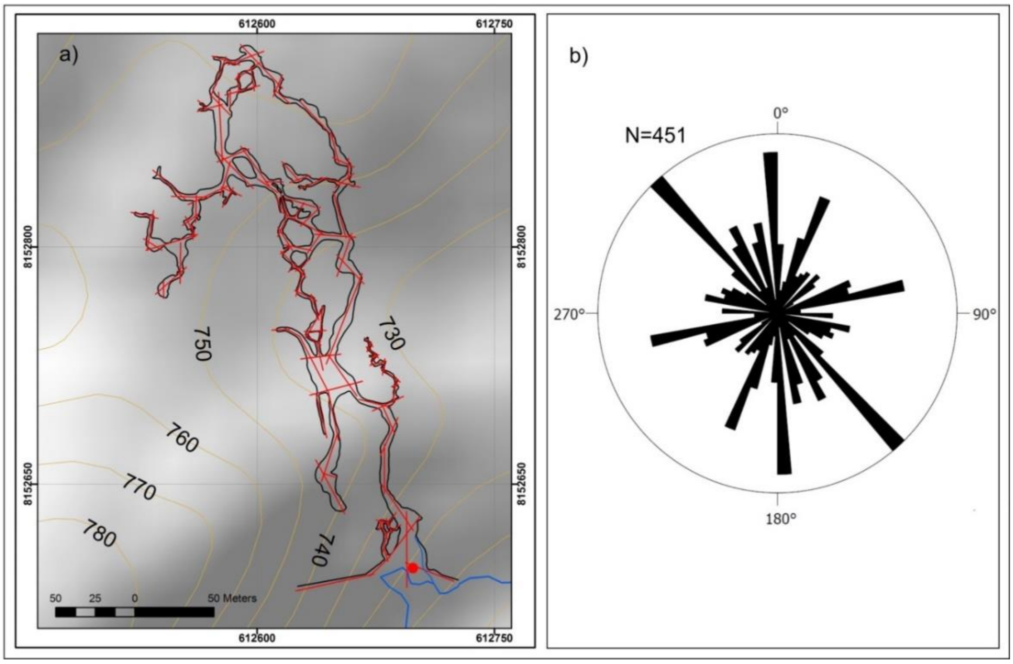


Figure 15: a) Simplified map of Lapa Grande with interpretation of fracture patterns; the red dot is located in the cave entrance hall. b) Rose diagram of fracture directions (Speleological map compiled from Barbosa et al. 2015).

Point 6 - Lapa d´ Água

Lapa D'Água is located near the entrance of Lapa Grande State Park, at coordinates 615,044 E, 8,525,542 N, it is approximately 1,234 meters long and has a 17-meter difference of level, its entrance is positioned at an elevation of 737 meters, in the limestones of the Lagoa do Jacaré Formation (Fig. 18). The predominant rock is medium-gray calcite limestone, with parallel wavy lamination, decimetric levels rich in intraclasts and also styloliths. Locally the rock presents decimetric cross stratifications, linsens laminations, drag folds and small faults. The decimetric fold axes control the direction of some conduits, mainly the one in the cave's final room.

The cave has a linear development pattern, conditioned mainly by the F1 and F2 fractures and also by the bedding (Fig. 19). The cave develops in a conduit with a meander-like geometry. One of its entrances is the drainage of the São Marcos stream, which runs underground through an unexplored and unmapped section because it is flooded most of the year. In the interior of the cave were observed perennial watercourse with siphoning at the end of the second level (Barbosa et al. 2015). The cave has many speleothems among which stalactites, stalagmites, curtains and travertines were described. But an unusual speleotheme found in the cave has drawn attention from researchers, the giant pearls.

Silva et al. (2003) described the pearls at Lapa D'Água. They occur right at the entrance hall which is about 70m in horizontal development by 20m in width and a maximum height of 5m. They cover much of the floor and many have been exposed by saltpeter mining excavations. On site, pearls up to 27 cm in diameter were measured.

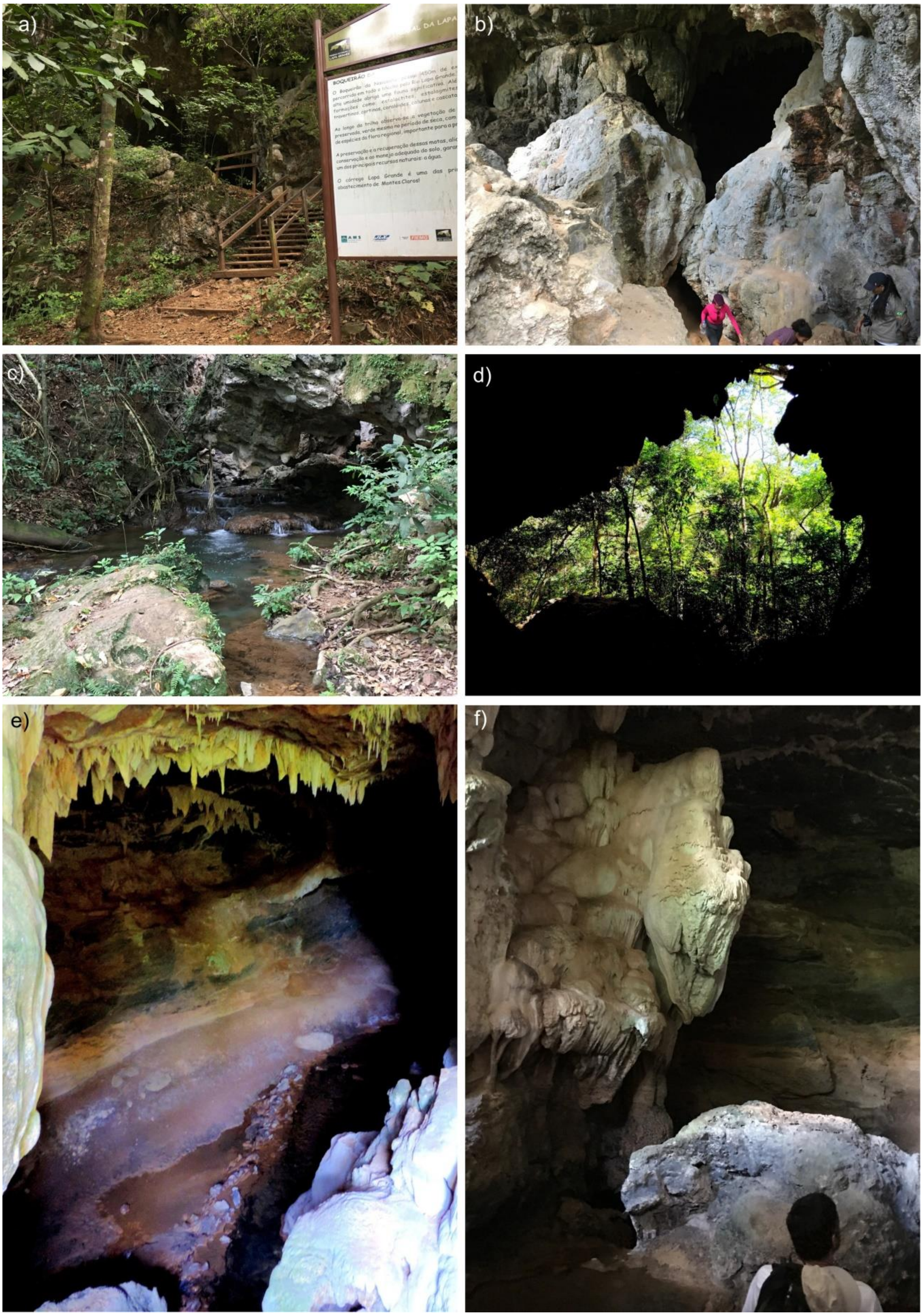


Figure 16: a) Main entrance of the Lapa do Boqueirão da Nascente"; b) detail of the entrance, seen from the top of the stairs that give access to the cave; c) spring of the Lapa Grande creek; d) view of the entrance of the cave from inside to outside; e) water course inside the cave; f) speleothems.

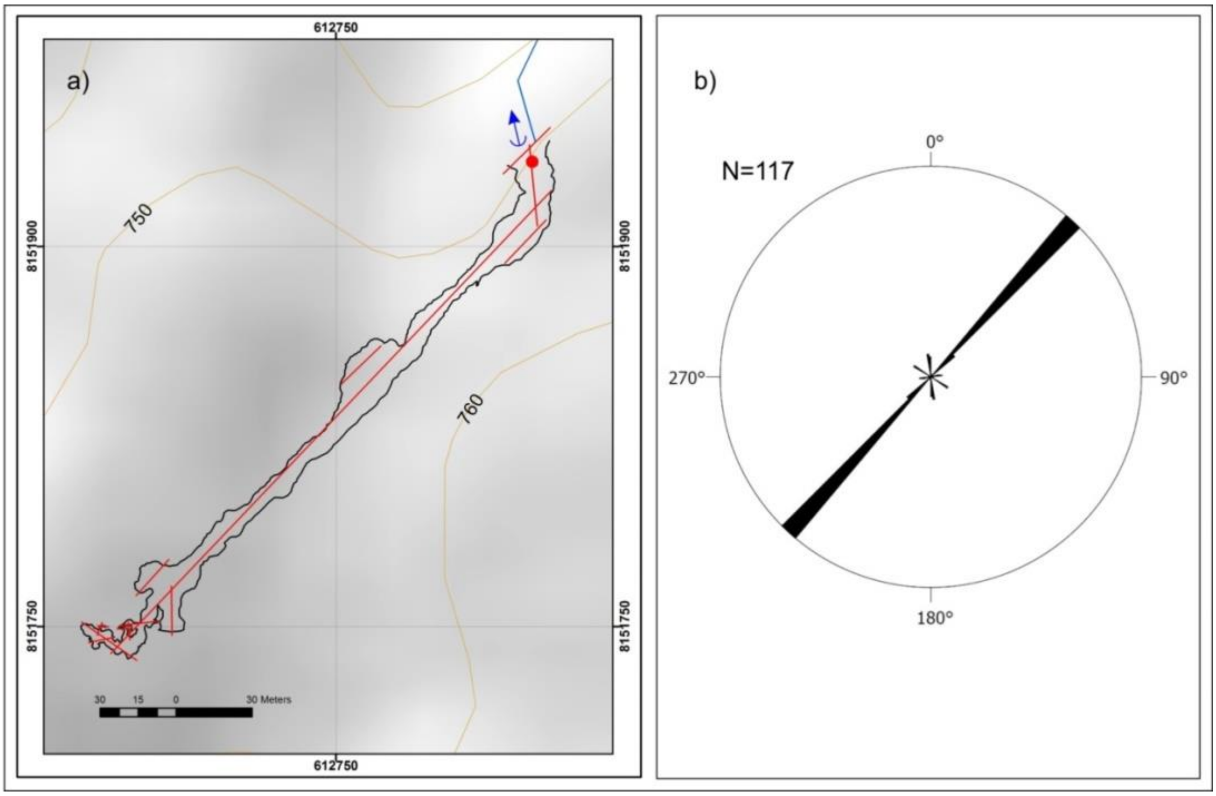


Figure 17: Simplified map of Lapa do Boqueirão da Nascente with interpreted lineaments; the red point is located in the cave entrance hall. b) Rose diagram of fracture directions and lengths (speleological map by Grande Sertão Institute).

Route 3

This route is composed of three outcrops where the main interest is hydrogeology and karst. There are two limestone tufa outcrops in the region of the source of the Vieira River and the source itself. The main access is by highway BR-365. Afterwards you follow an unpaved road and then a trail that leads to the natural pools of the limestone tuffs of the Vieira River. Following the trail along the banks of the river Viera you will reach a waterfall that is the main source of the river's perennial water.

Point 7 - Waterfall Tuffs

Outcrop located in Palmital Farm at coordinates 8,143,113 E, 614,940 N and altitude of 769m. It is a waterfall where the watercourse is intermittent. It forms a wall about 15m high composed of limestone tuffs (travertines) in tones of yellow and orange. In the lower part, fine calcarenite outcrops with lenses rich in intraclasts.

Point 8 - Spring of Vieira River

Outcrop located in Palmital Farm at coordinates 8,142,736 E, 614,714 N and altitude 749m. It is a limestone wall with vertical fractures widened by the dissolution. The spring is a perennial waterhole, which continues to form the bed of the Vieira River. Further ahead is a wall in the form of an amphitheater with a waterfall that is also in an intermittent watercourse. In the wall there are several conduits controlled by vertical fractures.

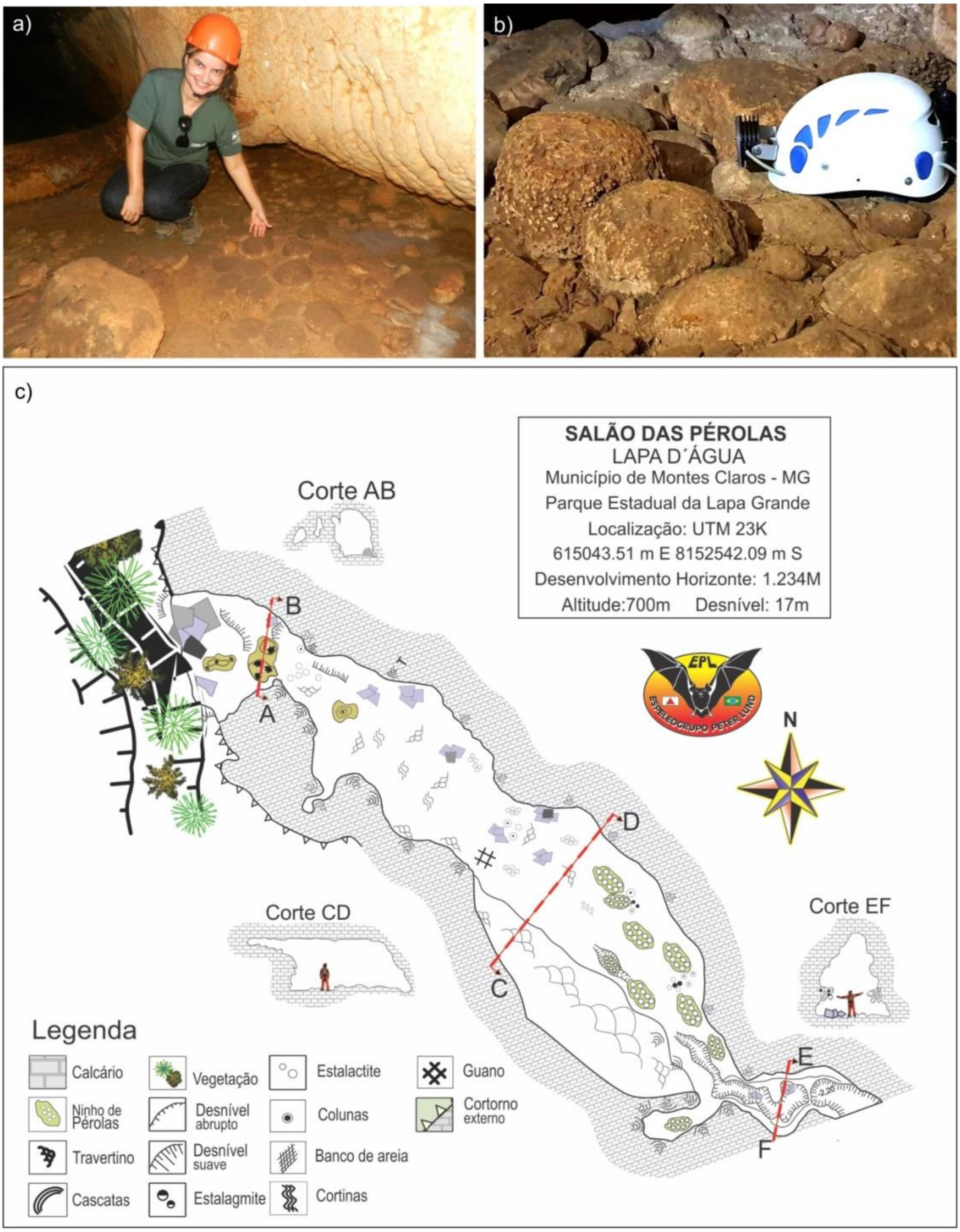


Figure 18. Lapa d'Água. a) Main hall where the giant pearls; b) detail of some giant pearls; c) speleological map of the hall where the giant pearl accumulations. Photos are courtesy of Eduardo Gomes and speleological map from Grande Sertão Institute.

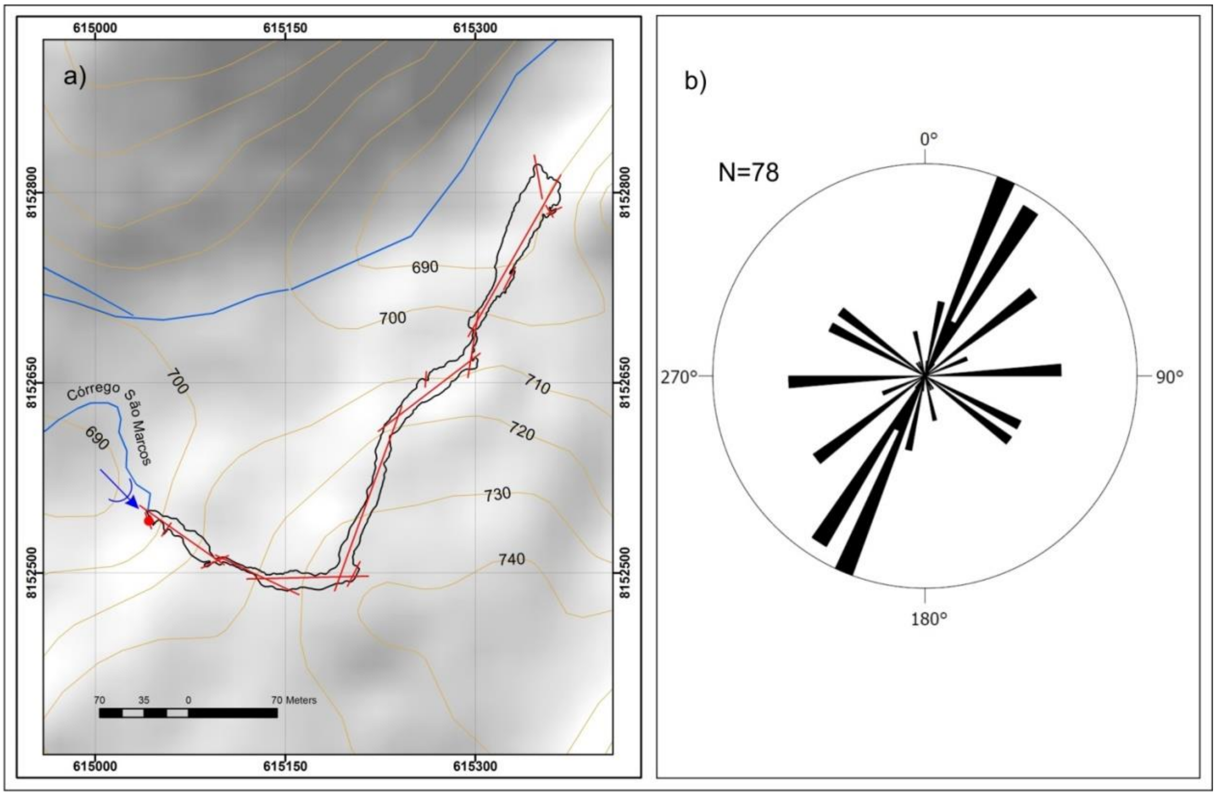


Figure 19: a) Simplified map of Lapa d'água with interpretation of the fracture patterns; the red dot is located in the cave entrance hall. b) Rose diagram of fracture directions and lengths (speleological map compiled from Barbosa et al. 2015).

Point 9 – Vieira River Tuffs

It is a rare scene in the Montes Claros region, a river with water flowing all year round. This underground water comes from the source of the Vieira River (Point 8). We are approximately 1km from the source. After mapping the whole basin, we identified three points with calcareous tuffs. One point near the PELG Visitor's Center where also the waters are green and crystalline; the other is the point 7 described above and this point, which is one of the most spectacular locations in the region.

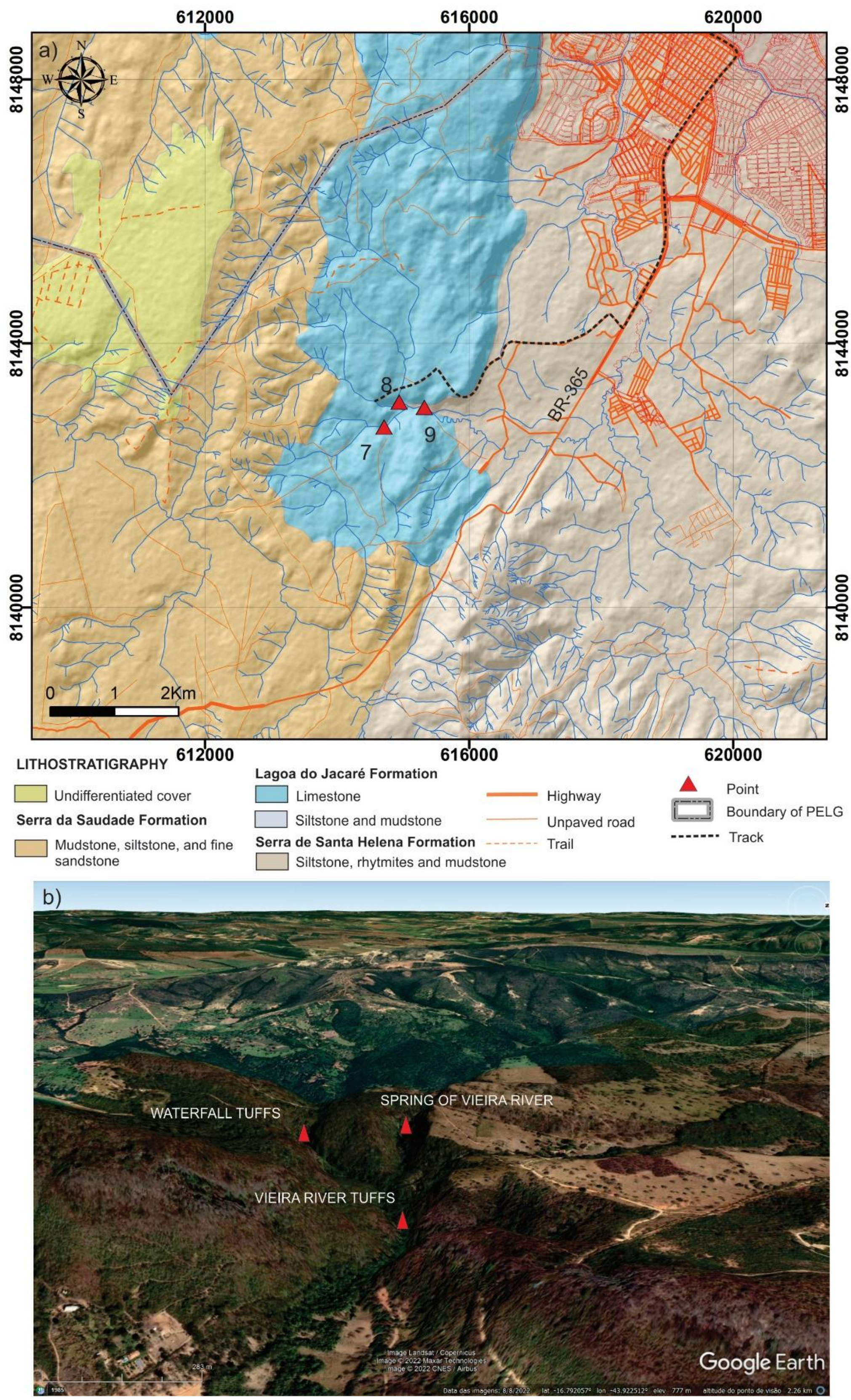


Figure 19: Route 3. a) Simplified geological map with the location of the points; b) Google Earth image in perspective with the location of the points. Points: (7) Waterfall Tuffs; (7) Spring of Vieira River; (9) Viera River Tuffs.

Figure 20: Waterfall tuffs. Pictures (a) and (c) tuffs in the dry season; pictures (b) and (d) tuffs in the wet season; e) calcarenite outcrop in the stream bed; f) detail of the calcarenite outcrop. Photographs (b) and (d) compiled from Travassos (2019) with permission.

Figure 21: Spring of Vieira River. a) place where the water flows from the limestone; b) detail of the waterhole; pictures (c) and (d) conduits controlled by vertical fractures; pictures (e) and (f) swarms of calcite veins in the calcarenite.

Figure 22: Vieira River tuffs. Pictures (a), (b), (c) and (d) several views of the tuffs along the Vieira River; pictures (e) and (f) dark gray siltstone outcropping on the banks of the Vieira River.

5. Final Comments

The structural controls of the karst can be considered on a regional and local scale. In regional scale they are represented by fractures and faults with main orientation NNE-SSW. These lineaments are parallel to the axes of the multi-scale folds generated by the thrust front of the Araçuaí orogen.

At the geological mapping scale (1:50,000) a pair of orthogonal fractures represented by fractures F1 (NNE-SSW) and F2 (WNW-ESE) predominates. The direction of the reverse faults coincides with the direction of the F1 fractures and the direction of the transcurrent faults associated with the thrust front coincides with the direction of the F2 fractures.

At the detail scale, the F1 and F2 fractures are the main controls on the cave conduits, along with the bedding (S0). These are the same directions described at regional and local scale, which shows us that the structural control of the exocarste is the same as that of the endocarste. In the cave maps conduits are also observed in other directions (N-S, E-W, NE-SW and NW-SE), which may indicate that fluid circulation can occur in a much more complex network of joints.

At all scales the structures that controlled the development of the karst features in the Vieira River basin are the F1 and F2 fractures and the bedding (S0). These structures are conditioned by persistent folding that occurs from kilometer to outcrop scale. The direction of fractures F1 coincides with: i) the direction of the normal fault that controls the São Francisco riverbed in the region; ii) the direction of the photolineaments described on a regional scale; iii) the axial planes of the folds that are perpendicular to the maximum direction of compression; iv) the preferential direction of cave development in the region; v) and also controls the surface drainage network. The F2 fractures are perpendicular to the fold axes and their origin was related to the direction of maximum distension (Fig. 23).

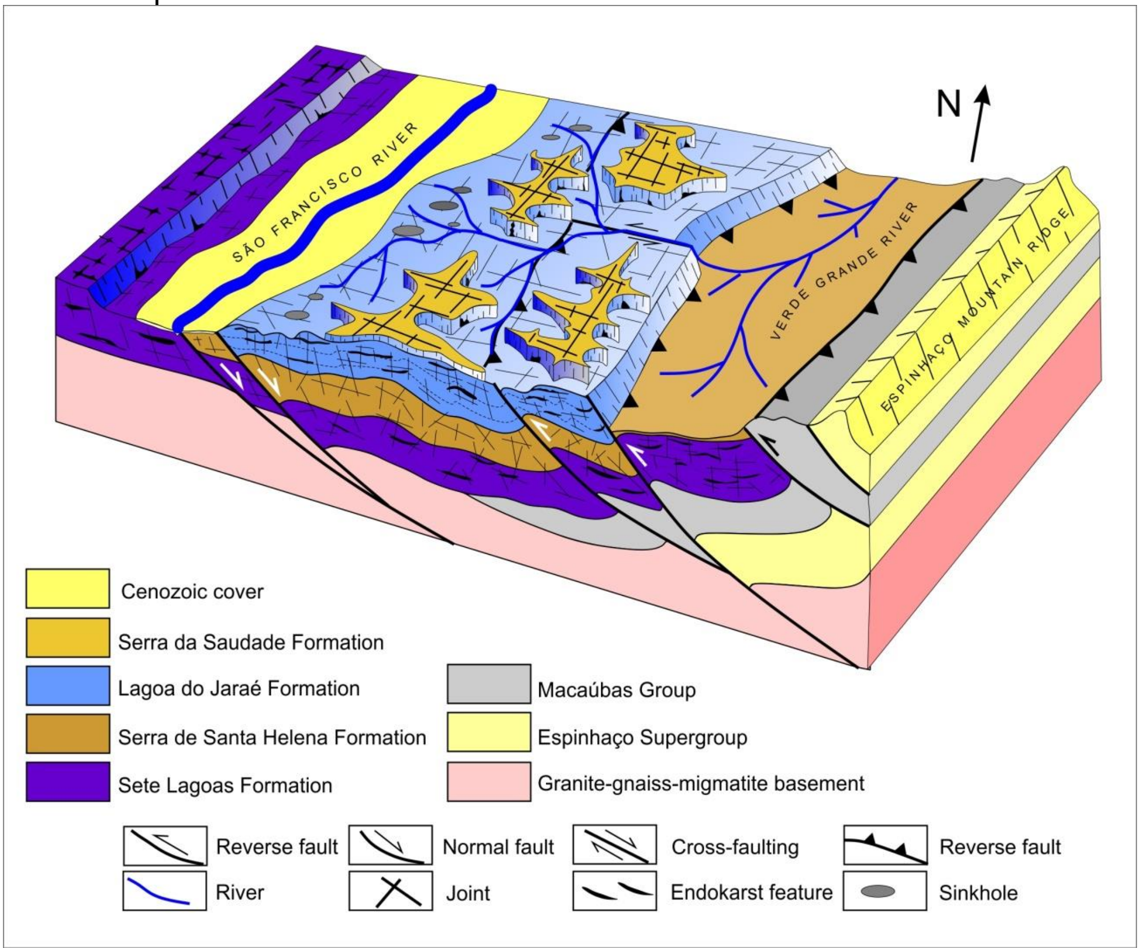


Figure 23: Block diagram with the stratigraphy and main karst features that occur in the Montes Claros karst (compiled from Cavalcanti 2022).

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