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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

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Abstract

The Neoproterozoic-Cambrian deformation imposed on the rocks of the Bambuí sedimentary basin, in the northern region of Minas Gerais, generated a system of folds, faults and joints. These structures were studied on a regional (1:100,000), semi detail (1:50,000 and 1:25,000) and detail scales in the maps of caves (1:100). Based on these studies, it was concluded that in the region there is a cropping karst (epigenetic) in the limestones of the Lagoa do Jacaré Formation and another non-outcropping (hypogenic) in the limestones of Sete Lagoas Formation and that the main structures that controlled its development are the folds, joints (F1 and F2) and bedding (S_0). The F1 joints have NNE-SSW direction, are parallel to the front thrust and to the folds' axial planes, control the geometry of the surface drainage network, are the main directions of the rock faces of the limestone massifs, the karstic valleys and the conducts of the studied caves. Whereas the F2 joints have WNW-ESE direction, are perpendicular to the F1 family, control the surface drainage network and the directions of the cave conducts. The intersection planes between the bedding and the joints and/or among different joints is what defines the geometry of the karstic features in the area. The F1 joints also coincide with the direction of the normal fault that controls the São Francisco river direction in this region. The faults, which are the deepest structures, can function as a connection among the different aquifers of the area, including the recharge of the non-outcropping karstic aquifers of Sete Lagoas Formation.

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1. Introduction

Karstic features have an intimate relationship with tectonic structures, such as folds, faults and joints (Klimchouk and Ford 2000, Ford and Willians 2007, Palmer 2007, Ennes-Silva et al. 2015, Awdal et al. 2016, Balsamo et al. 2019, Bagni et al. 2020, La Bruna et al. 2021). The Bambuí sedimentary basin (BSB) was affected by the deformation related to the Brasiliano cycle, mainly on its borders. The studied area is located at BSB, close to the boundary between the São Francisco Craton (CSF) and the Araçuaí orogen, in the region of Montes Claros, north of Minas Gerais. This limit is defined by the foothills of Serra do Espinhaço, which, in structural terms, is represented by a thrust fault that marks the contact between the rocks of Macaúbas and Bambuí groups, establishing the boundary between the São Francisco Craton and the Araçuaí orogen. Locally, the thrust front generated a system of folds and joints that possibly influenced the development of karstic features in the region.

The main objective of this article is to discuss the structural controls in the evolution of BSB karst's morphological features in the northern region of Minas Gerais, specifically in Vieira river basin area. The importance of this study is related to its immense potential for groundwater and also because the BSB karst may constitute important reservoirs of natural gas (Reis et al. 2017, Alkmim 2018) and Pb-Zn-Ag and fluorine deposits related to hydrothermalism that occurred in the basin (Misi et al. 2004, Nobre-Lopes 2002, Costa 2011). More recently, research has been carried out on the potential for natural H2 production (Prinzhofer et al. 2019, Donzé et al. 2020, Simon et al. 2020).

2. Geological Context

The Bambuí sedimentary basin (BSB) partially covers the São Francisco Craton, stretches for 146,000 km^2, occupying part of the states of Minas Gerais, Bahia, Goiás and Tocantins

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(Dardenne 2000, Nobre-Lopes 2002, Valeriano et al. 2004) (Figure 1a). In the northern region of Minas Gerais, BSB is limited to the east by the Araçuaí orogen, where the Macaúbas Group outcrops which is composed of metasedimentary pre-glacial and glaciogenic rocks ranging from a continental and glacial-marine rift stage to a proximal passive margin and late continental rift deposited between 750 and 667 Ma (Costa and Danderfer Filho 2017, Castro et al. 2020) (Figure 1b, c).

Regarding the stratigraphy, BSB has a record of three sedimentary megacycles (Dardenne 2000). The first megacycle composed of pelitic-carbonatic sediments from Sete Lagoas Formation, which is a coarsening upward sequence with dark gray to black calcilutite, at the base, going to limestone and dolomite at the top. The second megacycle is composed of carbonate-siliciclastic sediments: i) Serra de Santa Helena Formation, which represents an essentially pelitic sedimentation, indicating a sudden subsidence of the basin; ii) followed by deposition of Lagoa do Jacaré Formation, which is composed of dark gray limestones deposited on a platform dominated by storms and tidal currents. The third megacycle is formed by pelitic-sandy sediments: i) Serra da Saudade Formation, which represent pelitic layers deposited on a medium depth slope platform, periodically subject to storms; (ii) and arkoses deposited on a shallow platform dominated by storm currents with tide facies and super tide of Três Marias Formation (Fig. 2).

According to Zalán & Romeiro-Silva (2007) the geometric characteristics of BSB when observed in the seismic sections are typical of an intracratonic basin deformed by the compressional thin-skinned and thick-skinned tectonics after its deposition. Using the concept of sequences stratigraphy, Reis et al. (2017) classified BSB as a first-order sedimentary sequence deposited in a foreland-type basin, generated by a convergent event during the formation of the supercontinent Gondwana, in response to a lithospheric load caused by the tectonic uplifting of the Brasília and Araçuaí orogens (Alkmim 2018).

BSB sediments were deposited during the Ediacaran–Cambrian period between 550 Ma and 515 Ma, over the São Francisco paleo-plate (Paula-Santos et al. 2015; Babinski et al. 2019). The paleo plate was affected by several tectonic events throughout its geological history, which generated Proterozoic rifts, Neoproterozoic belts of the fold thrust type and cretaceous rifts (Reis et al. 2017) (Figure 2).

The first event occurred around 1.80 to 0.9 Ga (Fig.2a, b, c), and was responsible for the Rodínia paleocontinent break-up, giving rise to a rifted passive margin, which allowed the deposition of Paranoá and Espinhaço sequences (Schobbenhaus 1993; Babinski et al. 1999). Whereas, around 900 and 630 Ma (Fig.2c, d), another distension event of the same nature gave rise to Macaúbas sequence, on the east side of the basin (Rodrigues 2008; Kuchenbecker et al. 2011; Castro et al. 2020). These events were responsible for the structuring of the São Francisco Craton basement and gave rise to Alto de Januária (Fig. 1b, 2).

During the Ediacaran period, the margins of the São Francisco paleo plate were converted into orogenic belts and in their central portion (Alkmim and Martins-Neto 2012) (Fig.2e, f). There was also the permo-carboniferous sedimentation of the Santa Fé Group on the Bambuí Group rocks, a result of the glaciation that affected the western portion of Gondwana (Sgarbi et al. 2001; Limarino et al. 2014; in: Reis et al. 2017). Whereas the sediments (Areado and Urucuia groups) and the volcanic rocks (Mata da Corda Group) were correlated to the cretaceous rifting, responsible for the South Atlantic opening (Sgarbi et al. 2001, Mohriak and Leroy 2013; in: Reis et al. 2017).

3. Material and Methods

Initially, the integrated geological map was elaborated, in scale 1:150,000, from ten geological charts in scale 1:100,000 (Chaves 2006, Chaves and Andrade 2011, Chaves and Andrade 2012, Chaves and Andrade 2013, Kuchenbecker et al. 2013a, Kuchenbecker et al. 2013b, Uhlein et al. 2013, Kuchenbecker and Costa 2014, Caxito et al. 2015, Romano et al. 2015), aiming to understand the geological context and the morpho-structural domains in which the research area is inserted, in order to later compare with the structural domains defined in the Vieira river basin area, mapped in scale 1:50,000.

In the construction of the geological map of Vieira river basin, the following components were used: field data, airbone geophysical survey data (magnetic and radiometric) deep profiles of the holes PSB-014-MG (Brandalise 1980) and PTRA-9A (National Petroleum Agency - ANP), 2D, seismic sections (ANP),, as well as the tubular well database of the Groundwater Information System (SIAGAS) platform of the Geological Service of Brazil. For the analysis of structures, joints and photo lineaments, 12.5-meter *Alos Palsar* (*Alaska Satellite Facility*) images, high-resolution satellite images from *ArcGIS* BaseMap , and magnetic airbone geophysical maps were used. Photo lineaments were drawn in the scale 1:25,000. Joints and bedding analyzes were carried out from field measurements in about 600 geological stations. In the analysis of the cave fracturing pattern, seven speleological maps were used in the scale 1:100 (Lapa Grande, Lapa D´ Água, Lapa do Boqueirão da Nascente, Lapa da Claudina, Lapa da Santa, Lapa das Andorinhas and Lapa da Lagoinha). The rosettes and stereograms were generated in the *OpenStereo software* (Grohmann et al. 2011).

4. Regional Analysis

4.1. Morpho-structural domains

The Brasiliano deformation imprinted on the rocks of the Bambuí group represents the result of the Araçuaí front thrust orogen, with tectonic transport from east to west. This deformation has a ductile-ruptile character and resulted in an asymmetrical bending system with vergence to the west, which is associated with faults and joints. Alkmim et. al. (1993) defined three structural domains in the BSB (Fig.1a). The east and west domains represent the intracratonic domains deformed by the Araçuaí and Brasília collision orogens, respectively; and the central domain was spared from the deformation. In the context of the studied area, the eastern and central domains occur.

The defined morpho-structural domains reflect the main differences in relation to the lithological content, the deformation imposed by the thrust front of the Araçuaí band and the rocks weathering alteration stage (Figures 3 and 4).

In the domains 1,2, 7 and 9, the limestone rocks of Sete Lagoas and Lagoa do Jacaré formations predominate, that is, where the karstic relief occurs, and consequently, it is the area

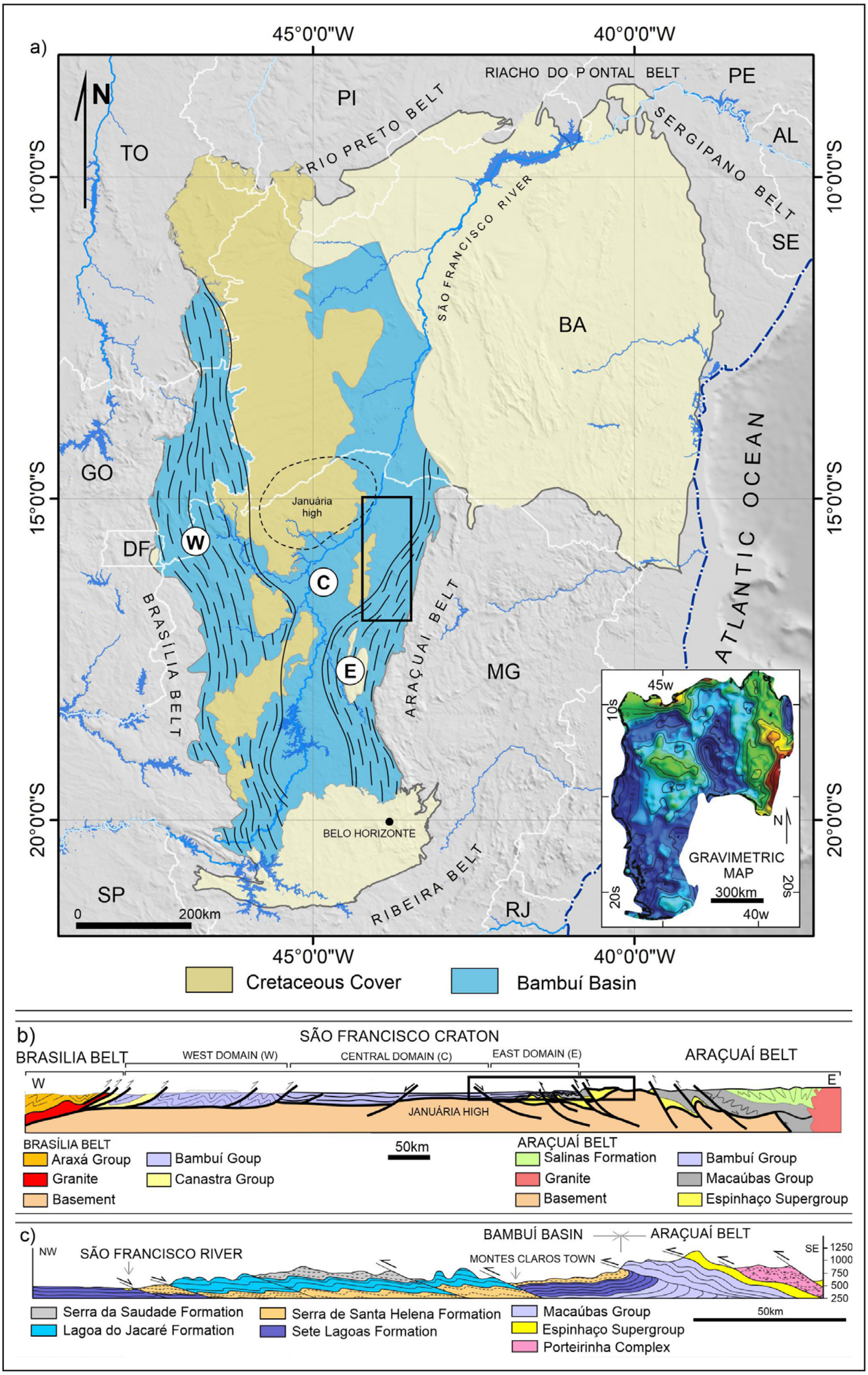

FIGURA 1. a) Articulation map between the São Francisco Craton and the Bambuí sedimentary basin (based in Almeida et al. 1977, Bizzi et al. 2003). Compiled gravimetric map of Bizzi and Vidotti (2003). b) Schematic geological section of the São Francisco Craton and mobile belts (modified from Alkmim 2018). c) Regional geological profile based on the geological map of Minas Gerais (Pinto and Silva 2014) and geological charts in scale 1:100,000, used in the integration map (See Figure 3).

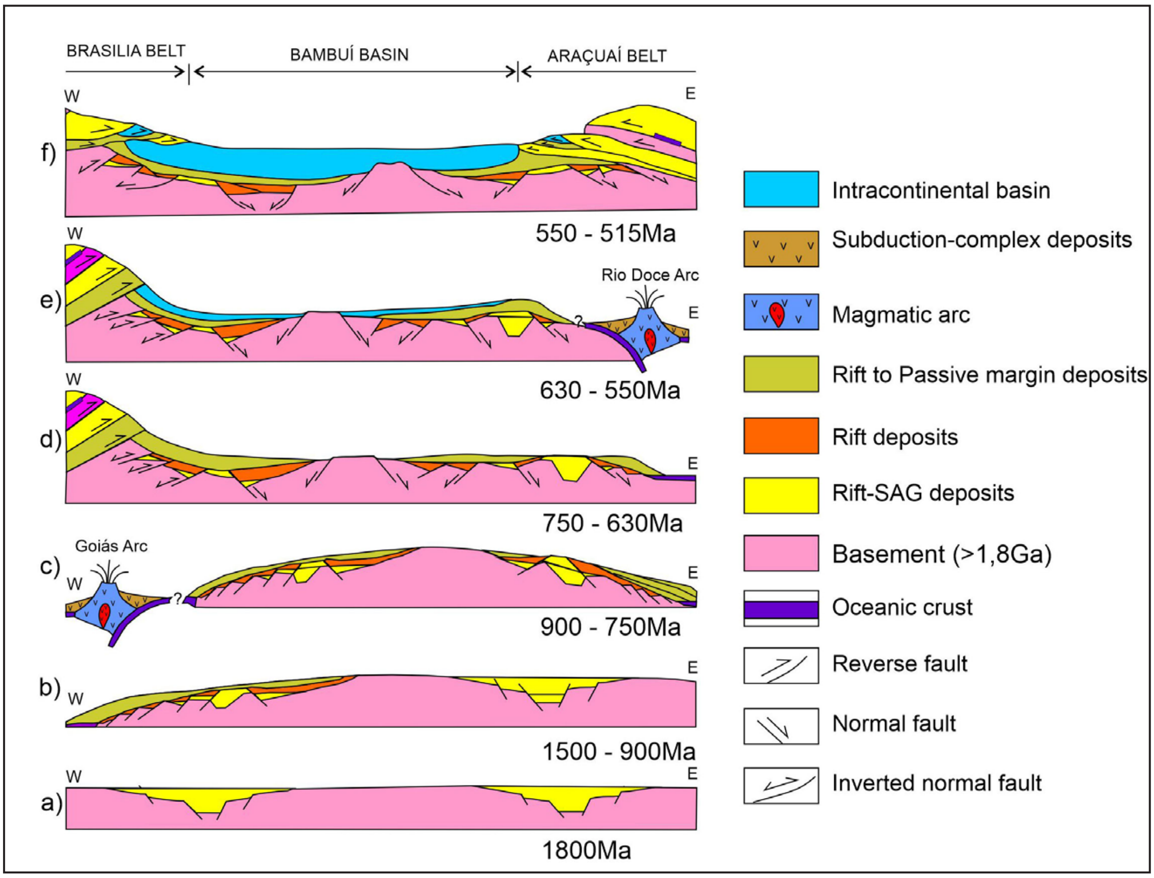

FIGURA 2. Tectonic evolution of the São Francisco paleo plate in Minas Gerais (modified from Martins-Neto 2009). The rift-SAG type deposits are the Espinhaço (east) and Araí (west) sequences; the rift and passive margin deposits are composed of Paranoá, Canastra and Vazante (west) sequences, and Macaúbas (east); and the intracontinental basin (*foreland*) corresponds to the Bambuí sequence.

with the greatest potential for the caves development . Domain 1 is characterized by the presence of the limestone of Sete Lagoas Formation. This is located in an undeformed sector of the Bambuí basin (Alkmim et al. 1993), distant from the thrust front of the Araçuaí orogen.

In domains 2, 7 and 9, NNE-SSW joints predominate and the limestones of Lagoa do Jacaré Formation are covered by a narrow layer of siltstones and fine sandstones of Serra da Saudade Formation modifying the superficial geomorphological pattern, but not the endokarst features.

In domain 8, the limestones of Lagoa do Jacaré Formation outcrop, where the karstic relief is very developed and concentrates most of the caverns of the region, which allows for greater rainwater infiltration and circulation. In this domain, the NNE-SSW and WNW-ESE joint families predominate.

In domains 3 and 4, the plains of the rivers are located in São Francisco and Grande Verde rivers, which are denuded areas, where siltstones and argillites predominate in Serra de Santa Helena Formation, as well as the recent alluvial-colluvial and alluvial deposits. In the areas where the rocks of Serra de Santa Helena Formation outcrop, mainly in domain 3, three families of joints predominate (NNE-SSW, WNW-ESE and E-W). These joints are responsible for the rainwater infiltration that can reach the deep aquifers of the limestones of Sete Lagoas Formation. In domain 5, the limestones of Lagoa do Jacaré Formation outcrop, partially covered by siliciclastic rocks of Serra da Saudade Formation, where E-W and ENE-WSW joints predominate. And, in domains 9 and 10, the relief is a tableland where the sandy soils of Areado group and the clay eluvial-colluvial sediments of the Cenozoic cover predominate.

4.2. Deep structures

Based on magnetic airbone geophysical survey data reverse faults, normal faults, indeterminate kinematic faults and dikes were interpreted (Fig. 5). The faults, most of the time, are outcropping structures and the dikes are non-outcropping structures. On a regional scale, the main fault that appears both in the geological map and in the aero geophysical maps has an approximate N-S alignment and represents the boundary between the São Francisco craton and BSB and puts in contact the rocks of the Macaúbas Group with rocks of Serra de Santa Helena Formation, of the Bambuí Group.

The normal parallel fault to the course of São Francisco river is the area where the limestones of Sete Lagoas Formation in the NW block and the siliciclastic rocks of Serra de Santa Helena Formation in the SE block outcrop. The other identified normal fault is located northwest of Montes Claros and has NW orientation.

The indiscriminate faults were interpreted from geophysical maps and often do not outcrop and are not represented on the geological map (Fig. 5). Others coincide with reverse (NNE-SSW) and transcurrent faults (WNW-ESE) that were identified in field.

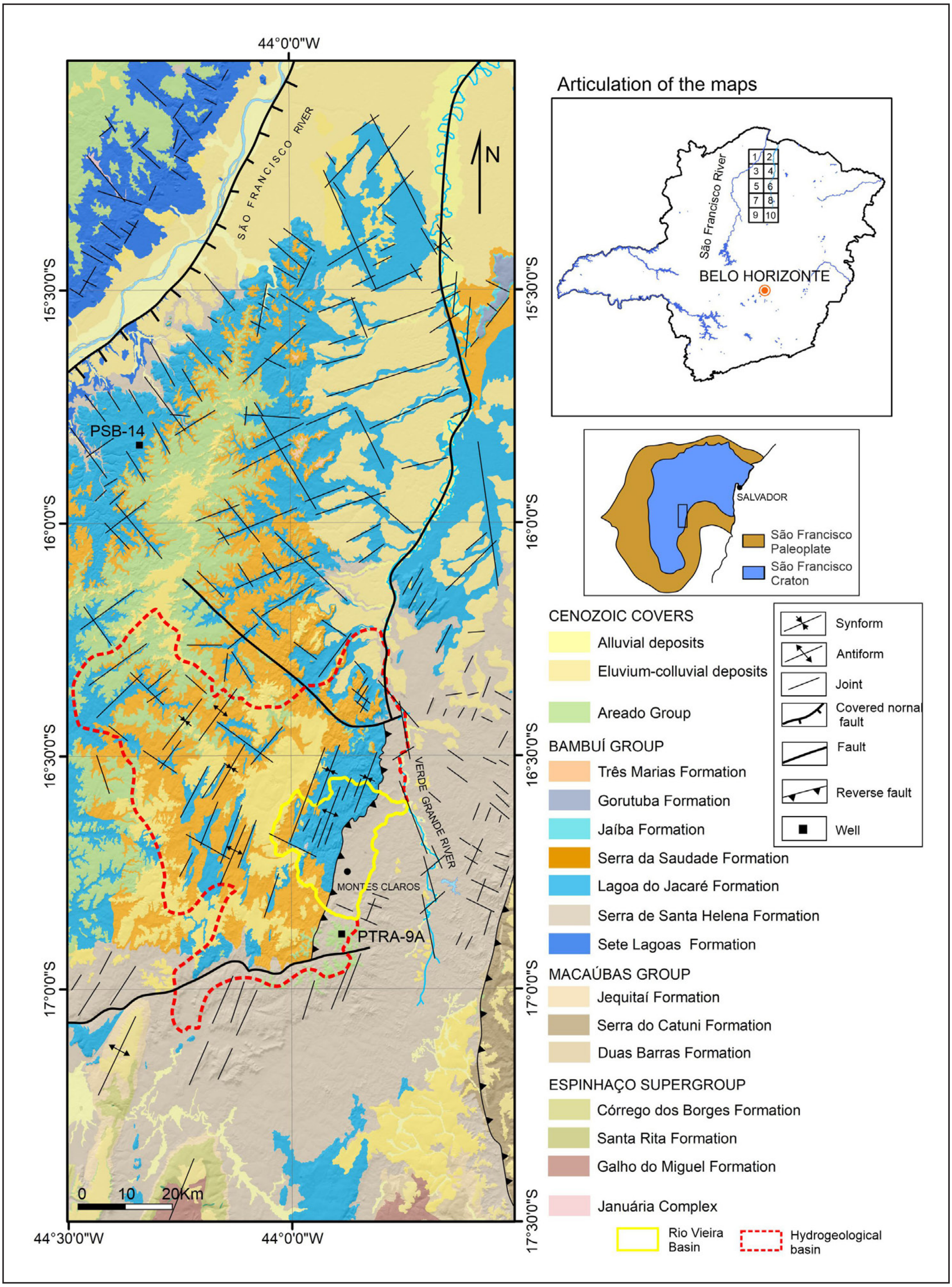

FIGURA 3. Simplified geological map of the region where the Verde Grande River basin is inserted with the location of the Vieira River basin and the hydrogeological basin. Booklet of São Francisco paleo plate with the location of the map area. Geological charts used in the construction of the integrated map: (1) Januária - SD-23-Z-C-II; (2) Mata do Jaíba - SD-23-Z-C-III; (3) São João da Ponte - SD-23-Z-C-V; (4) Barreiro do Jaíba - SD-23-Z-C-VI; (5) Brasília de Minas - SE-23-X-A-II; (6) Capitão Eneas - SE-23-X-A-III; (7) Coração de Jesus - SE-23-X-A-V; (8) Montes Claros - SE-23-X-A-VI; (9) Jequitaí - SE-23-X-C-II; (10) Bocaiuva - SE-23-X-C-III.

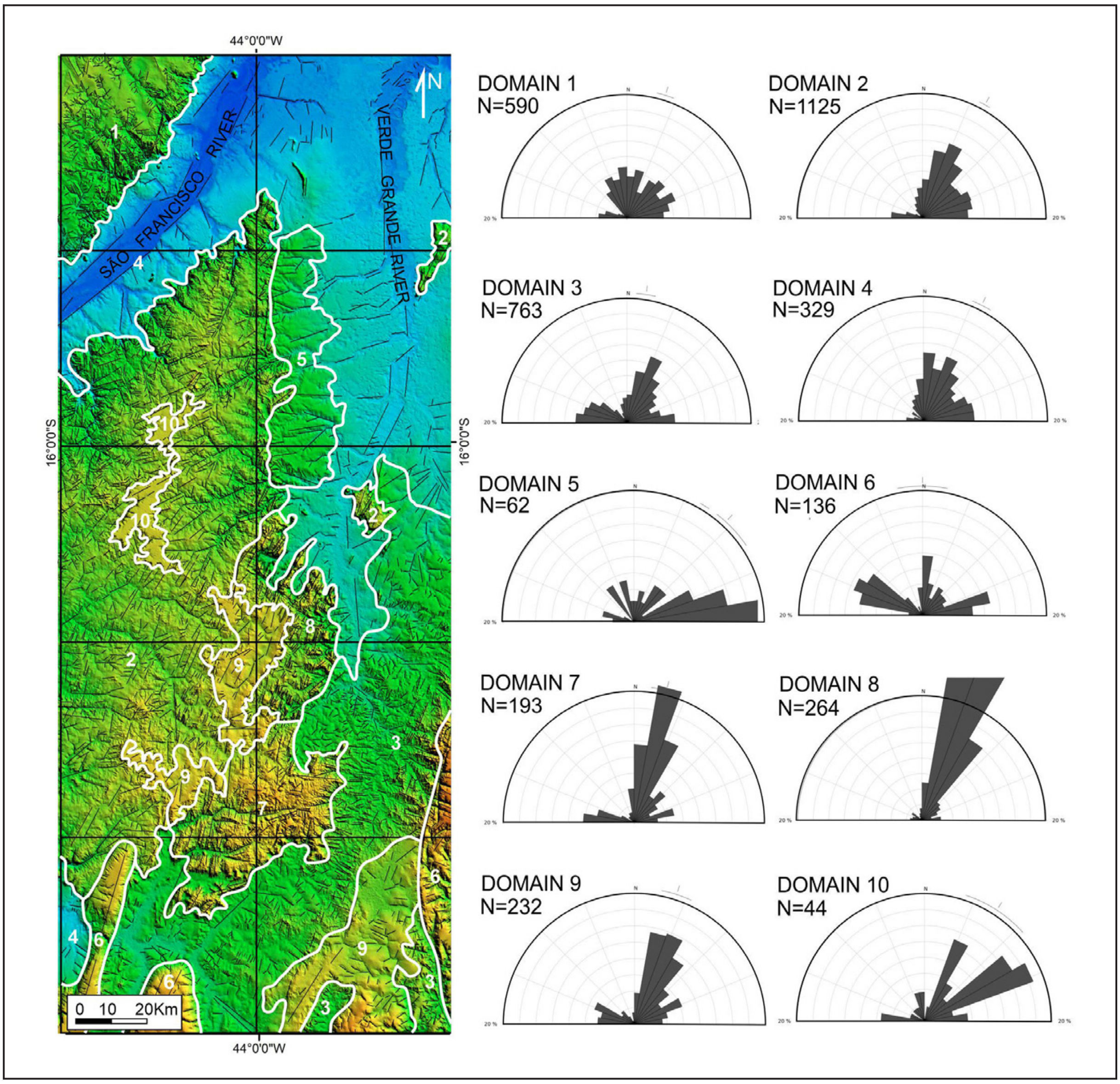

FIGURA 4. Morpho-structural domains and photo lineaments rosettes.

The dikes are also non-outcropping structures. In the geological map of the State of Minas Gerais (Pinto and Silva 2014) all the structures forming swarms are sectioned which define several families with ages from Pre-Cambrian to the Lower Cretaceous period. According to Coelho and Chaves (2017), the dikes of the north of Minas Gerais (named Transminas Swarm) are aged between 135 - 128 Ma, crossing not only the São Francisco Craton and its pre-neocretaceous sediments, but also the Brasiliano Brasilia, Ribeira and Araçuaí mobile belts. In the studied area they constitute swarms with NNW-SSE alignment.

5. Local Geology

5.1. Lithostratigraphy

In the area of the Vieira river basin, the rocks of the Bambuí group outcrop, represented by the formations Sete Lagoas (maximum thickness 670m), Serra de Santa Helena (maximum thickness 450m), Lagoa do Jacaré (maximum thickness 415 m) and Serra da Saudade (maximum thickness 120m) (Fig. 6). In the western portion, the rocks of the Bambuí group are covered by alluvial-colluvial sediments.

The Sete Lagoas Formation does not outcrop in the area of the Vieira river basin, but it was identified from the sampling profiles, the tubular wells profiles (SIAGAS) and the seismic sections. Based on the description of the PSB-14-MG hole, the formation has an average thickness of 400m, consisting of three carbonatic facies (Fig. 7): i) dolomite, consisting of light gray dolomite of fine granulation, containing galena mineralization; ii) limestone, consisting of gray-dark limestones, fine granulation, with intercalations of black carbonaceous clay layers and thick layers of intraformational breccias; (iii) brown dolomitic limestone, composed of light gray limestone, fine granulation, with intercalation of fine greenish and yellowish layers and, toward the base, it becomes more clayey (Brandalise 1980).

Seismic data show that the Sete Lagoas Formation becomes thicker toward the city of Montes Claros, reaching more than 600m thickness (Fig. 8). Whereas in the PTRA-9A hole, located in the south of Montes Claros with a depth of 1160m, the estimated thickness of Sete Lagoas Formation was 670m, and the unit was divided into three members: i)

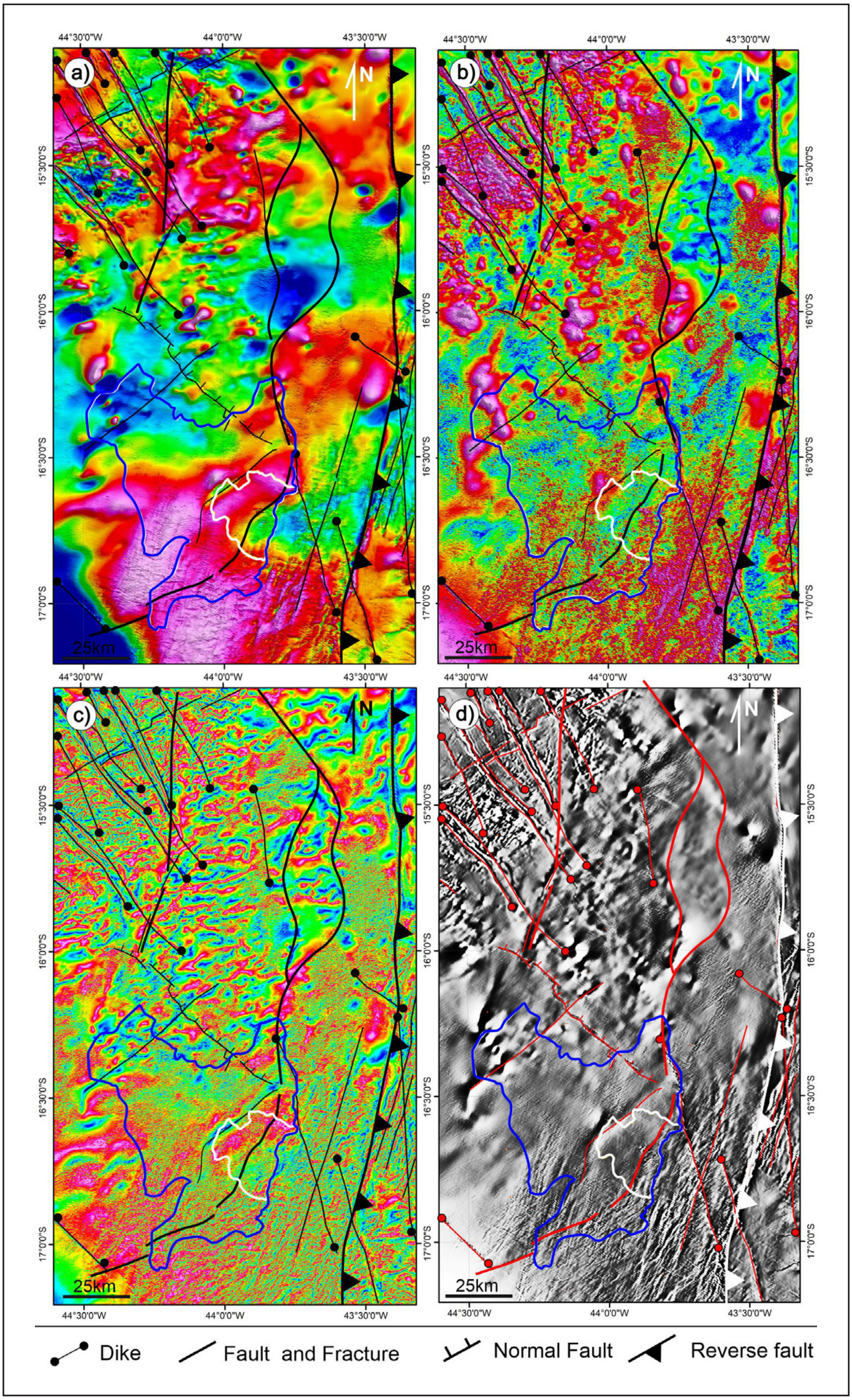

FIGURA 5. Interpretation of deep structures from magnetic airbone geophysical survey data maps. a) map of the anomalous map of reduced-to-pole magnetic anomaly (CMA-RP); b) amplitude map of the analytical signal (ASA); c) map of analytical signal intensity (ISA); d) map of horizontal derivative “X”. The reverse fault represents the boundary between the Araçuaí belt and the Bambuí sedimentary basin. Aero geophysical maps compiled from Gomes (2021).

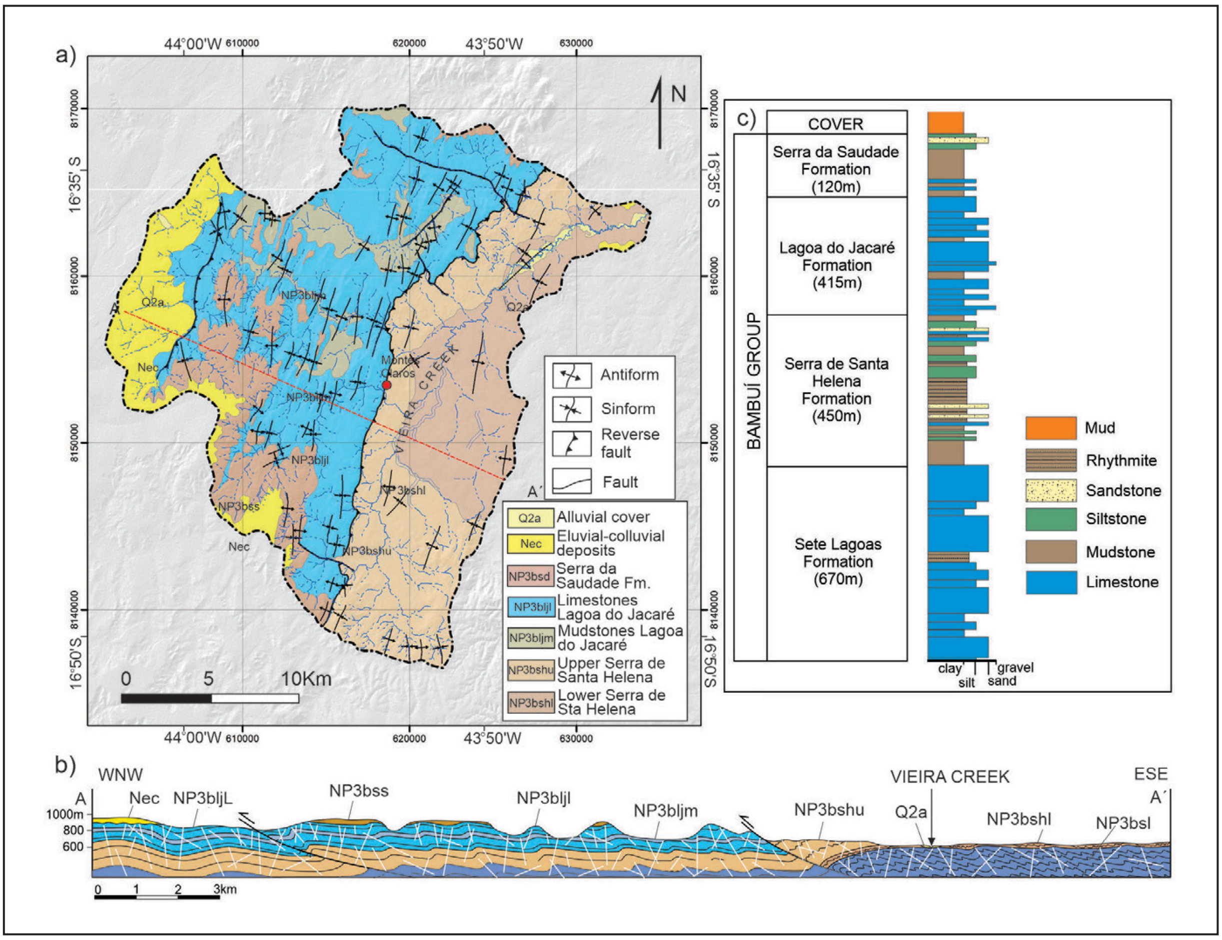

FIGURA 6. a) Simplified geological map of Vieira river basin area. b) geological profile AA'; (c) lithostratigraphic column for the Vieira river basin area.

carbonatic lower member with 150m thickness, ii) siliciclastic-carbonatic intermediate member with 170m thickness; and (iii) siliciclastic upper member 350m thickness (Fig. 8).

In the eastern portion of the Vieira river basin, where the urban nucleus of Montes Claros is located, the limestones of Sete Lagoas Formation occur just below the siliciclastic sequence of Serra de Santa Helena Formation. In this area there is a large concentration of tubular wells used in the exploitation of groundwater. In the well profiles, the carbonatic rocks occur between the elevations 645m and 410m, totaling a layer of at least 230m thick and the siliciclastic rocks of Serra de Santa Helena Formation reach thicknesses around 40m.

Serra de Santa Helena Formation is composed of siliciclastic rocks that only affect the eastern portion of the area. In the profile of hole PSB-014-MG, the formation is 151m thick and in the hole PTRA-9A it shows thickness of 390m (Fig. 7 and 8). In profile 5 (N-S), the predominance of pelitic rocks was verified (argillites, siltstone and rhythmites) and thickness that can reach 400m. Two members were individualized, the inferior being composed of argillites, siltous argillites and rhythmites, very weathered, with thickness around 150m (Fig. 8). In the urban area of Montes Claros, this member has a mean thickness of 40m, based on the tubular well profiles in SIAGAS. Below the siliciclastic rocks, only limestone rocks were described, from where a large part of the water consumed by the local population is exploited. The upper member is composed of siltstones (at the base) and siltous rhythmites (at the top) containing marls and calcarenite intercalations, and can reach 290m thick.

Lagoa do Jacaré Formation is composed mainly of limestones with rare intercalations of lenses/layers of siltstones, argillites and marls. The total thickness can reach about 380m. The limestones occupy almost the entire western and northern portion of the area where karstic relief and caves predominate and can reach 200m of outcropping thickness. They exhibit different facies throughout their length, with predominance of calcarenite, Calcilutite, calcirudite and layers of oolitic limestones, and, in a smaller proportion, intraformational breccias and conglomerates, stromatolitic limestones and interleaving of pelitic rocks occur (Fig. 9c, d, e, f). The main sedimentary structures are rippled bedding, planar stratification, cross-planar stratification, choppy stratification and herringbone stratification, *hummocky stratification*, *and flazer*, lenticular, *wavy and* horizontal stylolites.

Serra da Saudade Formation outcrops mainly in the southwest portion of the basin, covering the limestones of Lagoa do Jacaré Formation and also constitute isolated portions over the intensely karstfied limestone massifs, as in the area of Parque Estadual da Lapa Grande (PELG). It is a siliciclastic sequence composed of argillite, siltstone, rhythmites and sandstone, and can reach up to 120m thickness (Fig. 9g, h).

5.2. Descriptive Structural Analysis

The area of Vieira river basin is inserted in the deformed domain of São Francisco Craton (East Domain), generated in response to the force imposed by the front thrust of Araçuaí

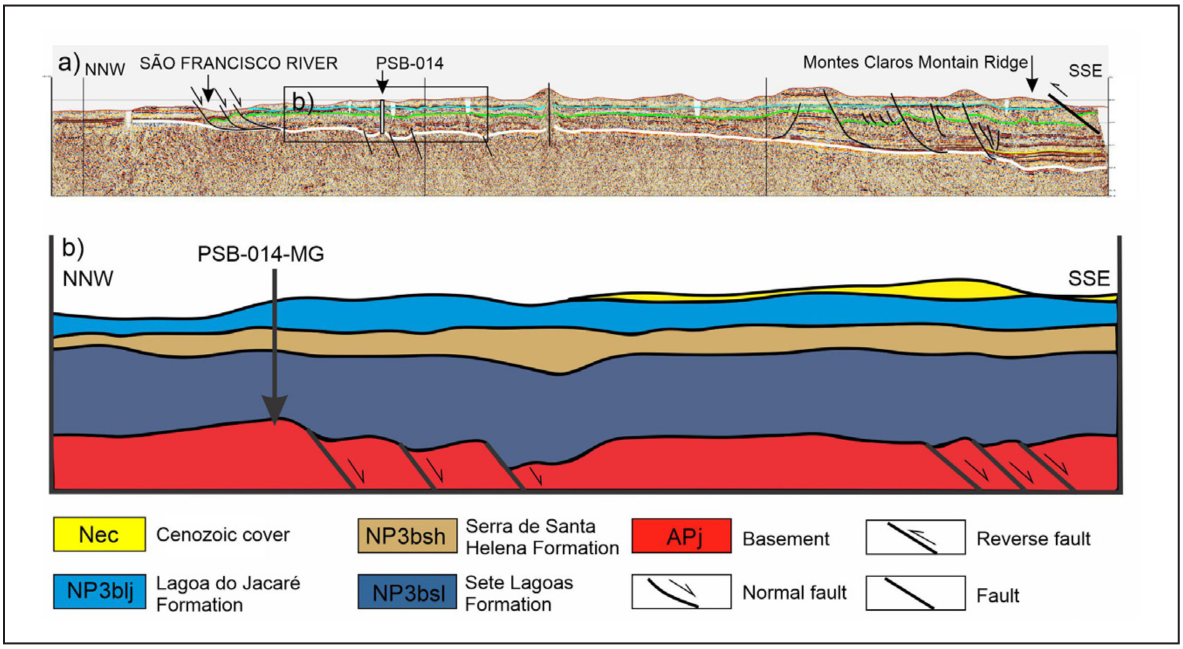

FIGURA 7. Hole PSB-014. a) Seismic section L0319-0400 between the São Francisco river and Montes Claros ridge; b) Interpretation of the seismic section in the vicinity of hole PSB-014 (see hole location in Fig. 3).

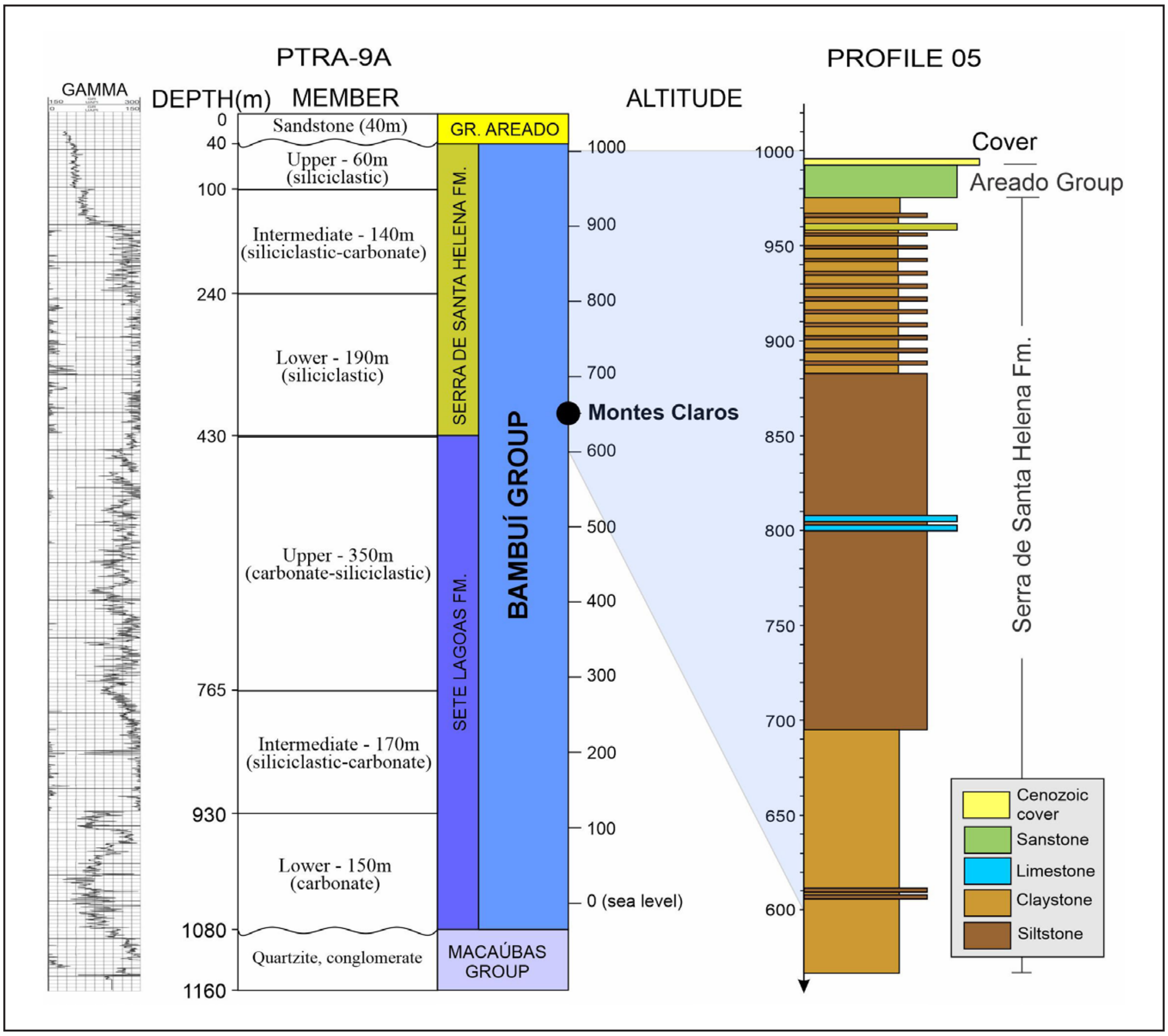

FIGURA 8. On the left stratigraphic interpretation of the PTRA-9A hole and on the right the field profile (N-S) in the Eastern domain of the area. Highlight for the position of Montes Claros at the altitude of 650m (see hole location in Fig. 3).

FIGURA 9. Main lithotypes of the Bambuí Group in the studied area. Serra de Santa Helena Formation: a) little weathered claystone with flat-parallel stratification; b) siltstone with marl and calcarenite intercalation, in the upper member of the formation. Lagoa do Jacaré Formation: c) fine-to-medium grained calcarenite with solid aspect; d) laminated calcarenite; e) oolitic limestone; f) columnar stromatolitic structures. Formation Serra da Saudade: g) weathered siltstone; h) very joined medium gray siltstone.

Belt (Alkmim and Martins-Neto 2001). In this context, the rocks of Bambuí Group exhibit asymmetric folds (with main vergence to the west) of kilometric amplitude, discrete zones of brittle shear, drag folds, cleavage fracture, diaclases, joints and veins. The collection of brittle structures is more diverse, zones of reverse faults have been identified, which are represented in map, narrow areas of low-angle shear and a large collection of joints that can represent at least two pairs in combination. These structures are the most important in the area, because, besides being responsible for the development of karstic relief, they are also responsible for the drainage and storage of groundwater.

Three structural domains were defined in the area: i) the east domain, where the siliciclastic rocks belonging to Serra de Santa Helena Formation predominate; ii) the central karstic domain, with predominance of limestones from Lagoa do Jacaré Formation and, at the top, a sequence of siliciclastic rocks from Serra da Saudade Formation; iii) and the western domain, unstructured and covered by Cenozoic elluvial-colluvial deposits (Fig. 10a).

The NNE-SSW and WNW-ESE lineaments are the main factors of the drainage network of Vieira river basin. As it can be observed in the lineament density map, its highest concentration occurs in the Central domain where the karstic relief of Lagoa do Jacaré Formation is more developed in surface (Fig. 10d).

The main ductile structure described in the area are folds that occur in various scales and styles (Fig. 11). In general, they are open on a kilometric scale, representing synformal and antiformal structures with vergence for W to WNW. 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 NW, making them an important kinematic indicator of the region. Kinematic indicators are rare in the region, but *tension gashes* have been observed that also indicate mass displacement to the west. The folds were correlated with the thrust phase of the Brasiliano cycle, which positioned the rocks of the Macaúbas Group (of Araçuaí Belt) over the rocks of the Bambuí Group. Depending on the lithology, the folds display varied patterns and dimensions, a good example is what occurs in deformed layers of limestone (calcarenite and calcilutite): the calcarenite facies have folds in metric scale, while in the calcilutite facies the folds are centimetric. An important point refers to the folds axial planes that can function as dissolution zones (karstification) of the limestone layers, representing weakness planes for reactivation or development of new structures related to the stage of crustal relaxation that occurred with the end of the Brasiliano compression. On the other hand, they may be related to the Cretaceous distension event, which culminated with the opening of the Atlantic Ocean.

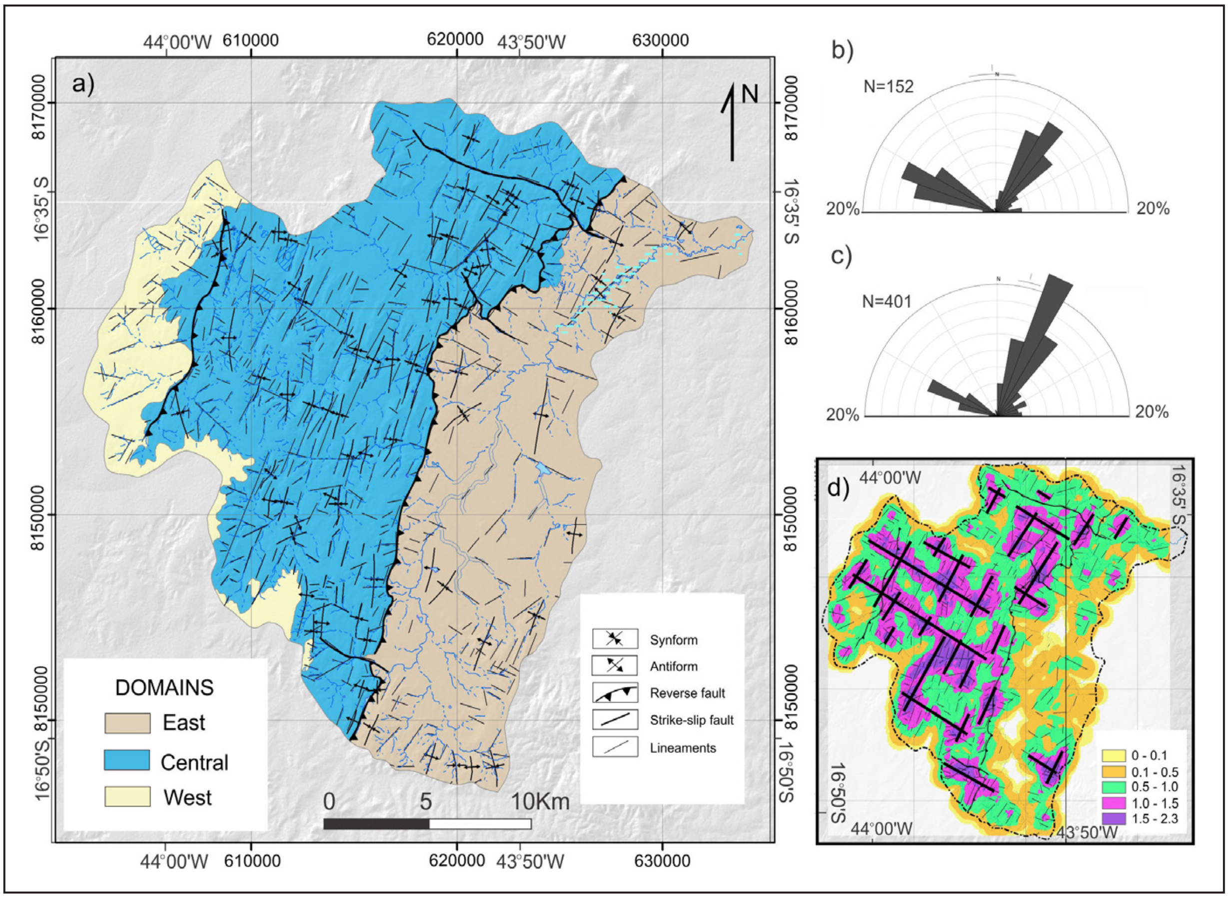

FIGURA 10. a) Structural domains of Vieira river basin watershed with the main mapped structures; frequency rosette diagrams of the Eastern domain photoalignments directions of the pelitic rocks of Serra de Santa Helena Formation (N35ºE; N65ºW) and the central domain, the carbonatic rocks of Lagoa do Jacaré Formation (N30ºE), respectively, figures (b) and (c); d) photolineaments density map (km/km²) with interpretation of the joint system.

FIGURA 11. Photos of the main types of folds and their vergences. a) open fold is a broad feature in which the limbs dip at a gentle angle away from the crest of the fold; b) flanks folds transposed with east vergence; c) open fold; d) drag folds with west vergence, in a 30-meter thick massif, approximately; e) folds with flank transposed and vergence to the west (detail in the area of the previous photo); f) fold drag with vergence to WNW; g) closed fold with vergence to WNW.

The joints are very pervasive structures in the area studied (Fig. 12). In the central domain, where the limestone rocks of Lagoa do Jacaré Formation predominate, three families of joints were identified: F1 (N10º - 30ºE), F2 (N75ºW) and F3 (N40º - 75ºE) (Fig. 13a). Whereas in the east domain, where the siliciclastic rocks of Serra de Santa Helena Formation predominate, four families were defined: F1 (N10º-30ºE), F2 (N60º-80ºW), F3 (N50º-60ºE) and F4 (N20º-40ºW) (Fig. 13b). 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 (Fig. 14). The F3 joints are posterior to F1 and F2 joints (Fig 12a).

Reverse faults were identified in two locations in the studied area (Fig. 6). The first and most important is marked by the foothills of Mel ridge (or Montes Claros ridge), where there is a clear discordance between the siliciclastic rocks of Serra de Santa Helena Formation and the limestones of Lagoa do Jacaré Formation. The *shear folds* type have vergence to the west and *the tension gashes* indicate reverse movement to the west (Fig. 15a). In the lower portion, the fault zone is almost always covered by talus deposits associated to the hillside. Another type of fault identified in the region is the transcurrent faults formed by the lateral escape in relation to the front thrust. Low-angle shear zones occur in banded limestones and siliciclastic rocks. In the limestones, they are associated with narrow pelitic layers that occur interspersed in the limestone (Fig. 15b). The sigmoids generated by the deformation indicate reverse movement, with the direction of mass displacement for W and WNW, corroborating with the regional tectonic. Whereas the high-angle shear zones are restricted to siliciclastic rocks.

Fracture cleavage was observed in the limestones and siltstones which are the most preserved weathering lithotypes. It was interpreted as a structure generated in response to crustal relaxation with the end of compression exerted by the Araçuaí orogen. It has direction parallel to the folds axial planes, but with a dip angle of the plane smaller than the F1 joints. In thin section, a slide manifested by a normal micro faults system was observed. The fracture cleavage has the same direction as the F1 joint (N25ºE), however it presents characteristic dip for SE, on average 37º (Fig. 16).

The veins are composed of quartz, calcite and, more rarely, the two components can occur in dimensions ranging from millimeter to decimeter. The quartz veins are mainly embedded in the pelitic rocks, while the calcite veins appear in the carbonatic rocks. They may occur parallel to the bedding, which may contain discordant apophyses, associated with the joints in an isolated way or showing a stockwork pattern, such as tension gashes associated with the compression that gave rise to the folds indicating the direction of transport and, also in fault and shear zones. The calcite veins are more common and occur in smaller dimensions. Most of the times they are white calcite, but black calcite veins may occur.

6. The karst

The two main types of karst are hypogenic and epigenetic, whose main difference is that epigenetic karst is formed by the action of fluids from the surface and the hypogenic karst is formed by ascending flow and this reflects in the hydraulic contour conditions and in its geochemical and physical characteristics in relation to the speleogenetic domains, which correspond to the karstic system (Klimchouk 2017).

The epigenetic karstic systems have their development closely related to the landscape and have surface and underground components. Whereas the hypogenic karstic systems do not have a direct relation to the surface and are represented by deep duct systems. These systems may outcrop due to the denudation and/or uplifting processes of the earth's crust and, at the same time, may be overlaid by epigenetic karstic systems, making their identification difficult. From the hydrogeological point of view, epigenetic karstification is mainly related to meteoric and fluvial water flow systems in open and shallow hydraulic environments, while the hypo genetic usually occurs at large depths and related to ascending flows of different origins nd varying degrees of confinement (Klimchouk 2017).

In addition to focusing on aquifers, studies on the deep karst (hypogenic) are also used in the research of oil and gas deposits (Hardage et al. 1996; Goldscheider et al. 2010; Zeng et al. 2010; Sayago et al. 2012; Kaufmann et al. 2014; Zhu et al. 2017; Basso et al. 2018). In Brazil, Toca da Boa Vista and Gruta Barriguda (from Campo Formoso-BA region) in the limestones from the Salitre Formation and some caves, which occur in the carbonatic rocks of Vazante Formation next to Brasília Belt, were classified as hypogenic caves (Auler 2017, Auler et al. 2017, Auler and Souza 2017).

The occurrence of a deep karst in BSB was pointed out in the study carried out by Donzé et al. (2020). According to these authors in the region, hydrogen gas infiltrations occur in the rocks of the Bambuí basin with a strong crustal signature. They also stressed the presence of a relatively high geothermal gradient, deep failures outlining graben and host structures affecting the sedimentary sequence and a possible gas karstic reservoir located about 400 meters from the surface (Fig. 17). The seismic sections used by these authors have shown that surface faults are deeply rooted and they can drain deep fluids and that the Bambuí Group rocks constitute the main portion that is cut by the fault systems, representing the main candidate for temporary gas accumulation zones. They also pointed out that the formation of dolines by deep dissolution may explain the presence of surface semicircular depressions, which can control the gases migration in temporary reservoirs.

6.1. Exokarst

In the north of Minas Gerais, specifically in the region of Montes Claros and surroundings, the karstic landscape unveils where the limestones of Lagoa do Jacaré Formation crop out. Lapa Grande State Park is the place that best represents the karstic landscape in the region. In addition to the rock faces, there are around 70 caves in the park area, among which many contain active sinks, sinkholes and upwellings, regardless of climate. Whereas, within the basin of Vieira river, there are about 90 caves, based on the Brazilian national registry of caves (National cave database of Brazil; CECAV 2019) and a large quantity of dolines, valleys and limestones massifs (Fig. 18).

Dolines are important recharging zones for karstic aquifers. In the area under analysis they appear aligned by zones of joints between the limestone massifs and also scattered in the karstic plains (Fig. 19a, b). When associated with joint zones they are approximately elliptical. In the plains they take circular and irregular forms that seem to be arranged randomly, since the plain may have been formed by the coalescence of several dolines and uvalas.

FIGURA 12. Main ruptile structures. a) pair of orthogonal conjugated joints (F1 and F2) and a third (F3) intercepting the first two, in the claystone; b) pair of shear joints in the siltstone; c) joints in siltstone and intersection with the plane of the bedding (in red); d) open joint as a result of the limestone dissolution; (e) and (f) pair of extensional joints in the limestone; (g) open joint in limestone; (h) bedding in limestone massif.

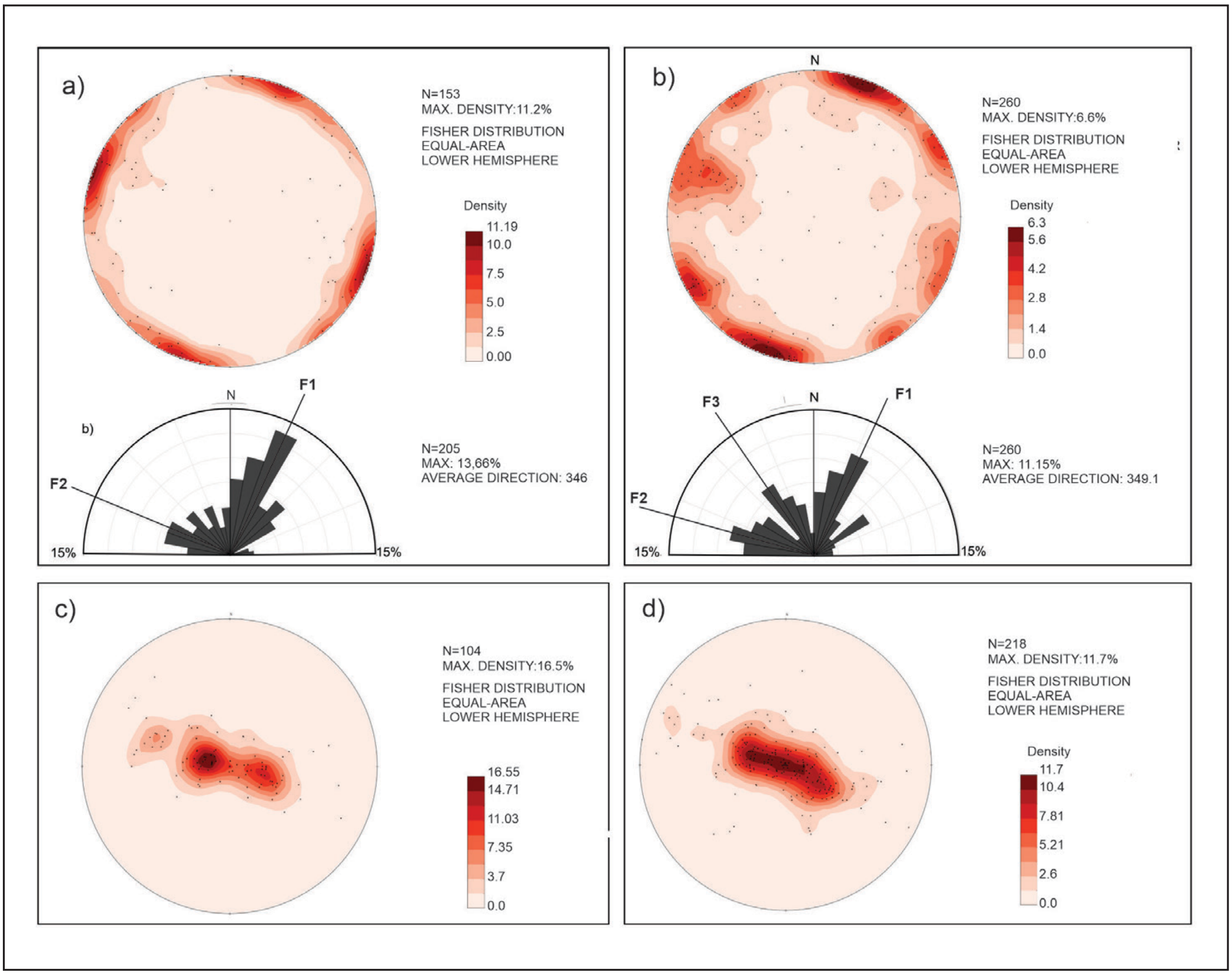

FIGURA 13. a) joints in the limestones of Lagoa do Jacaré Formation, central domain, carbonates subdomain (stereogram of poles density and rosette of joint directions); b) joints in the siliciclastic rocks of Serra de Santa Helena Formation, eastern domain (stereogram of pole density and rosette of joint directions); c) stereogram of bedding (S_0) in the limestones of Lagoa do Jacaré Formation; d) stereogram of bedding in the siliciclastic rocks of Serra de Santa Helena Formation.

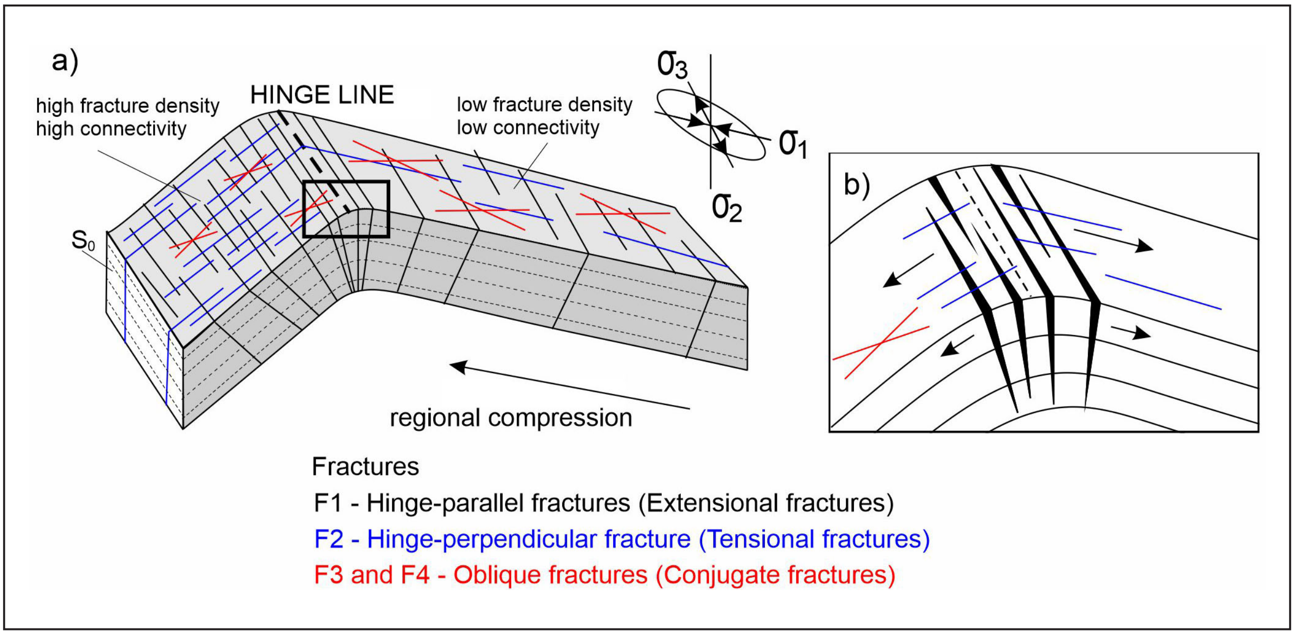

FIGURA 14. a) Joint model associated with an asymmetric fold (adapted from Price 1966, Awdal et al. 2016, Watkins et al. 2017); b) detail of the hinge area of the asymmetric fold (based on Jadoon et al. 2007, modified from Stearns 1968, Nelson 1979).

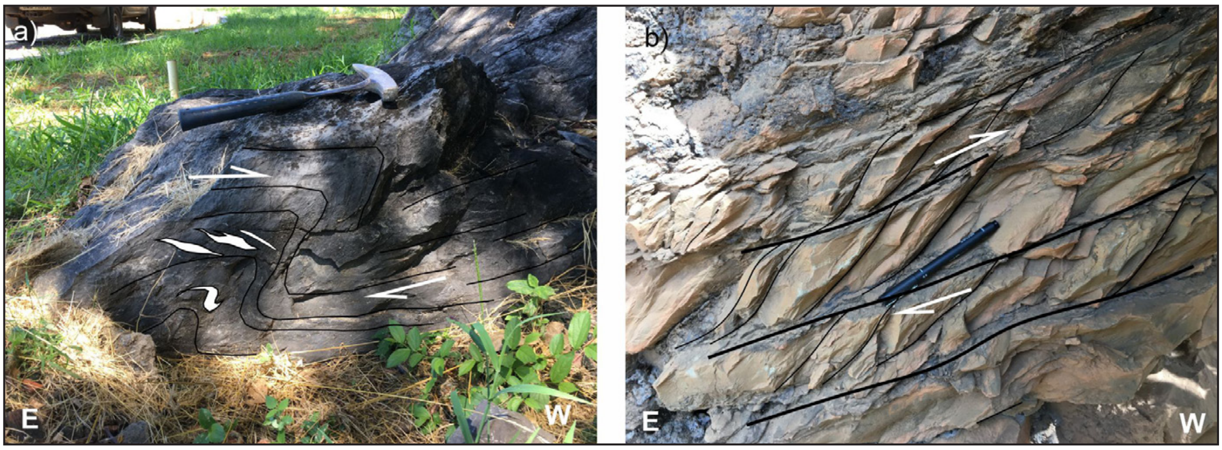

FIGURA 15. Indicators of reverse movement to the west. a) Drag fold *with tension gashes*; b) low-angle shear zone;

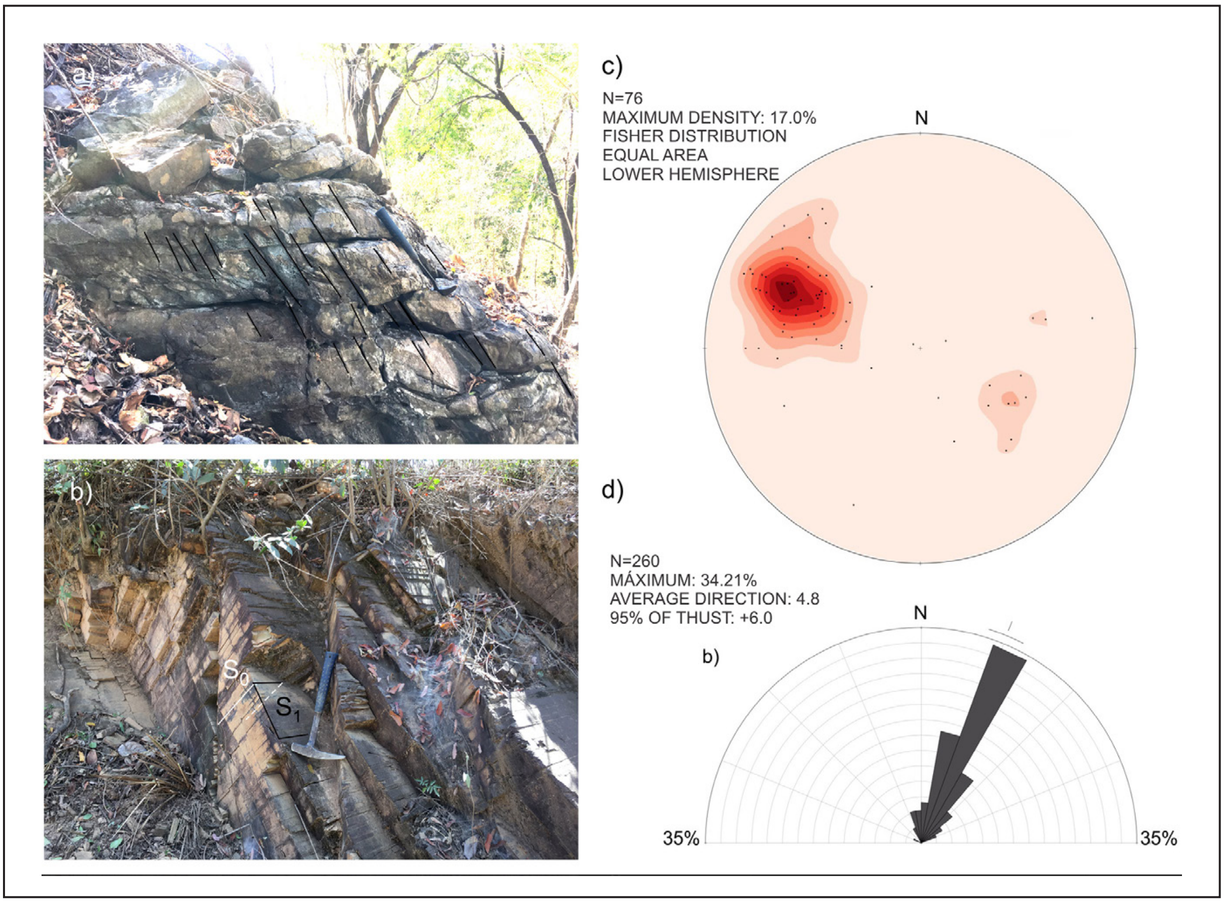

FIGURA 16. a) Fracture cleavage in the limestone of Lagoa do Jacaré Formation; b) Fracture cleavage in the siltstone of Serra de Santa Helena Formation; c) stereogram of S1; d) rosette with the main direction of the cleavage fracture.

In the karstic valleys it is where the majority of caves are concentrated and it is also where the limestones rock faces occur (Fig.20 c, d). Karstic plains are wide and commonly used as cultivation or housing areas. The valleys and karstic plains were formed among the massifs, and it is also where the caves represent the geological history of the local karst, where there is evidence that can explain how the karstic hydrogeological system works. The massifs represent the residual relief, which remained after intense surface dissection along the Neogene. In the Lapa Grande State Park area, the irregularity between the top of the massifs and the bottom of the valleys reaches 200 m, which shows how much the carbonatic rocks were dissolved to give rise to the karstic system, responsible for the significant amount of water that supplies the city of Montes Claros.

6.2. Endokarst

The speleological knowledge in the region is still quite incipient, among so many caves, a few were mapped and/ or studied. Barbosa et al. (2015) published a speleological

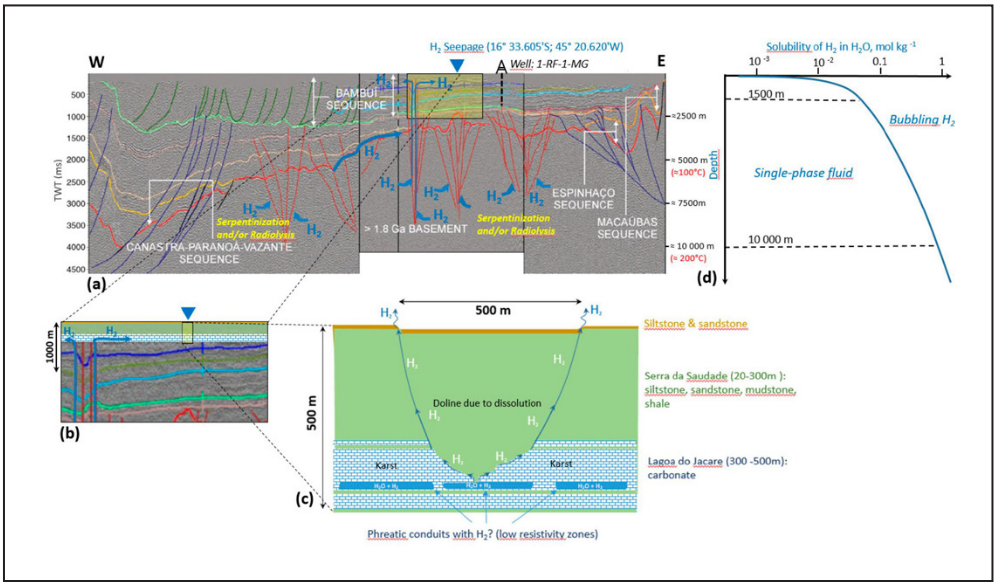

FIGURA 17. Evidence of a deep karst in BSB. a) seismic section interpreted by Martins-Neto (2009) with deep basement faults; b) detail of the upper portion of the Bambuí Group; c) possible presence of a karstic structure related to surface dolines formation; d) solubility of H_2 calculated in H_2O vs. depth (Bazarkina et al. 2020). Compiled from Donzé et al. (2020).

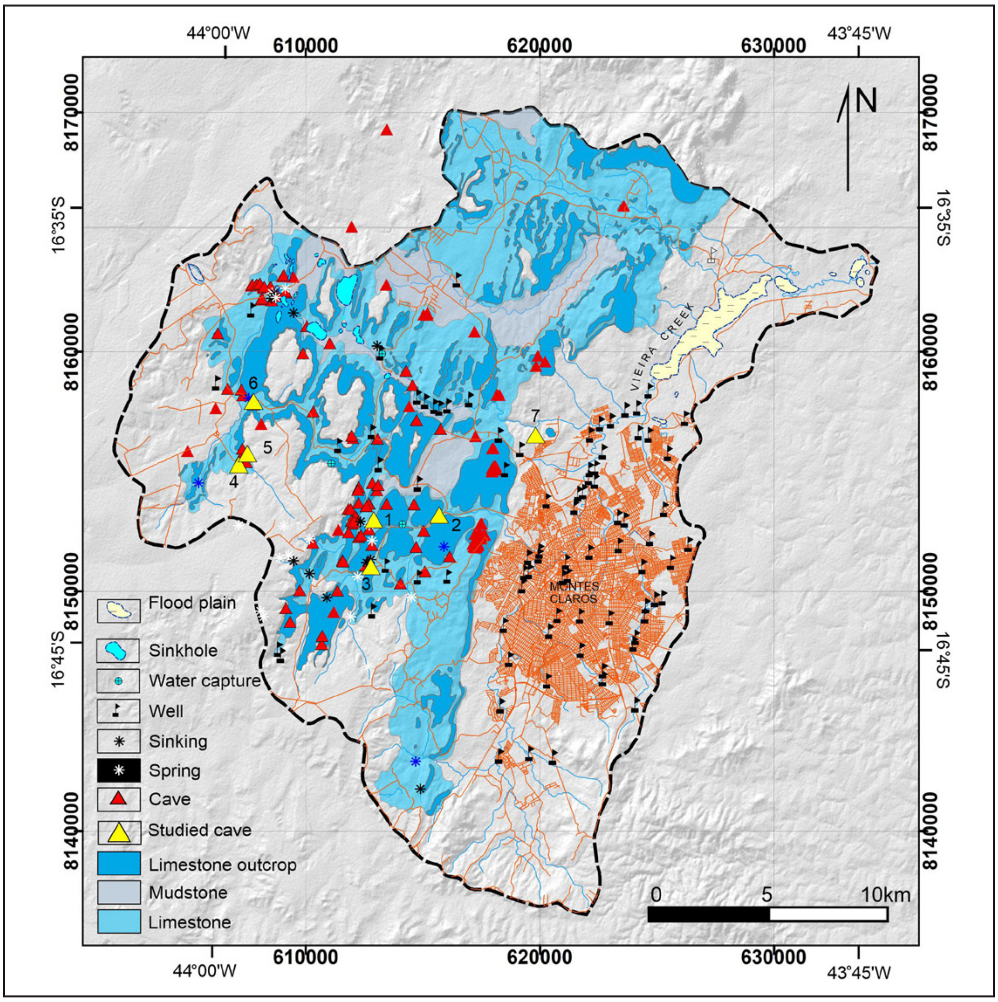

FIGURA 18. Map with the main features of the karst of Vieira river basin. Location data of the caves obtained from Barbosa et al. (2015) and CECAV (2019) while the wells location data are from SIAGAS. The outcropping karst occurs in the western domain of the area and the hypogenic karst in the eastern domain, where the city of Montes Claros is located. Caves studied: (1) "Lapa Grande"; (2) "Lapa d´Água"; (3) "Boqueirão da Nascente"; (4) "Lapa da Claudina"; (5) "Lapa da Santa"; (6) "Lapa Andorinhões"; and (7) "Lapa da Lagoinha".

survey carried out by IGS (Instituto Grande Sertão), where the existence of about 150 caves in the Lapa Grande State Park area was pointed out (Fig. 18). Among these caves, some were pointed out for their water potential and from the point of view of tourist use (Lapa Grande, Lapa do Boqueirão da Nascente, Lapa D´Água, Lapa da Claudina, Lapa da Santa, Lapa do Meireles, Lapa das Andorinhas, Lapa Pintada, Abrigo do Lagarto and Lapa dos Cristais). Studies of joint patterns and cave developments were carried out in six speleological maps. The identified joint families were correlated with those defined in the Vieira river basin area (F1 = NNE-SSW; F2 = WNW-ESE; F3 = NE-SW; e F4 = SSE-NNW). Later, its relations with the local structures (bedding, folds, joints, faults and photo lineaments) were verified (Fig. 20).

“Lapa da Claudina” is situated at the height of 825m and the country rock is a calcirudite with a large collection of primary sedimentary structures, such as plane-parallel bedding, planar cross bedding, channel-fill cross-bedding, and herring bone bedding. It has features of a cave that developed in a deep karst (hypogenic) environment, marked by elliptical “galleries”, domes and roof pendants. The cave has two very distinct structural domains (Fig. 20a). In the western domain the reticulated pattern predominates, controlled by a pair of orthogonal joints (F1) and (F2). Whereas in the east domain, the cave has a dendrite pattern controlled by closed-angle joints (shear pair) where another direction of joint appears that is little evident in the studied area.

“Lapa da Santa” is situated at the 810m elevation and has a pattern of linear development (Fig. 20b). It is a cave typical of a hypogenic environment, with few speleothems and “galleries” with elliptical shapes containing many pendants, domes and bed shapes in the roof. The joints that control the directions of the ducts are F1 and F2.

“Lapa Andorinhões” is situated at the 800m elevation and has a pattern of cross-linked development (Fig. 20c). The cave floor is horizontal and its “galleries” are narrow and very high, controlled by vertical joints, typical of a cave that developed in a regime of vadose water. The cross-linked development pattern of the cave is controlled by joints (F1), (F2) and (F3).

“Lapa Grande” has development, in horizontal projection, around 2200m and is situated at the 710m elevation (Fig. 20d). The cave has a pattern of linear development, with meandering and cross-linked “galleries”. The structures described in the cave are plane-parallel and planar cross beddings, and drag folds with vergence to the west with the axial plane parallel to the joint (F1). The joints (F1), (F3) and (F4), together with the bedding plane (S0) control the cave development, but most galleries are controlled by the joint (F3).

“Lapa d´Água” is located near the seat of the Lagoa Grande State Park, with approximately 1234 m of extension and 17 m of irregularity, its entrance is positioned at the elevation of 737m. The cave has a linear development pattern, conditioned mainly by the F1 and F2 joints and So bedding. The cave is formed by only a “galleries” with geometry similar to a meander.

“Lapa do Boqueirão” da Nascente has a linear form controlled mainly by the F1 joint, with an approximate length of 450 m. Boqueirão complex has several sinkholes and upwellings of Lapa Grande creek, and the underground sections are known as: Boqueirão de Cima (upwelling), Boqueirão do Meio and Boqueirão da Nascente (sinkholes), upstream to downstream (Barbosa et al. 2015).

FIGURA 19. Karst features. a) doline field; b) detail showing a doline in a karstic plain; c) karstic valley (at the top there are the pelites of Serra da Saudade Formation, the rock faces are made of limestone and the bottom of the valley of a layer of pelite); d) detail showing the rock face of the karstic valley of Lapa Grande (photo courtesy of Eduardo Gomes).

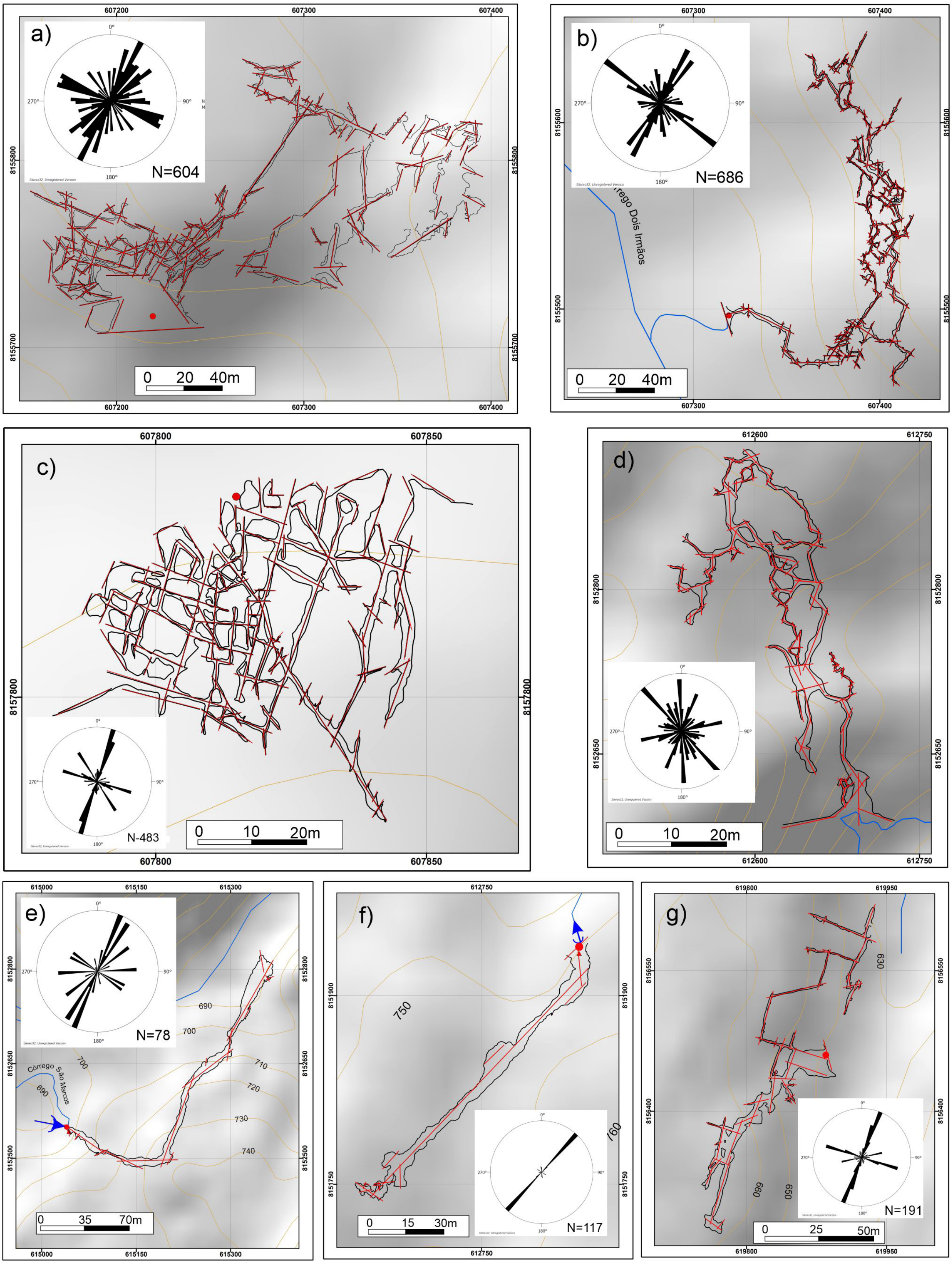

FIGURA 20. Simplified cave maps with the interpretation of the main directions of the joints and the rosettes of each cave. a) "Lapa da Claudina", b) "Lapa da Santa"; c) "Lapa Andorinhões"; d) "Lapa Grande", e) "Lapa D´Água", f) "Lapa do Boqueirão da Nascente" (Source: Peter Lund Speleogroup); g) "Lapa da Lagoinha" (Source: Machina Mundi Geology and Environment Ltda).

“Lapa da Lagoinha” is located in the eastern portion of the Vieira river basin, in the domain of Serra de Santa Helena Formation and has horizontal linear development of about 1000m, it is located at the elevation of 635 m (Fig. 20 g). The cave is embedded in a lens/layer of dark gray pure limestones, inserted in the context of siliciclastic rocks (siltstones and argillites) and has a cross-linked pattern, controlled by pairs of joints, being the main direction of development (F1) and the secondary direction (F3).

6.3. Features of the non-outcropping karst

In the area studied, groundwater is a natural resource of major importance, since it is a region that is constantly beset by long dry seasons and that most surface water courses are constantly dry. The discussion about the existence of a non-outcropping karst (hypogenic) in the region creates a perspective for the presence of an unexplored aquifer and thus a greater water availability for the region. This premise arose from the following findings: i) in the urban area of Montes Claros, groundwater that is exploited from tubular wells becomes an important source of supply in an area where limestone rocks do not outcrop; ii) the perception that the limestone rocks of Sete Lagoas Formation in the different regions where they outcrop (Januária-Itacarambí, Arcos-Pains and Sete Lagoas) exhibit very developed karstic features; iii) in the limestone rocks of the region, quartz, calcite, fluorite and galena veins were observed, in addition to speleothem gypsums, which are signs of hydrothermal activity. This led us to explore the possibility of a deep non-outcropping karst in the limestones of Sete Lagoas Formation, which in the urban area of Montes Claros are covered by the pelitic rocks of Serra de Santa Helena Formation.

Segments of seismic sections located in the Eastern portion of Vieira River basin, where the limestones are covered by siliciclastic rocks, were analyzed. In these sections, cave features related to faults and deep joints were identified in the limestones of Sete Lagoas Formation (Fig. 21). These structures are evidence of karstic structures in depth. The existence of these structures shows us that groundwater extracted from the tubular wells in the urban area of Montes Claros is part of the non-outcropping karstic aquifer of Sete Lagoas Formation.

The tubular wells used in underground water collection in the urban area of Montes Claros are further evidence of the existence of a deep karstic aquifer in the limestones of Sete Lagoas Formation.

Some features observed in the limestones Lagoa do Jacaré Formation that affect the caves of the region point to a karst that has a phase of hypogenic development that evolved to an epigenetic or vadose phase. These caves were possibly formed in depth and, subsequently, due to denudation and/or uplifting were raised to a shallower level of the earth's surface from that moment on, a new phase of vadose karstification (epigenetics) overlaps the previous phase, generating chemical and clastic deposits (speleothems) partially covering the pressure conduits.

The hypotheses for the deep karst formation in this region would be: i) the presence of an early formed paleokarst when the limestone rocks were exposed after their deposition; ii) the formation of a hypo genetic karst resulting from the circulation of deep waters associated with bacinal fluids and/or from the deep circulation of meteoric waters in fault areas.

6.4. Karst structural controls

The development of most caves in the region can be represented by lines of intersection between the bedding plan and the F1 and F2 joints planes.(Fig. 21). With this structural control the caves of the region are usually horizontal, or at most with small irregularities.

The galleries have circular, elliptical and ogival sections. Other characteristic features that occur in the caves are pendants, roof channels, pressure phreatic ducts, domes and paleokarst features (Fig. 22). The levels of karstification occur throughout the exposed section of the limestones of Lagoa do Jacaré Formation, as it can be observed in lithostratigraphic profiles (Fig. 23). In the caves below the elevation of 750m, the water has a perennial regime and, in the caves between the 800m and 850m elevations, the water flow is seasonal.

The faults are rare structures in the region, but when they are present, they can represent the infiltration plane (recharge aquifers) and circulation of groundwater, including on a regional scale. They can also provide the link among different aquifers. The fracture cleavage is a little penetrating structure and occurs in a restricted way in areas associated with folds and fault areas , and can function as zones for water infiltration and circulation. Karstic features are rarely controlled by this structure. On the other hand, the axial planes of the folds act as a dissolving plan in the limestones, but they occur less frequently than the joints, which are much more common and are present in almost the entire area.

7. Discussion

The karst structural controls can be considered on a regional and local scale. On a regional scale, the morpho-structural controls are represented by joints and faults that occur in domains 3, 7, and 8. Domain 3 is where the siliciclastic rocks of Serra de Santa Helena Formation outcrop and the fracturing pattern is represented by photo lineaments in the NNE-SSW, E-W and ESE-WNW directions. In the morpho-structural domains 7 and 8, where the limestone rocks of Lagoa do Jacaré Formation outcrop, the structural pattern is represented mainly by the NNE-SSW photo lineament.

In the magnetic airbone geophysical map structures with NNE-SSW orientation appear which can be interpreted as fault zones and deep joints. Another structure observed was a swarm of dikes (outcropping) of NNW-SSE orientation, which possibly do not cut the rocks of the Bambuí Group.

In the scale of geological mapping (1:50,000) two structural domains (Central and East) were defined where a pair of orthogonal joints represented by the F1 (NNE-SSW) and F2 (WNW-ESE) joints predominate, which is also present on a regional scale. The direction of the reverse faults coincides with the direction of the F1 joints and the direction of the transcurrent faults associated with the front thrust coincide with the F2 joints direction.

In detailed scale, the F1 and F2 joints are the main controls of the cave ducts, along with the bedding. These are the same directions described on a regional and local scale, which shows that the structural control of the exokarst is the same as that of the endokarst. In the cave maps, ducts also occur 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.

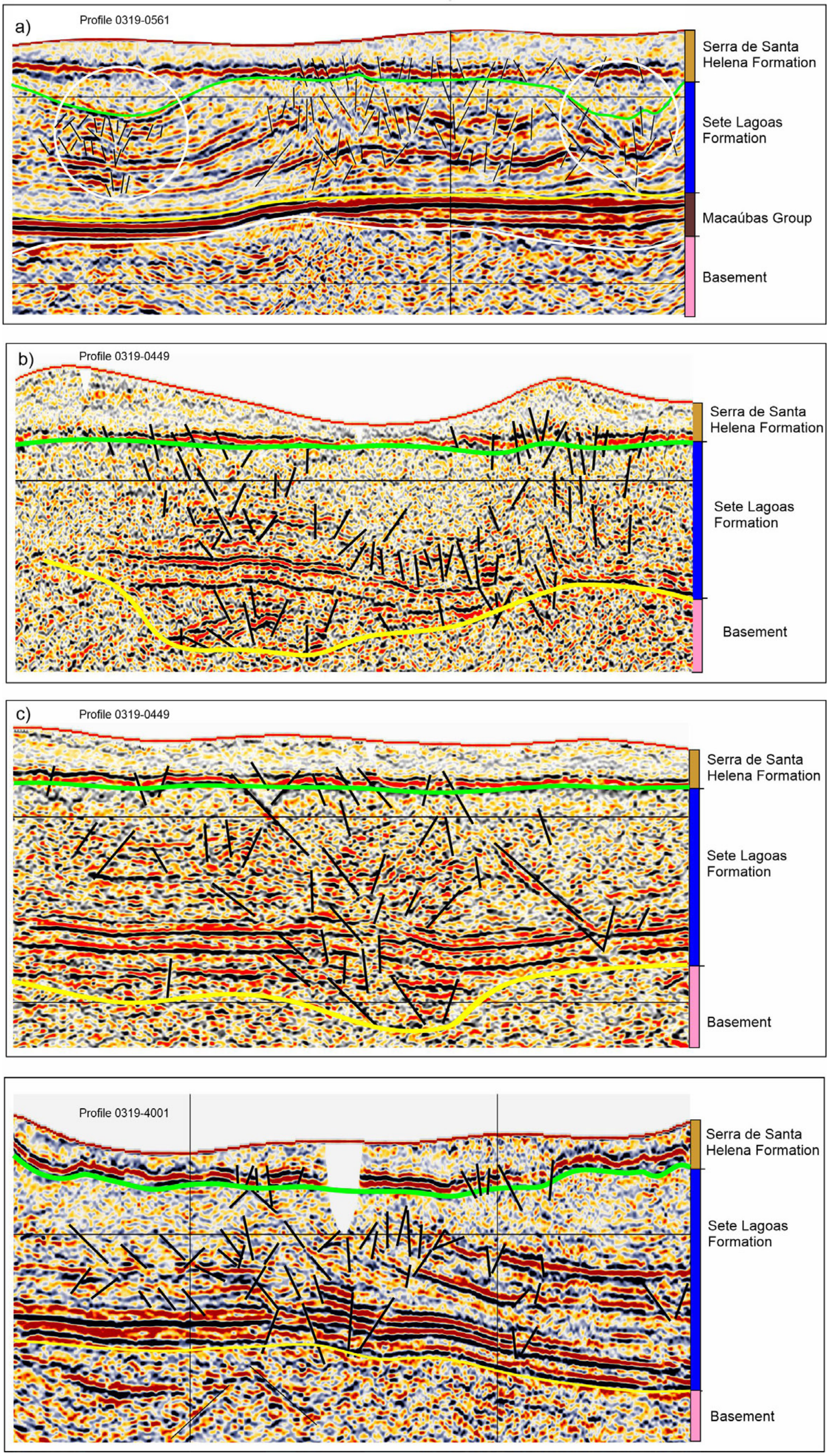

FIGURA 21. Detail of part of the seismic sections located in the Eastern domain of Vieira river basin, where collapse features associated with a joint system and doline formation (circles) have been interpreted that may be related to a deep non-outcropping karstic environment in the rocks of Sete Lagoas Formation in Montes Claros region.

In all scales the structures that controlled the development of karstic features in the Vieira river basin are the F1 and F2 joints and the bedding (S_0). These structures are conditioned by the persistent folds that occur from kilometers to outcropping scale. The F1 joints direction coincides with: i) the direction of normal fault that controls the São Francisco river bed in the region (Fig.3); ii) the direction of photo lineaments of the morpho-structural domain "8" described in the item regional analysis (Fig. 4); (iii) with the axial planes of the folds perpendicular to the maximum direction of compression (Fig. 4); iv) with the preferential direction of the caves development of the region; v) and also controls the surface drainage network (Fig. 24). The F2 joints are perpendicular to the folds axes and their origin was related to the maximum distension direction.

The F1 and F2 joints are the most penetrating ruptile structures in the rocks of the studied area and together with the

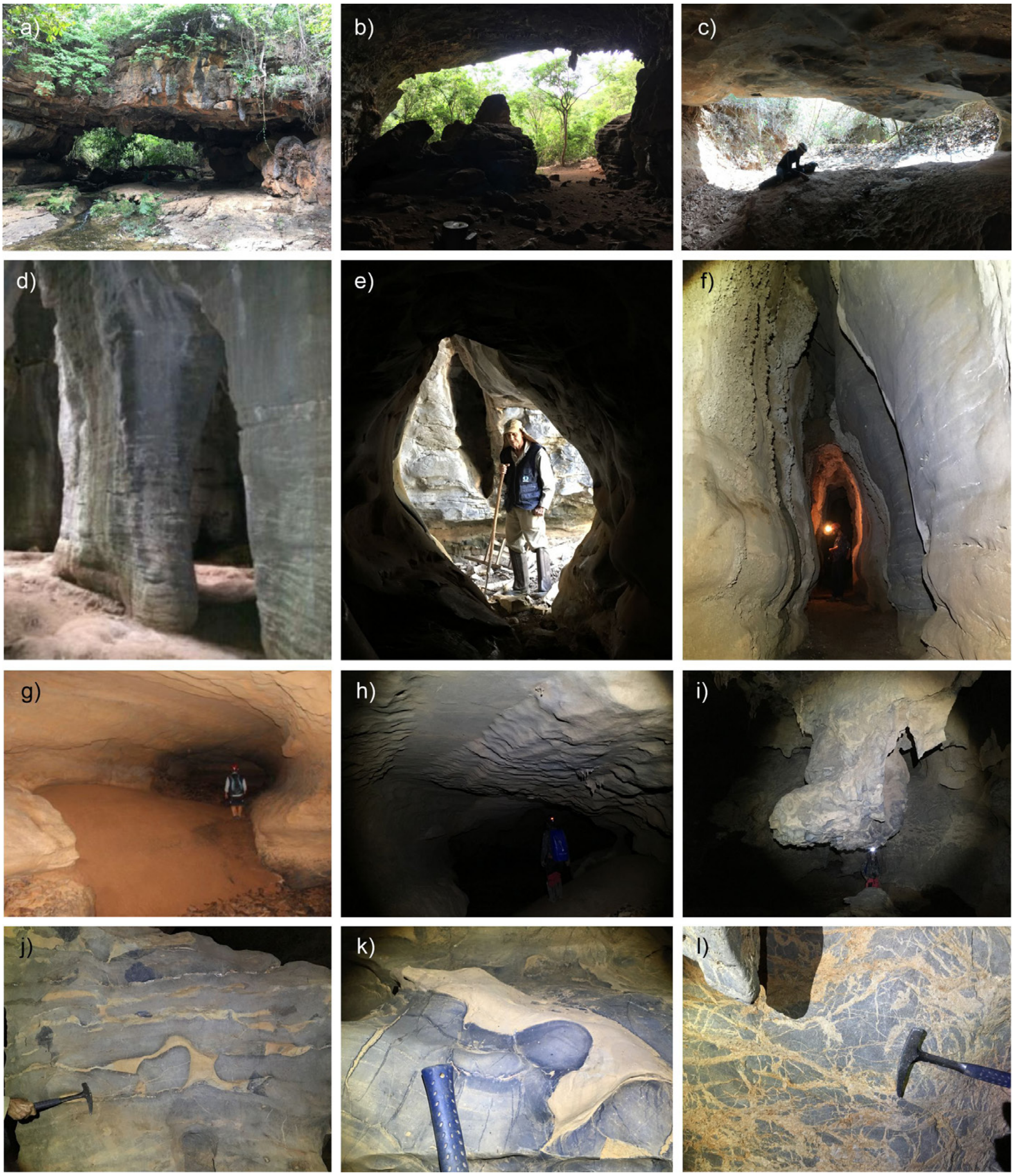

FIGURA 22. Main features of the karst described in the studied caves. a) Natural bridge in the Lapa Grande State Park, controlled by the bedding; b) entrance of Lapa Grande, controlled by the bedding and joint F1; c) elliptical entrance of Lapa da Santa controlled only by the bedding; d) conduits of Lapa das Andorinhas, controlled only by a pair of joints (F1 and F2); e) joint-controlled conduit; f) joint-controlled conduit of Lapa das Andorinhas; g) Santa Lapa pressure conduit, with clay deposit partially clogging the gallery; h) roof channel of Lapa da Santa; i) pendant dinosaur paw, in Lapa da Santa; j) paleokarst feature in Lapa da Claudina; k) paleokarst feature in Lapa da Santa; l) calcite stockwork veins, in Lapa da Claudina "cave".

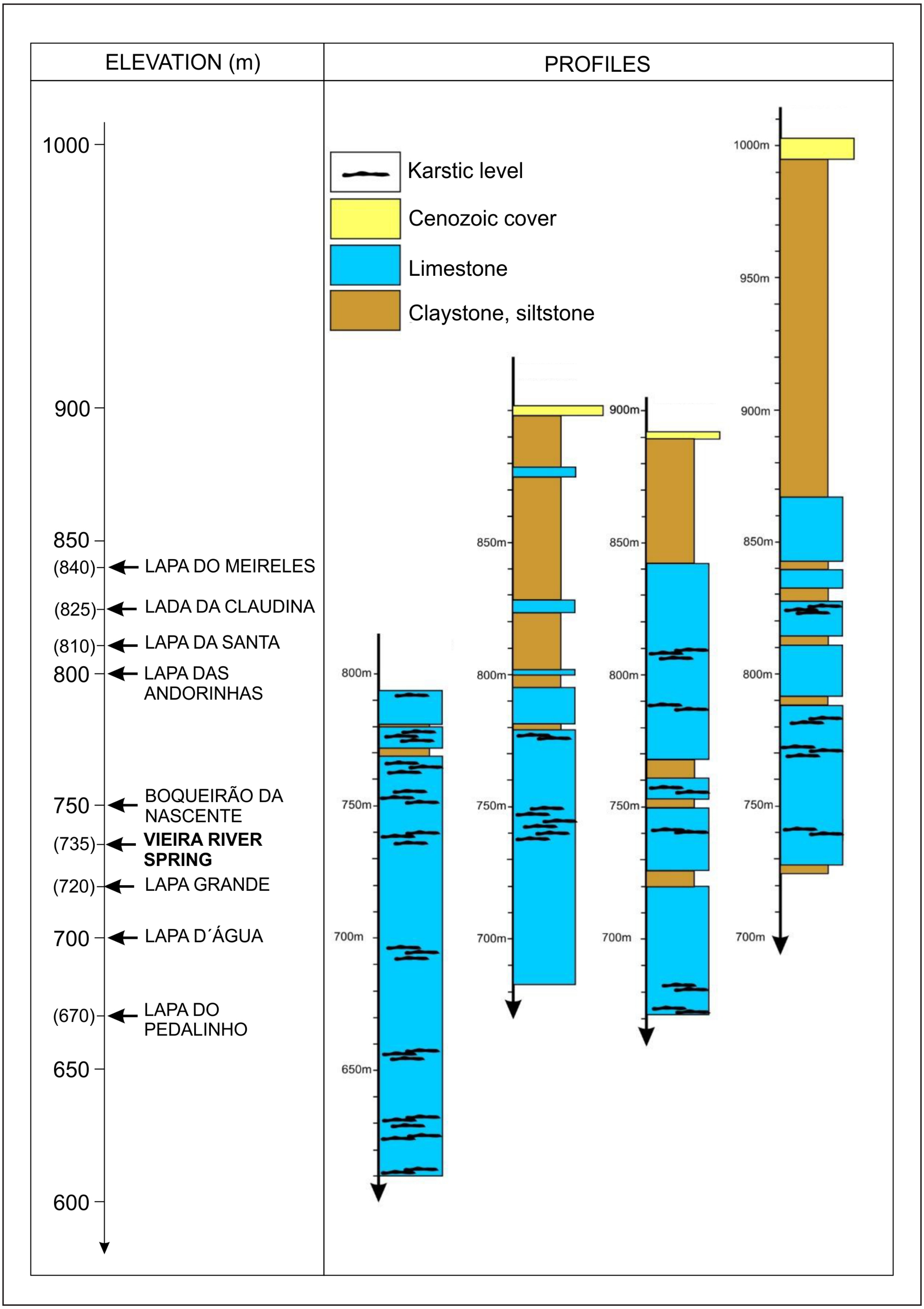

FIGURA 23. Lithostratigraphic profiles with the location of karstification levels in the limestones of Lagoa do Jacaré Formation and its relationship with some caves and the spring of Vieira river.

bedding (S0) are the main structures that allow the limestone dissolution and consequently the groundwater circulation in the studied region, either for the recharge or for the storage of water, which led to the formation of the karstic aquifers of the region.

Dissolution in the bedding plan is common in the area, even where there are no caves. The development of most caves in the region can be represented by lines of intersection between the bedding plan and the F1 and F2 joints planes. With this structural control the caves of the region are usually horizontal, or at most with small irregularities.

These structures were related to the Brasiliano compressive event, which generated a fold system related to the front thrust of Araçuaí orogen. The South-Atlantic tectonics, represented by dikes that are deep structures (interpreted from airbone geophysical map), may have reactivated the older structures or even created new brittle structures that can also exert control in the non-outcropping karst.

8. Conclusion

In the area studied, groundwater is a natural resource of major importance, since it is a region that is constantly beset by long dry seasons and that most surface water courses are constantly dry.

The groundwater occurs in two different karstic systems: i) one in the outcropping karst of Lagoa do Jacaré Formation; ii) and another in the non-outcropping karst of Sete Lagoas Formation.

The conclusion of this study is that the main structures that controlled the karst development in the region of Montes Claros are the joints (F1 and F2) and the limestones primary bedding. The F1 joints have NNE-SSW direction, parallel to the front thrust and to the folds axial planes, control the geometry of the surface drainage network, are the main directions of the limestone rock faces, the karstic valleys and the galleries of the studied caves. Whereas the F2 joints with WNW-ESE direction, are perpendicular to the F1 family, control the surface drainage network and the cave galleries directions. The intersection planes between the bedding and the joints and/or among different joints is what defines the geometry of the karstic features in the area.

Acknowledgements

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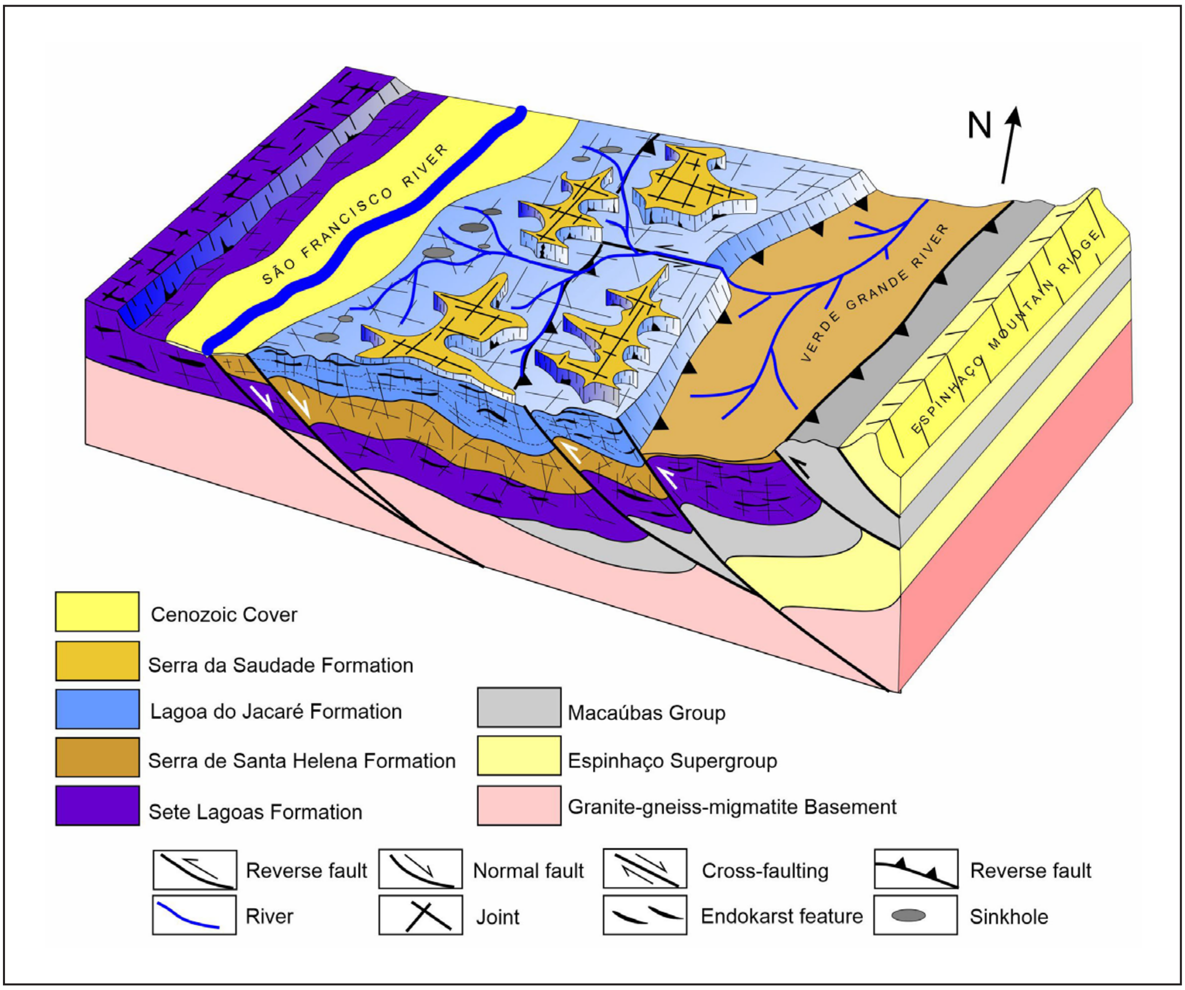

FIGURA 24. Simplified block diagram with stratigraphy and the main karstic structures and features that occur in the studied region.

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Authorship credits

Author	A	B	C	D	E
JADC					

A - Conceptualization
B - Methodology
C - Data Interpretation/ Validation
D - Writing
E - Review/Editing

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