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GEOMORPHOLOGICAL UNITS IN ARCOS-PAINS KARST REGION, MINAS GERAIS, BRAZIL

GEOMORFOLOŠKE ENOTE NA KRAŠKEM OBMOČJU ARCOS-PAINS, MINAS GERAIS, BRAZILIJA

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Mariana Barbosa Timo & Luiz Eduardo Panisset Travassos: Geomorphological units in Arcos-pains karst region, Minas gerais, Brazil

The Arcos-Pains Karst Region is approximately 850 km^2, formed by massive carbonate rocks that host hundreds of caves, rock shelters and shafts. Many fossil discoveries exist in the region; one can also find rock paintings and other archaeological remains. A ruiniform landscape, weathered caves and continuous or isolated outcrops characterize the karst. They are cut by diaclasis, fractures and fissures, separated by flattened relief with dolines, uvalas, ponors and blind valleys. The evolution of karst morphology in the region reflects pluviometric and paleoclimatic variations, with faults and fractures from neotectonics events exerting control over water flows. One can observe four geomorphological compartments in this region, each with specific characteristics. The region is an outstanding example of the Brazilian intertropical karst and one of the most important Brazilian mineral deposits of limestone and dolomite. So, delimitating its geomorphological units can facilitate understanding the speleological heritage and guide strategic decisions for sustainable use.

Keywords: geomorphological unit, karst, speleology, delimitation.

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Mariana Barbosa Timo & Luiz Eduardo Panisset Travassos: Geomorfološke enote na kraškem območju Arcos-Pains, Minas gerais, Brazilija

Kraško območje Arcos-Pains meri približno 850 km^2, tvorijo pa ga masivne karbonatne kamnine, v katerih je več sto jam, spodmolov in brezen. Na območju je veliko najdišč fosilov, najti je mogoče tudi jamske slikarije in druge arheološke ostanke. Za kras so značilni ruševnata pokrajina z denudiranimi jamami in neprekinjeni ali osamljeni izdanki razpokanih in močno zakraselih karbonatov. Med temi so uravnana območja z vrtačami, uvalami, požiralniki in slepimi dolinami. Kraška morfologija odraža pretekle hidrološke in paleoklimatske razmere, pri čemer na vodne tokove pomembno vpliva tudi neotektonika. Na območju je mogoče opaziti štiri geomorfološke enote, vsaka ima specifične značilnosti. Območje je izjemen primer brazilskega tropskega krasa in eno najpomembnejših brazilskih nahajališč apnenca in dolomita. Zato lahko razmejitev njegovih geomorfoloških enot olajša razumevanje speleološke dediščine in usmerja strateške odločitve za trajnostno rabo.

Ključne besede: geomorfološka enota, kras, speleologija, razmejitev.

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1. INTRODUCTION

In the Brazilian territory, the carbonate areas cover between 425,000 and 600,000 km^2, representing approximately 7 % of the country's area (Karmann, 1994). The "Brazilian Speleological Region Map" displays 19 speleological regions (Cecav, 2011). Among these speleological regions, the Bambuí Group currently stands out with the largest number of identified caves (Figure 1). The Bambuí Group region, also known as the Bambuí speleological province, covers about 150,000 km^2 and encompasses the west-central, north and northwest portions of Minas Gerais, east of the Federal District, northeast of Goiás, southeast of Tocantins, and west of Bahia.

The karst associated with this province develops in two geological units: the Sete Lagoas Formation and the Lagoa do Jacaré Formation (Roldan et al., 2004). Great caves such as Toca da Boa Vista (107,000 m), the Boqueirão Cave (15,170 m), São Matheus III Cave (10,828 m), São Vicente I Cave (10,130 m), the Terra Ronca Cave System (7,500 m), Janelão Cave (4,740 m), Morena Cave (4,620 m), Lapa Nova Cave (4,550 m), Areias-Chico Bento Cave System (4,610 m), Eden Cave (2,600 m) and the numerous caves registered in the region of Sete Lagoas and Lagoa Santa in Minas Gerais, are all located within the limits of the Bambuí speleological province.

Due to the wide area occupied by the Bambuí speleological province, it can be divided into districts. However, the government's environmental agency has not yet established the exact limit of these districts. According to the Cecav (2011), currently it is possible to identify nine districts, as follows: 1) São Domingos (Goiás), 2) Formosa (Goiás), 3) Lagoa Santa (Minas Gerais), 4) Cordisburgo-Montes Claros (Minas Gerais), 5) Vazante-Paracatu (Minas Gerais), 6) Arcos-Pains (Minas Gerais), 7) São Francisco-São Desiderio (Bahia), 8) Irecê-Campo Formoso (Bahia) and 9) Alto Paraguaçu (Bahia).

The Arcos-Pains Karst Region has approximately 850 km^2, formed by massive limestone that hosts hundreds of caves, rock shelters, and abysses in which fossils, rock paintings, and archaeological artefacts have been found. This karst region is an extremely eroded karst composed of extensive massive limestone marked by different types of karren, underground drainage with ponors, estavelles, dolines, canyons, and other geological structures such as folds and faults.

The caves in this Speleological Unit are smaller when compared with others located in other units of the Bambuí speleological province. However, this does not imply that this unit has a lower speleological relevance (Teixeira & Dias, 2003). It is widely known in the national caving scenario due to its important scientific discoveries.

According to Piló (1999), one of the most important Brazilian mineral deposits of limestone and dolomite is in the Arcos-Pains Karst Region. As a result, several companies are installed in the region to exploit these rocks. Such type of land use, coupled with poor management of the Speleological Heritage, has caused significant environmental impacts on a regional level. In addition to the impacts of mining, there are also large deforested areas for agricultural and pasture use. The unplanned use of karst for urban occupation and tourism is also an issue. Despite the impacts observed in the area, the region still hosts many research possibilities, particularly at the local level of geomorphological units.

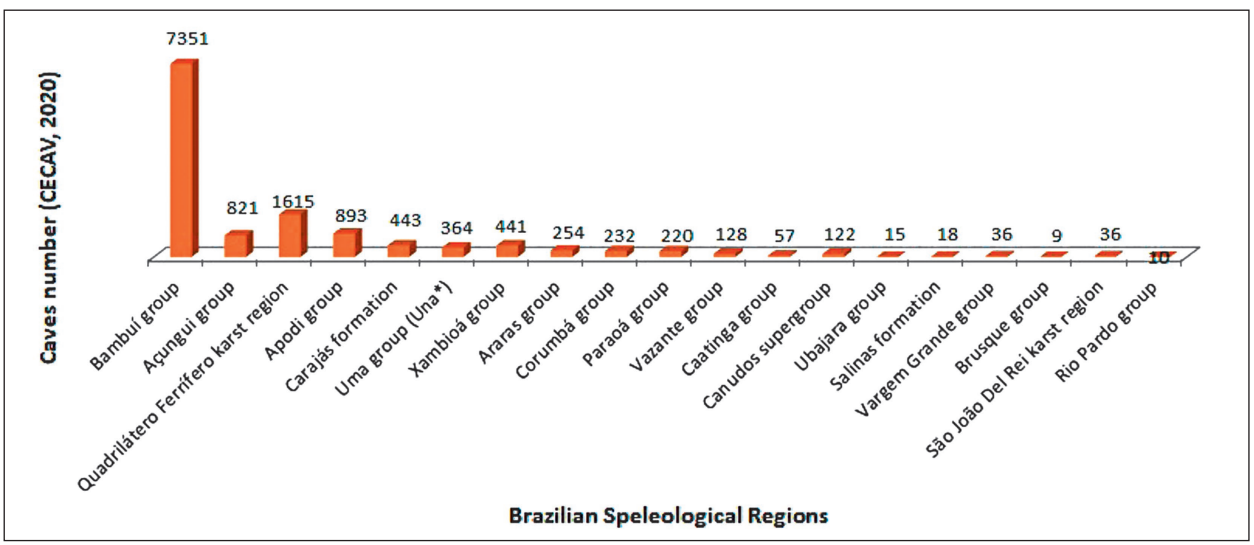

Figure 1: Brazilian cave distribution available in the CECAV database (CECAV, 2020).

2. CHARACTERIZATION OF THE STUDY AREA

The Arcos-Pains Karst Region is located at the southern end of the Intracratonic São Francisco basin, in the southeastern part of the eponymous Craton (see Figure 2), on the border with the Brasilia Fold Belt. The main outcropping lithostratigraphic unit is the São Francisco Supergroup. In a subordinate unit occur fragments of the St. Hilario Formation and the Boa Esperança Sequence at the southern end of the area, all of Neoproterozoic age. In addition to these units, there are Phanerozoic sedimentary covers (Martins Neto & Pinto 2001).

The units of the São Francisco Supergroup recorded very different tectonic arrangements and gave the basin its poly-historical character (Dominguez, 1993; Alkimim & Martins Neto, 2001). The evolutionary geological model includes different stages showing structures originated by rift-margin basins with passive and convergent stages related to the Gondwanaland formation, followed by the development of the backarc and foreland.

The largest unit of São Francisco Craton is the São Francisco Supergroup, composed of the Macaúbas and the Bambuí groups. The study area is located within the so-called Bambuí Speleological province, composed of a succession of carbonate and pelitic rocks and occasionally conglomerate and sandstone (Figure 2), registering a widespread marine transgression (Dardenne, 1978; Dominguez, 1993; Dardenne & Schobbenhaus, 2000).

The geological and structural framework of the study area was described by Alkmim and Martins Neto (2001). According to these authors, this basin has three structural compartments. They are defined as follows: 1) West, representing the external zone of the Brasilia Fold Belt and Rio Preto Fold Belt; 2) East, covering the ends of the Araçuaí Belt; and 3) central portion, represented by the Upper Sete Lagoas, where the Precambrian units were almost entirely unaffected.

According to Martins (2013), the region's topography of the Arcos-Pains Karst Region can be divided into two large morphostructural areas: the Craton São

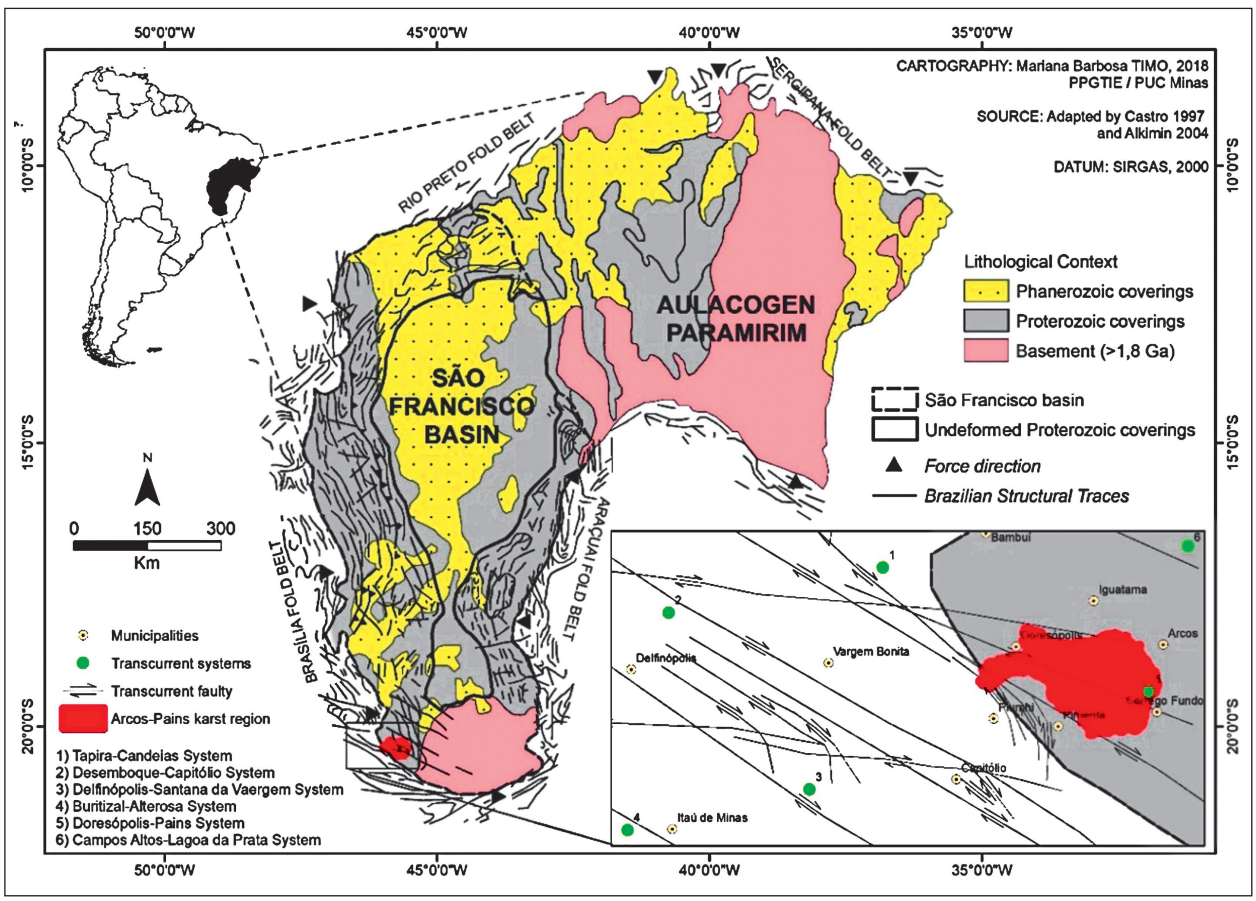

Figure 2: São Francisco Craton localization and its fold range in the geotectonic regional context. In the southwestern portion of the São Francisco Basin, transverse faults associated with jerk failures and positioning of the studied region can be observed, evidenced in red. Source: Adapted by Castro (1997, p. 51) and Alkmin (2004, p. 21).

Francisco and the Brasilia Fold Belt. According to the author, the morphostructural complex craton can be divided into three distinct morphostructural units. These are classified as the Alluvial Cenozoic Deposits, the São Francisco Sedimentary Basin and the Basement. This classification considers the genesis, age and rock types of the units. The author also suggests that the Brasilia Fold Belt can be called the Piumhi Greenstone Belt.

Considering the classification Martins (2013) developed, this research is located in the morphostructural unit of the São Francisco Sedimentary Basin. This morphostructural unit developed along the São Francisco river drainage, initially in the valleys of large rivers oriented by fractures, later extending by aggradation processes. One can predominantly observe flattened geomorphology and undulating surface pediments, except in karst areas with peculiar morphology.

According to the CETEC (1983), the spatial arrangement of landforms of the Upper São Francisco Depression results from the combination of lithological and structural factors associated with dissection events, aggradation, river accumulation, and rock dissolution.

The Piumhi Greenstone Belt relates to the Canastra Group rocks, consisting of quartzites and phyllites, possibly originating from the Craton. It outcrops west of Minas Gerais (Baptista et al., 2010).

The relief dissection is most noticeable southwest of the unit, where the Canastra Ridge intercepts the different rocks of the Bambuí Group. Throughout the rest of the region, drainage produces hills with slopes covered with surface sediments resulting from the local alteration of rocks (Baptista et al., 2010).

The region is within the boundaries of the Cerrado vegetation (IBGE 2004). However, due to its soil and climatic characteristics, it is possible to identify variations of the Atlantic Forest Biome. The area is in a transitional environment between the Atlantic Forest and the Cerrado (Brazilian Savana), two of the most biodiverse and threatened ecosystems in the world (Myers et al. 2000). In Brazil, in the Cerrado Biome, Dry Forests associated with carbonate rocks are widespread, especially linked to carbonate karst (Rodrigues, 2011; Rodrigues & Travassos, 2013).

The vegetation has been used extensively throughout the Arcos-Pains Karst Region, but some remaining regions remain intact. In most regions, the Dry Forests occur only on the carbonate outcrops (Figure 3). The anthropogenic pressure is present through traditional activities such as extensive livestock and crops such as beans and corn to supply regional markets.

The Cerrado area's solar radiation is usually intense, with October being the warmest month. Winter is dry almost cloudless, and the solar radiation is also intense, especially at noon. This intensity can be reduced in August and September due to the abundance of haze produced by fires and burning vegetation (Inmet, 2013).

One of the most important Brazilian rivers, the São Francisco, is critical for the amount of water transported from areas with high water potential for the Brazilian semiarid region where such resources are scarce. The San Francisco River Basin covers 521 municipalities in six states. With 2700 kilometres in length, the San Francisco River sources in the Canastra Ridge in Minas Gerais and flows just a few kilometres to the south, then to the north through the states of Bahia and Pernambuco, when it changes its course slightly to the southeast, reaching the Atlantic Ocean in the border between Alagoas and Sergipe. Due to its length and the different environments along its course, the region basin is divided into Upper, Middle, Lower-Middle and Lower São Francisco (Ana, 2013).

The study area is located in the Upper São Francisco River. The main drainage of the region corresponds to the São Miguel River and the Patos Stream, both situated on the right bank of the San Francisco River in the midwest of Minas Gerais. Although situated in karst, the main

Figure 3: General view of one outcrop of Posse Grande Region, Arcos (MG), during the dry period. Note the occurrence of Dry Forest just on the residual features. Photo: Mariana Barbosa Timo, 2013.

course of these drains is perennial and shallow. For the most part, land uses include pasture fields for livestock, agriculture, urban occupation, mining, and processing of carbonate rocks (Haddad, 2007). The author further states that these human activities favour water quality change. The predisposition to pollution is facilitated by karst features such as sinkholes and ponors, which often promote a broad connection between the surface and underground drainage.

3. ARCOS-PAINS KARST REGION

A ruiniform landscape, weathered caves and continuous or isolated outcrops characterize the karst. They are cut by diaclasis and chasms, separated by flattened relief with dolines, uvalas, sinks and blind valleys. The evolution of karst morphology in the region reflects pluviometric and paleoclimatic variations, with faults and fractures (neotectonics) exerting control over water flows (Barbosa, 1961; CPRM, 2008).

Santos (2002) still attributes regional karst morphogenesis to neotectonics and their association between upright and transcurrent shear N50W. Probably, the karstification process happened consecutively to the graben's generation. This karst region's chronological evolution occurred in the following stages (Figure 4): 1) during the Eocene, the region was flattened. The principle of the karstification process generated dolines possibly

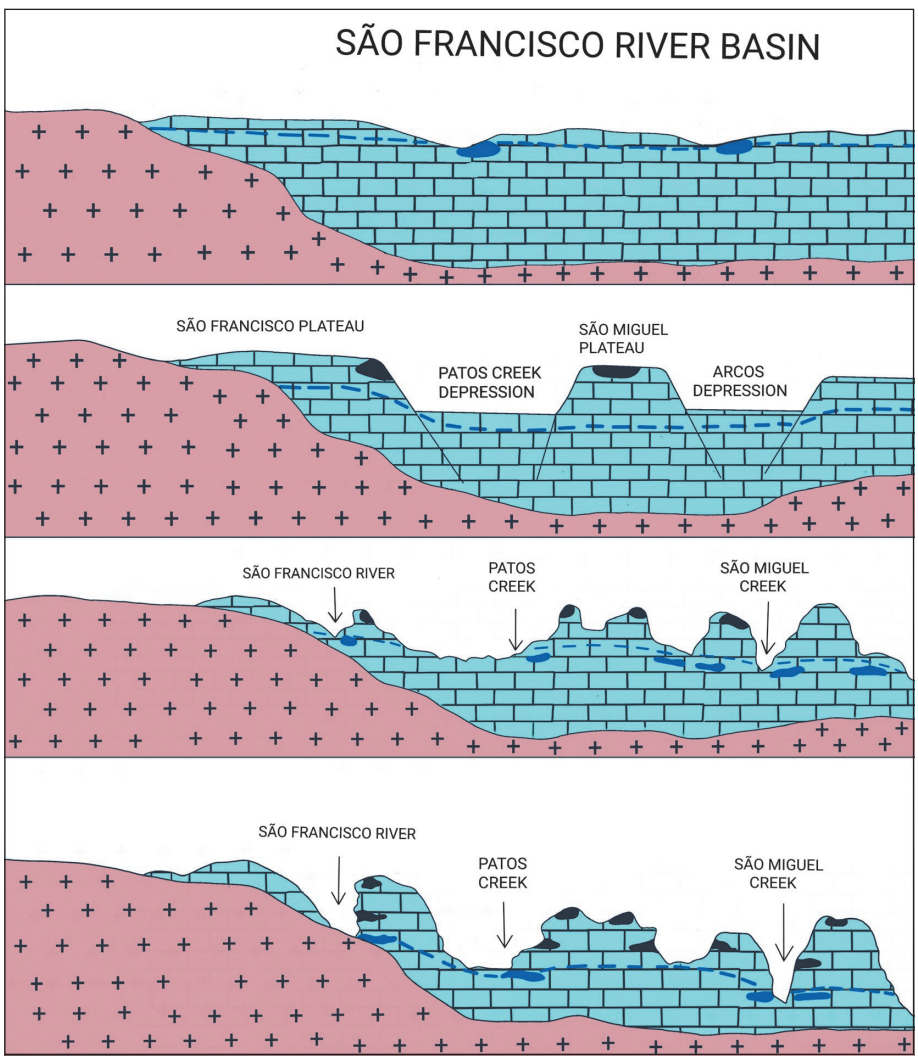

Figure 4: Simplified sketch (without scale) of the chronological evolution of the Arcos-Pains karst region. Source: Designed by Juliana Barbosa Timo and Mariana Barbosa Timo, from Santos (2002).

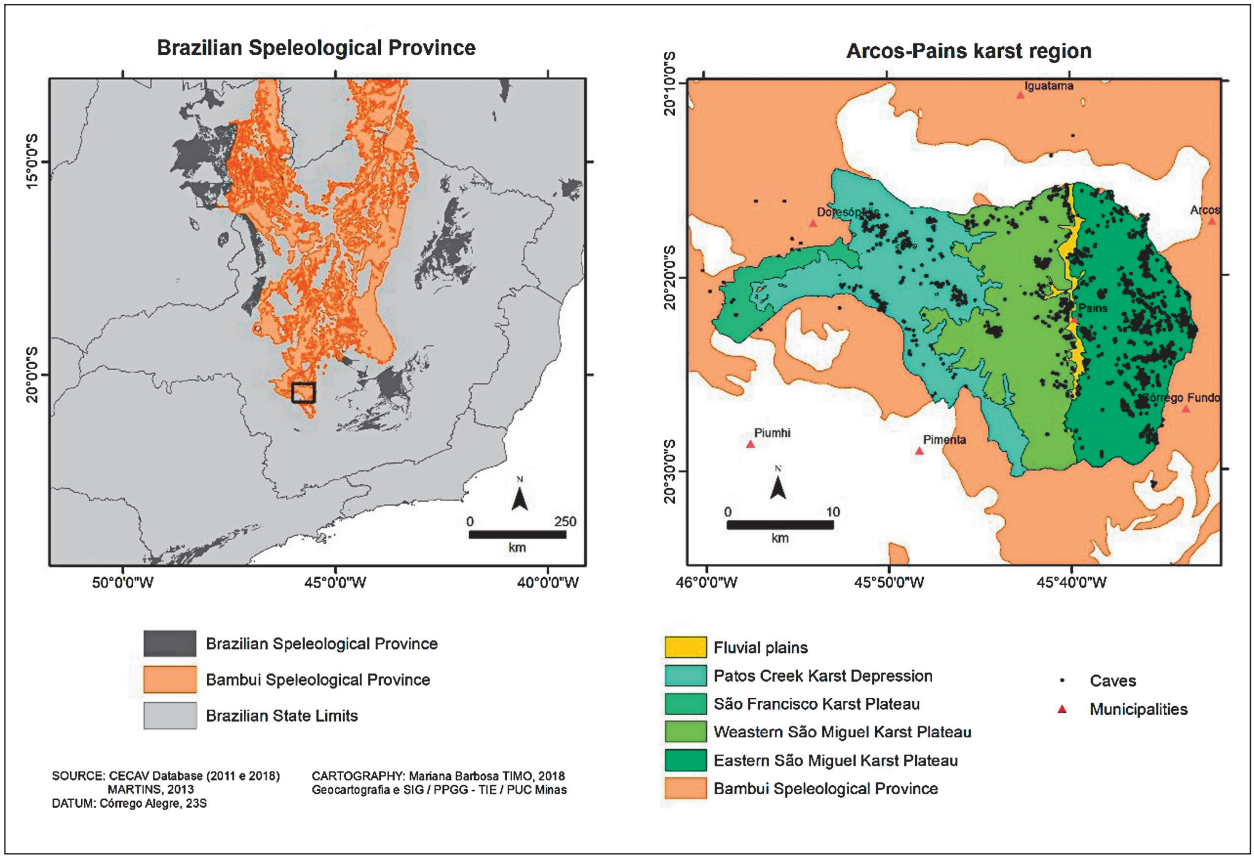

Figure 5: Location map of Arcos-Pains Karst Region and its geomorphological units.

controlled by passive faults N50W to N70W. With the rise of the Bom Despacho Structural High, N-S fractures were opened and used to form the first generation of caves in the province. 2) in order to activate the karst, the grabens of Arcos (N30W) and Doresópolis (N40W) are formed. With this, the local base level is lowered, favouring the São Francisco River Canyon's genesis. Another consequence of this process is the erosion of the pelitic cover in the province's southern portion. The caves of the first generation are then emptied, and the tops of the limestone masses begin to be exposed and lapped. 3) the second generation of caves begins to form from the newly established base level, probably in the Lower Pleistocene. The formation of dolines is then controlled by active distension faults in the N30W and N40W directions. With the upraised southern part (basement), the dissection process reaches the basement's gneisses, feeding the terraces with quartz. 4) the uplift continues more intensely to the south, keeping the arching in the N-S direction. This process favours the province's main watercourses, the Patos Creek and the São Miguel River. The base level is lowered during the incision, allowing dolinas and uvalas to function as sinks in the southern portion. 5) current stage of karstification. The caves are mostly dry.

Figure 5 shows the geomorphological units proposed for the Arcos-Pains Karst Region, followed by their descriptions.

3.1. EASTERN SÃO MIGUEL KARST PLATEAU

It corresponds to the portion of the Arcos-Pains karst region where it is possible to visualize the entire stratigraphic sequence of Carbonate Facies described by Muzzi Magalhães et al. (1989). It is the geomorphological unit that is located further inside the Craton. Although more continuous limestone occurrences are prevalent (Figure 6), there are portions where the intercalation of pelitic rocks is present, and residual features like towers and mogotes are recurrent (Pizarro, 1998). Martins (2013) considers that the emergence of the Graben of Arcos elevated the carbonate rocks of the Arcos-Pains karst region, and the existence of a long N-S fault in the São Miguel river led to the division of the plateau into two distinct geomorphological units (east and west of São Miguel).

In this domain, main caves are dry at higher topographic levels (vadose zone) or wet and with the aqueous flow in the intermediate zone (epiphreatic). They usu-

Figure 6: High and continuous outcrops observed in the Corumbá region, Pains (MG). Photo: Bruno Durão Rodrigues, 2013.

ally have linear or low meandering with a flat profile and are built with a predominance of vertical ellipsoidal cuts (Teixeira-Silva et al., 2013).

This block has the most extensive and continuous outcrops, marked by several types of karren, reaching some kilometres long and heights up to 50 m (Pizarro 1998). Because of that, most mining companies exploiting the limestone are located in this region. This characteristic is probably due to a higher upwelling of this area concerning the others (Teixeira-Silva et al., 2013). Surrounding the outcrops, the surface has a moderate slope modelled by large hills (Martins, 2013). The exokarst features like sinks-spring systems, blind valleys, dolines, and uvalas are standard, indicating Karst's well-developed activity. A dry valley can be seen in the Corumbá region. The drainage channel of this river remains dry throughout the year. However, in the rainy season, the water volume is substantial when it is possible to perceive its superficial course. According to Ford, Palmer, and White (1988), one can identify the doline karst type.

3.2. WESTERN SÃO MIGUEL KARST PLATEAU

Includes a north-south range in the west of the Eastern São Miguel Karst Plateau, bordered in the east by the Mina District, in the southwest by Costina village, west by Capoeirão village and the location of Cunhas (Pizarro, 1998). Geomorphological hosts hills and gentle ridges, typical of pelitic rocks with sparse outcrops and/or massive limestones, moderately deformed. The drainage pattern is generally dendritic to sub-parallel, mainly oriented at E-W and NE-SW direction, with sinks-spring systems with flooded dolines. The São Miguel River maintains its superficial course, with no underground capture evidence.

The south-central portion of this geomorphological unit is characterized by sparse limestone lenses, metric outcrops and isolated massive due to pelitic rocks interference. The northern portion consists of a set of continuous massive, quite deformed by tectonic processes. According to Martins (2013) and Teixeira-Silva et al. (2013), one perceives intercalation between covered and bare karst in this region.

The caves are controlled mainly by structures such as axial planes of folds, fractures of cleavages and fault planes. This domain's caves' general morphology is characterized by linear and branched plants, horizontal and inclined profile, secondarily edged and predominantly irregular and ellipsoidal sections (Teixeira-Silva et al., 2013).

In the eastern portion, the main caves are the Ressurgência cave and the Loca D'Água ponor. To the west

Figure 7: Horizontal and vertical karren outcrop intercepted by flooded doline in Capoeirão road. Photo: Luiz Eduardo Panisset Travassos, 2021.

stands out Davi and Capoeirão caves. One can see the Recanto and Teto Alto caves near the Mina district to the south. On the Capoeirão road, extensive limestone outcrops are marked by horizontal and vertical karren and many dolines. Most of them have water throughout the year, probably due to pelitic rocks' influence on permeability (Figure 7). The Archaeological Museum of the Upper São Francisco Karst is also located in this region.

3.3. PATOS STREAM KARST DEPRESSION

This geomorphological unit is characterized by limestone outcrops in almost all its extensions (Martins, 2013).

According to the author, this area is relatively flat. It is flooded in places and, in others, is susceptible to flooding. Teixeira-Silva et al. (2013) consider that this unit presents rocks of the Bambuí Group as more deformed than the rocks of the other characterized geomorphological units. Structurally, features are solid continuous limestone, oriented in NW-SE direction, resulting from transcurrent faultings systems related to guideline Doresópolis-Pains. The geomorphology is characterized by extensive massive limestone, dolines, uvalas, ponors, springs, and karrenfields with great scenic beauty (Figure 8).

The basement's contact is observed on the Patos Creek west bank, favouring the carbonate rock's dissolution. The altitude is higher in the contact region, and the rainfall direction favours the karst region.

The result can be observed in the caves' size and the number of dolinas flooded in most cases. According to Martins (2013), highlighting the Martins Lagoon is a representative example of one of the most characteristic features of this geomorphological unit.

The most representative caves of this compartment are the Brega (Figure 9) and Sanctuary caves, located on Patos Creek's east bank. The Zezinho Beraldo cave is located on the west bank.

Figure 9: Entrance salon of Brega Cave, Pains (MG). Photo: Mariana Barbosa Timo, 2013.

3.4. SÃO FRANCISCO KARST PLATEAU

It consists of two types of limestone on the banks of the San Francisco River: 1) the Canyon San Francisco Range, with limestones shown as continuous and deformed, forming the canyon of the river (2.5 km to the southwest of Doresópolis). Highlight for an alignment of sinkholes in the N-S direction near the canyon, and 2) Arraial Novo Range is characterized by an isolated outcrop located mainly on the left bank (northeast of the Arraial Novo location). The rocks of this unit had a strongly tectonic process.

This geomorphological unit's most representative karst feature is the San Francisco Canyon (Figure 10), carved in a rock about 80 meters high. One can still observe dolines, uvalas, blind valleys and limestone outcrops. Its morphology is probably related to the occurrence of faults, allowing a further deepening of the

Figure 8: Karrenfield, Cavalo's Stream Region, Piumhi (MG). Photo: L.E.P. Travassos, 2014.

Figure 10: San Francisco Canyon, Doresópolis, MG. Photo: Luiz Eduardo Panisset Travassos, 2021.

upstream river and the formation of steep rocky walls in both margins (Martins, 2013).

Large caves are usually found in the Araras Stream's canyons and the São Francisco River. Most have flooded waterways throughout the year. This region's caves' predominant morphology is linear plants, ellipsoidal cuts and edged and horizontal profiles (Teixeira-Silva et al., 2013).

CONCLUSIONS

In the Arcos-Pains Karst Region, human activities may impose profound changes in the landscape, especially quarrying. Several limestone extraction companies and industries are installed for cement and lime production. Such land use, coupled with poor management of the Speleological Heritage, has caused significant environmental impacts on regional Karst. Thus, being based on the karst studies makes it extremely necessary because the sensitivity of karst aquifers to pollution is very high.

The Karst in this region is an outstanding example of the Brazilian intertropical Karst for its geological, geomorphological, hydrological, and archaeological features. Therefore, its surface and underground development should be understood as a complex phenomenon.

Due to its inherent fragility and growing anthropic disturbance, such a landscape needs progressive care regarding its protection. The delimitation of its geomorphological units can facilitate a better understanding of its Speleological Heritage with the consequent expansion of the sample universe for comparative studies. With the level of knowledge about the speleological set in the study region, the current scenario demands constant proposal revisions submitted for a better adaptation to reality and to guide the strategic decisions.

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