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Research Article

Beyond the Traditional and Non-Traditional Karst Dichotomy: Insights from Sandstone Landforms in the Central Plateau of South America

Além da dicotomia do Carste tradicional e não tradicional: novas perspectivas sobre geoformas areníticas no Planalto Central da América do Sul

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Abstract: This study analyses two distinct karstic sandstone landscapes—Serra das Galés and Ponte de Pedra (GO)—located in the Central Plateau of South America, Brazil. Considering that the former constitutes a ruiniform relief and the latter a fluviokarst, the objective was to discuss the conceptual boundaries between traditional and non-traditional karst. Based on geomorphological mapping, aerial photogrammetry, and geochemical analyses by X-ray fluorescence (XRF), morphogenetic processes in both areas were investigated. In Serra das Galés, the high silica purity, absence of calcium and magnesium oxides, and the geometry of the features suggest a process dominated by arenization and mechanical collapse (piping). In contrast, at Ponte de Pedra, caves, speleothems, and structural collapses associated with the dissolution of carbonate lenses interbedded within sandstone indicate hybrid morphogenesis. The results challenge the binary classification between traditional karst (in carbonate rocks) and non-traditional karst (in non-carbonate lithologies), suggesting the need to understand karstification as a spectrum of processes that vary according to lithological solubility and erosion mechanisms. This approach is relevant for geomorphological mapping, geoheritage inventories, and the management of areas with geoconservation value developed in mixed or atypical substrates.

Keywords: Mixed lithology karst; Ruiniform Relief; Fluviokarst; Sandstone speleogenesis

Resumo: Este estudo analisa duas paisagens distintas de relevo cárstico em arenito — a Serra das Galés e a Ponte de Pedra (GO) — localizadas no Planalto Central da América do Sul no Brasil. Considerando-se que a primeira constitui um relevo ruiniforme e a segunda um fluviocarste, objetivou-se discutir os limites conceituais entre carste tradicional e não tradicional. A partir de mapeamento geomorfológico, fotogrametria aérea e análises geoquímicas por fluorescência de raios X (XRF), investigaram-se os processos morfogenéticos nas duas áreas. Na Serra das Galés, a alta pureza silicosa, a ausência de óxidos de cálcio e magnésio e a geometria das feições sugerem um processo dominado por arenização e colapso mecânico (*piping*). Já na Ponte de Pedra, observam-se cavernas, espeleotemas e colapsos estruturais associados à dissolução de lentes carbonáticas intercaladas ao arenito, indicando morfogênese híbrida. Os resultados desafiam a classificação binária entre carste tradicional (em rochas carbonáticas) e não tradicional (em litologias não carbonáticas), sugerindo a necessidade de se compreender a carstificação como um espectro de processos que variam conforme a solubilidade litológica e os mecanismos de erosão. Tal abordagem é relevante para o mapeamento geomorfológico, inventários de geossítios e gestão de áreas com geopatrimônio desenvolvido em substratos mistos ou atípicos.

Palavras-chave: Carste em litologia mista; Relevo ruiniforme; Fluviocarste; Espeleogênese em arenito.

1. Introduction

Karst systems are traditionally associated with carbonate rocks, such as limestone and dolomite, which, due to their high solubility, promote the development of typical landforms such as caves, sinkholes, and ruiniform reliefs (Cvijić, 1895; 2017; Ford and Williams, 2007). Karst hydrology and physical speleology are thus two aspects of the subterranean karst phenomenon and should be viewed congruently (Bögli, 1980). Although there are many typical karst landforms in non-carbonate rocks such as sandstones and quartzites, due to the low solubility of quartz, predominantly quartzose rocks, with high silica content, were considered immune to dissolution, so the karst-like landforms associated with these lithologies were initially understood as pseudokarst (De Waele and Gutiérrez, 2022). However, for Ford and Williams (2007), typical karst features such as karren, sinkholes, and caves can develop in low-solubility lithologies, including quartzose ones, as long as there is the presence of a groundwater flow organized by the action of dissolution, characterizing the karst system.

In this context, later studies expanded the concept to include karst landforms developed in other lithologies, particularly siliciclastic rocks such as sandstones and quartzites, giving rise to what is now referred to as non-traditional karst (Andreychouk et al., 2009; Travassos, 2019). Indeed, the dissolution processes that act on siliciclastic rocks, although distinct from those observed in carbonate rocks, also play a relevant role in the development of karst in sandstones (Briceño & Schubert, 1990; Wray, 1997). White (1988) describes the existence of complex systems of surface and subsurface watercourses in non-carbonate rocks such as sandstones, where dissolution occurs mainly through the alteration of soluble minerals that cement the rock grains, as well as through the dissolution of amorphous silica, which is intensified under conditions of high temperature and the presence of acidified water (Veress, 2020). This dissolution process weakens the internal structure of siliciclastic rocks, making them more susceptible to physical erosion and subsequently leading to collapse episodes. This phenomenon is extremely important in the development of karst in sandstones and is known as arenization (Martini, 1979).

Examples of non-traditional karst have been described in various parts of the world, such as Canaima National Park in Venezuela (Aubrecht et al., 2008) and Purnululu National Park in Australia (Young, 2010), among others. In Brazil, studies on karst developed in siliciclastic rocks have gained prominence in recent decades, with notable examples documented in Chapada dos Guimarães (Hardt et al., 2008), Rurópolis (Hardt et al., 2022), and Serra da Capivara (Silva and Maia, 2024). However, these systems still require further investigation, particularly concerning the morphogenetic evolution of fluviokarst systems developed in sandstone.

Indeed, although the development of karst features in carbonate lithologies is well established in the literature (Klimchouk, 2015; Travassos, 2019; De Waele and Gutiérrez, 2022), the question remains as to what extent features developed in non-carbonate lithologies can be legitimately recognized as karst, or whether they originate from distinct morphogenetic processes, even if they result in morphologically analogous landforms. A detailed investigation into the morphogenesis of these features is essential for refining the criteria that define karstification, thereby broadening the epistemological debate on what constitutes a karst system, including the division between traditional and non-traditional karst.

In this context, two areas located a few kilometers apart, each with numerous karst features and a similar sandstone lithology, coexist in the Central Plateau of South America, in the municipality of Paraúna in the state of Goiás, Brazil. However, these two areas also have many unique characteristics, as a ruiniform relief characterizes one—Serra das Galés—and the other by a typical fluviokarst—Ponte de Pedra. This study seeks to analyze the mechanisms responsible for the morphogenesis of these two areas to debate the boundaries of the division of karst relief into traditional and non-traditional karst. For this purpose, regional geological mapping, aerial photogrammetry using drones, and chemical analysis of samples by X-ray fluorescence were employed.

2. Study Area

The study area encompasses two locations of scenic and didactic relevance of the State of Goiás in the Brazilian Central Plateau (Figure 1). Both are situated in the municipality of Paraúna: the first is the Serra das Galés in the Paraúna State Park, and the second is the Ponte de Pedra ("Stone Bridge"), located less than 20 km from each other.

The predominant biome in the area is the Cerrado, characterized by vegetation with multiple physiognomies, including forest, savanna, and grassland formations. However, most of the original vegetation has been replaced by livestock farming and, more prominently, by agricultural areas.

The Serra das Galés in the Paraúna State Park is located within the Paraná Sedimentary Basin II, specifically in the Itararé Group, Aquidauana Formation (Figure 2), which is the only formation of this group present in the state of Goiás (CPRM, 2008). This formation exhibits significant facies variation, resulting from fluvial and lacustrine deposition, with evidence of glaciation. At its base, quartz pebbles and sandstone layers are found. Above this layer, medium to coarse-grained, friable sandstones predominate, occasionally containing feldspar. Overlying these, there are fine siltstones and mudstones, as well as red to greenish-grey shales.

The Ponte de Pedra, a Natural Monument (a Natural Private Reserve), lies atop the Bauru Group, within the Vale do Rio do Peixe Formation (Figure 2). The Bauru Group consists of continental siliciclastic sediments deposited on the South American Platform during the sedimentation of the Paraná Basin in the Cretaceous period (135–65 Ma) (Stradioto et al., 2008). The Vale do Rio do Peixe Formation is composed of fine- to very fine-grained sandstones, with quartz crystals and occasional carbonate cementation (Fernandes, 1998). The soils within the state park are mostly dystrophic quartzarenic neosols (Moreira et al., 2024). At Ponte de Pedra, according to georeferenced data from the State Geoinformation System (SIEG, 2017), gleysols are found in the area surrounding the fluvial channel, which is regionally bordered by red latosols.

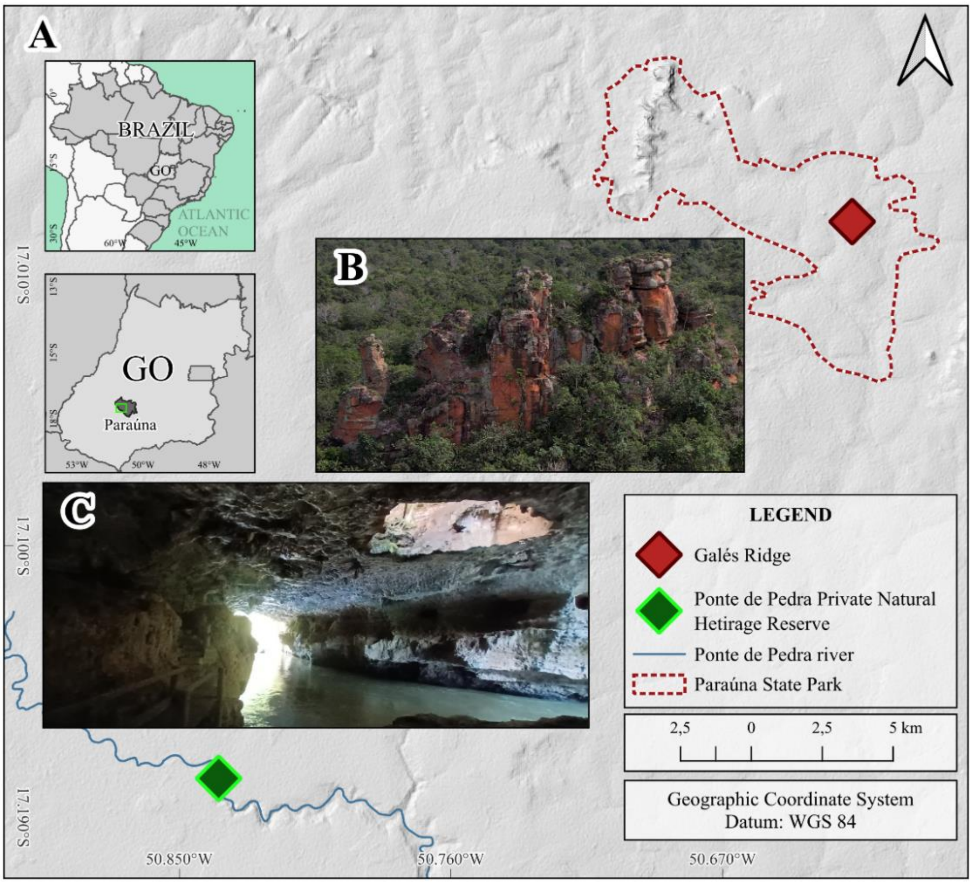

Figure 1. A Location map of the geoheritage sites in the municipality of Paraúna in Goiás State; B: Serra das Galés geoheritage; C: Ponte de Pedra geoheritage.

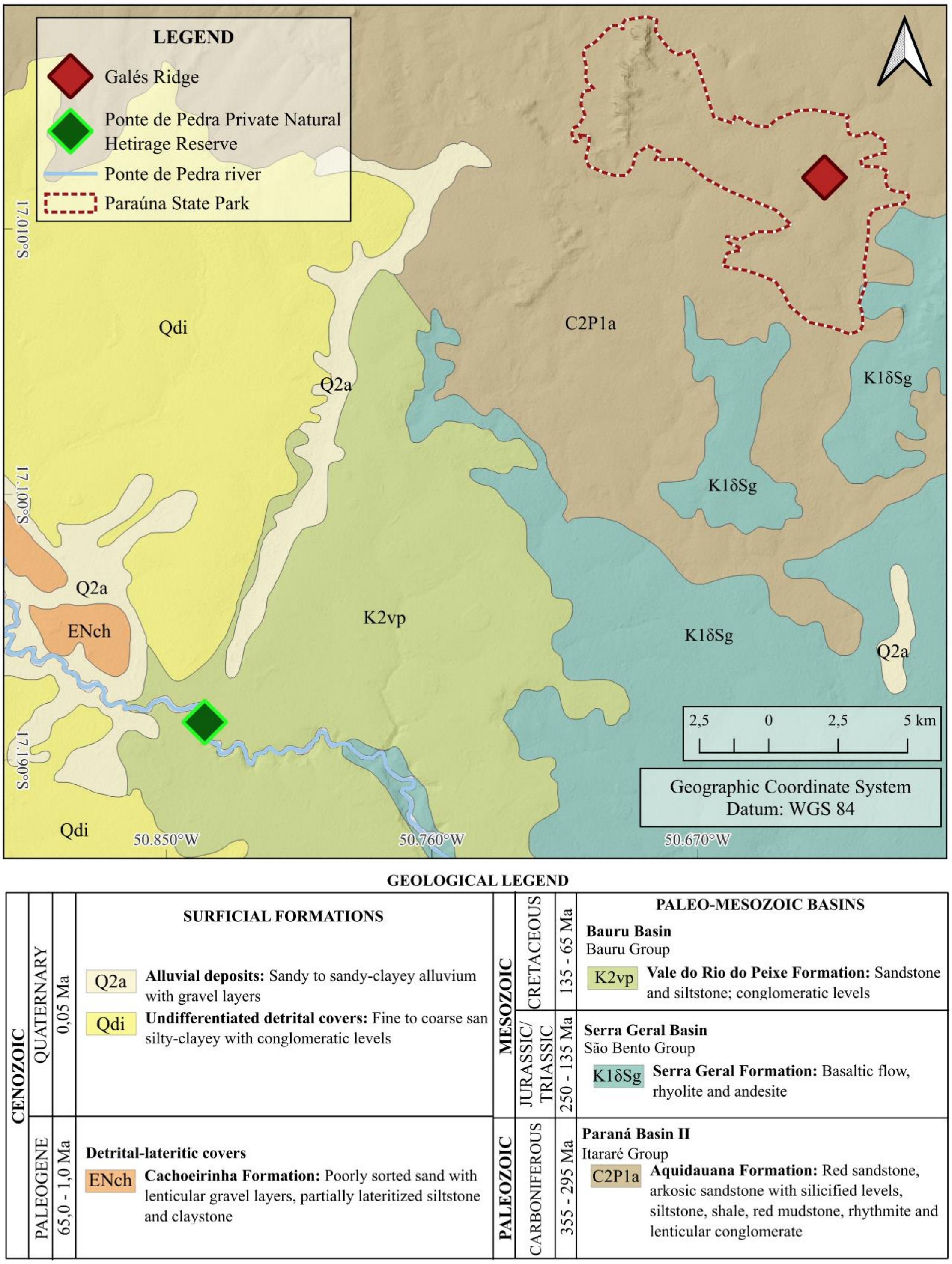

Figure 2. Lithological map of the Paraúna area; adapted from CPRM (2008).

The regional climate by the Köppen-Geiger classification (Alvares et al., 2014) is a sub-humid tropical, with two well-defined seasons: a rainy summer (October to April) and a dry winter (May to September). The average temperature of the hottest month is around 30°C, while that of the coldest months is approximately 18°C. The annual mean temperature is 22°C (Ferreira, Lima and Candeiro, 2020).

According to the geomorphological mapping of the state of Goiás (Latrubesse and Carvalho, 2006), the rocks of the Paraná Basin have undergone regional planation processes. As a result, the predominant landforms are regional planation surfaces associated with tabular reliefs. These processes have given rise to minimally dissected plateaus, with gentle slopes (3–8%) transitioning to moderate, rolling relief (8–20%). However, within the Paraúna State Park, areas of differential erosion occur, featuring silicified layers that give rise to ruiniform reliefs (CPRM, 2008).

The cavity that characterizes the Ponte de Pedra, according to Ferreira et al. (2020), originated from ancient underground drainage channels that were deactivated and now remain suspended above the current base level, where the Ponte de Pedra River flows. A skylight is also observed at the top of the gallery, which gradually expands over time.

3. Materials and methods

The study was carried out in five stages: (1) literature review; (2) regional analysis of the area using geoprocessing techniques; (3) field data collection; (4) laboratory analyses; and (5) data analysis in the office. Details and procedures for each stage are outlined below.

As the first stage, the research began with a theoretical review of topics related to karst geomorphology, including the characterization of traditional and non-traditional karst landforms, karst in sandstones and quartzites, fluviokarst, and ruiniform reliefs in karst environments (Cvijić, 1895; 2017; Bögli, 1980; Jennings, 1985; White, 1988; Wray, 1997; Piló, 2000; Ford and Williams, 2007; Willems et al., 2008; Klimchouk, 2015; Travassos, 2019; Hardt et al., 2022; De Waele and Gutiérrez, 2022). This stage was essential, as it provided the theoretical foundation to classify the regional karst landforms accurately.

For the second stage, geoprocessing and remote sensing tools were employed to analyze the regional geomorphology. Data on the geodiversity and geology of the state of Goiás, provided by the Brazilian Geological Survey, were used to identify lithological and slope-related aspects. Additionally, ALOS-PALSAR digital elevation model (DEM) imagery was used for topographic visualization. This enabled the creation of thematic maps of the study area.

The third stage involved fieldwork for data collection. This included: (a) identification and interpretation of the karst landforms developed in Paraúna; (b) aerial imaging of the Serra das Galés and the Ponte de Pedra River using a DJI Air2S drone (Model DJI-MVA200S-C1), equipped with a 1-inch CMOS sensor camera capable of recording videos in 5.4K resolution and capturing 20-megapixel photographs. The georeferenced orthophotos (GNSS: GPS + GLONASS + GALILEO), generated during the flights (authorized by DECEA under protocols #46FA6E99 and #523AD5D9), resulted in images with dimensions of 6033 × 8000 and a resolution of 8.83 cm/pixel; (c) In total, nine samples were collected. Five of them were obtained from Serra das Galés, one from Pedra do Cálice, the geoform that symbolizes the park, and four from other nearby residual hills. The remaining four samples were collected at Ponte de Pedra and included: (1) PP01 - a flowstone speleothem, (2) PP02 - a paleo fluvial level, (3) PP03 - the cave floor, and (4) PP04 - a stalagmite.

The fourth stage was conducted at the Regional Centre for Technological Development (CRTI) of Goiás Federal University - Brazil. During this stage, the field-collected samples were crushed, and X-ray fluorescence analysis was performed to determine the chemical composition of the samples. Finally, in the fifth stage, data collected by aerial imaging were used to generate a digital terrain model (DTM) using the software CloudCompare and Agisoft Metashape. This approach enabled a more accurate office-based analysis, allowing detailed visualization of relief in areas with difficult access, as well as the production of larger-scale maps.

4. Results

4.1. Serra das Galés

According to the geological mapping of the state of Goiás (CPRM, 2008), the Serra das Galés lies within the Itararé Group, Aquidauana Formation, which is lithologically composed primarily of medium to coarse-grained sandstones, mostly feldspathic, with the presence of residual hills formed at silicified levels. Morphologically, it exhibits typical characteristics of ruiniform relief, marked by residual features sculpted into the rock. Among these, residual towers stand out with a morphology similar to karst towers, easily identifiable in the landscape both from the ground and by drone overflight (Figure 3A).

In addition to the towers, indentations developed along fracture zones between two rock blocks can be observed. These have elongated shapes with gently rounded bases, resembling degraded natural conduits (Figure 3B). Circular concavities that completely perforate the rock have also been recorded (Figure 3C). Another notable feature is the presence of paired concavities carved in symmetrical opposition, as seen in the case of Pedra do Cálice (Figure 3D), a symbolic landform of the Serra das Galés. Taken together, these concave features resemble ancient underground conduits that have been almost entirely degraded by erosion.

Figure 3. Serra das Galés, in the Parque Estadual de Paraúna. (a) View of the ruiniform reliefs of Serra das Galés; (b) Elongated indentation with a rounded bottom between two massifs; (c) Circular cavity completely traversing the rock; (d) Double opposing concavities in the rock. Yellow lines highlight the boundaries of the features, and the empty spaces are filled with low-opacity yellow polygons.

Regarding the chemical analysis by X-ray fluorescence (XRF), all samples showed silicon (SiO_2) contents above 90%, ranging from 92.12% to 94.79% (Table 1). Aluminium oxide (Al_2O_3) contents ranged from 2.75% to 4.06%. Iron oxide (Fe_2O_3) values remained relatively constant, between 0.59% and 0.71%. Magnesium oxide (MgO) and calcium oxide (CaO) were below the limit of quantification in all samples and, therefore, not quantified. Loss on ignition (LOI) was low, with values below 1.2%. These results are consistent with the geological mapping of the state of Goiás, which identified medium to coarse-grained feldspathic sandstones in the area (CPRM, 2008).

Table 1. Major oxides by X-ray fluorescence (XRF) at Serra das Galés

Oxides Analyzed (%)	SG 01	SG 02	SG 03	SG 04	SG 07
SiO_2	93,32	92,47	94,33	94,79	92,12
Al2O_3	2,75	3,32	2,92	2,90	4,06
FeO_3	0,59	0,71	0,68	0,60	0,69
MgO	< LQ[2]	< LQ	< LQ	< LQ	< LQ
CaO	< LQ	< LQ	< LQ	< LQ	< LQ
LOI[1]	1,01	0,94	0,81	0,60	1,18
Other oxides	2,33	2,56	1,26	1,11	1,95

[1] Loss in Ignition; [2] Below the quantifiable limit;

4.2. Ponte de Pedra

Geological mapping of Goiás (CPRM, 2008) indicates that the Ponte de Pedra is situated within the Vale do Rio do Peixe Formation, which is composed of sandstone layers interbedded with siltstone or mudstone, and may include carbonate cementation and lenses of clayey or carbonate intraclasts (Fernandes, 1998; Fernandes and Coimbra, 2000). Ponte de Pedra itself is characterized by a sinkhole and an upwelling feature (Figure 4A), separated by a decametric distance, as well as a skylight at the top of the landform (Figure 4B).

Inside the Ponte de Pedra cavity, flowstone speleothems (Figure 4D), along with stalactites, stalagmites, and columns (Figure 4C), were identified. Fluvial paleolevels are also present, evidenced by the occurrence of rounded pebbles at the bottom of the cavity (Figure 4E). In broader terms, Ponte de Pedra can be described as a small cave-like cavity traversed by a stream, regionally entrenched within a canyon.

Drone imaging revealed several sections of collapsed blocks along the Ponte de Pedra River as it flows through its canyon (Figure 5). These blocks are angular, exhibit minimal to no rounding, and vary in size. Given the lack of rounding typically associated with fluvial transport, it is reasonable to infer that these blocks likely originated from the collapse of the roofs of former cave extensions along the canyon. Notably, little to no vegetation cover is observed on the blocks, and there is no visible evidence of fluvial transport.

The results of chemical analyses performed by X-ray fluorescence (XRF) on the four samples from Ponte de Pedra indicate significant variations in chemical composition (Table 2). Calcium oxide (CaO) is predominant in samples PP 01 (flowstone; 41.54%) and PP 04 (stalagmite; 50.98%), substantial in PP 03 (cave floor; 29.10%), and less pronounced in PP 02 (paleofluvial level; 17.06%). Silicon dioxide (SiO_2) shows the highest value in PP 02 (51.89%) and the lowest in PP 04 (2.61%). Loss on ignition (LOI) yielded high values, with a maximum in PP 04 (43.65%) and a minimum in PP 02 (19.89%). Magnesium oxide (MgO) contents are relatively consistent across the samples, ranging from 2.89% to 5.89%. Aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3) are present in lower concentrations, with PP 02 exhibiting the highest values for both: 2.53% and 2.04%, respectively. These values are consistent with the geological mapping of the area, as the elevated CaO levels appear to be related to the carbonate cementation identified in local sandstones (Fernandes, 1998; Fernandes and Coimbra, 2000).

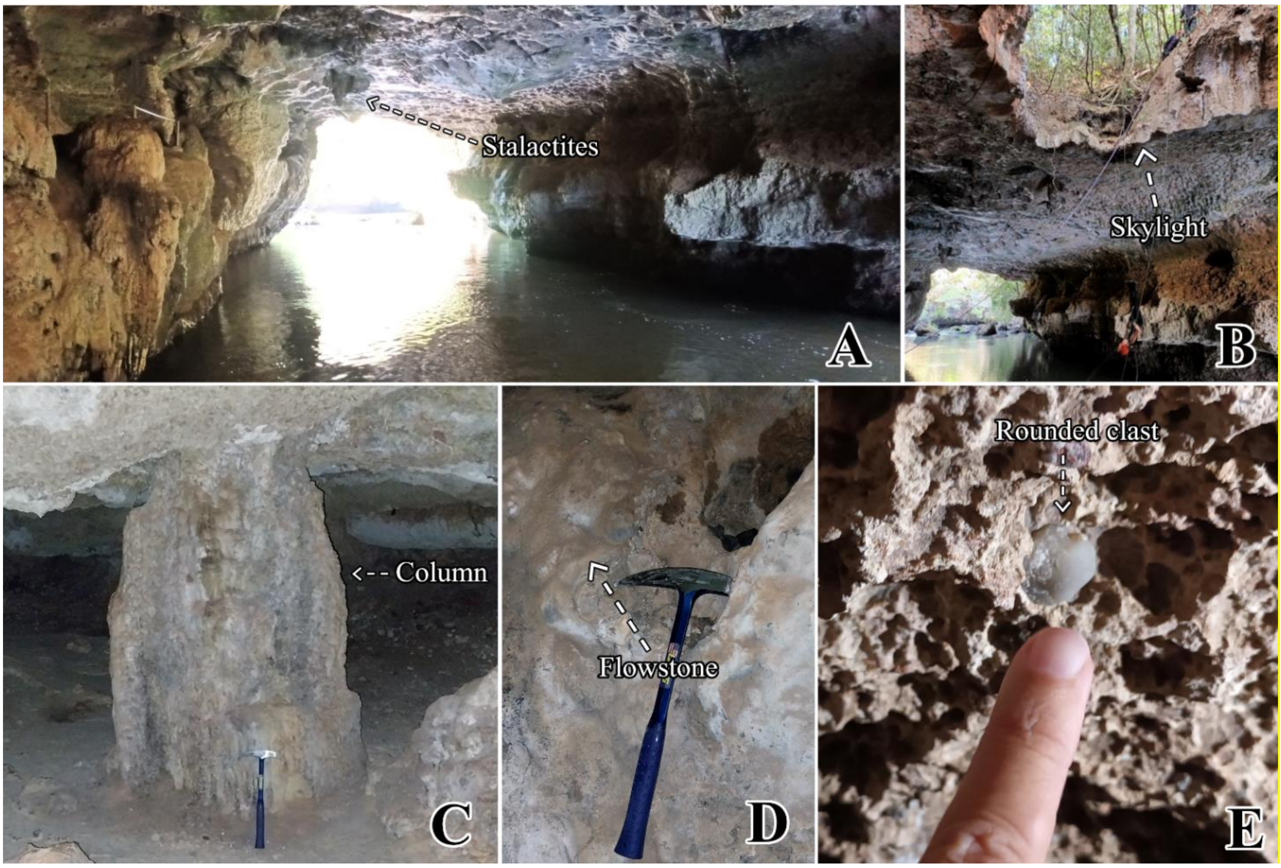

Figure 4. Ponte de Pedra: (a) Internal view of the cave exit, with the presence of stalactites on the ceiling; (b) Skylight at the top of the cavity; (c) Column-type speleothem; (d) Flowstone speleothem; (e) Rounded pebble present in a fluvial paleolevel.

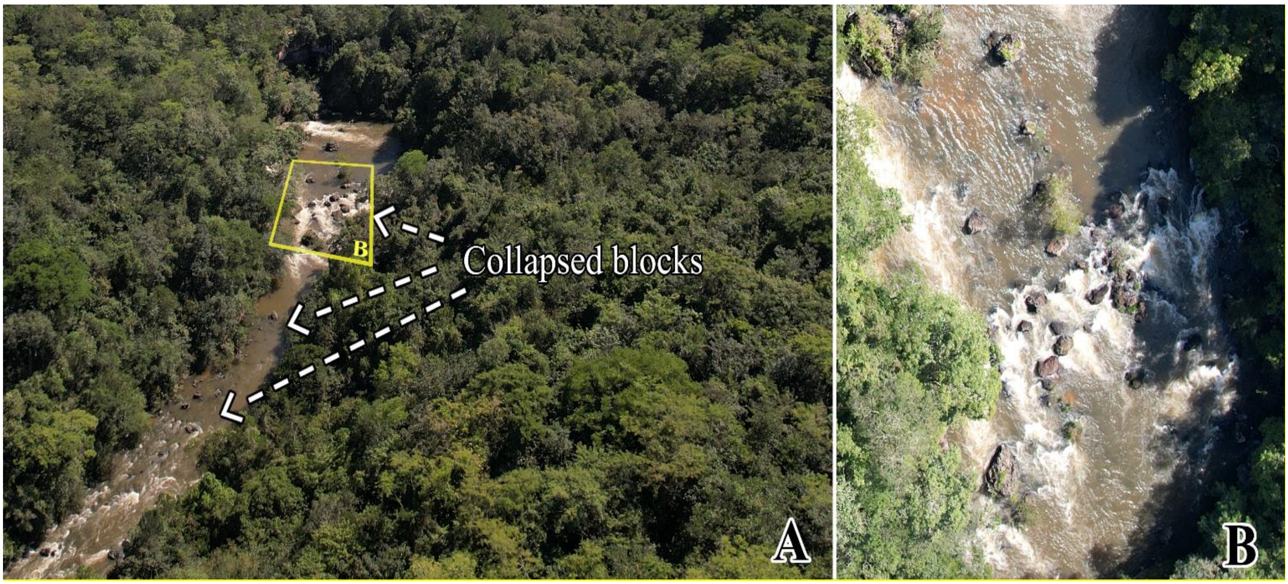

Figure 5. (a) Collapsed blocks along the course of the Ponte de Pedra River; (b) close-up view of the fallen blocks.

Table 2. Major oxides by X-ray fluorescence (XRF) at Ponte de Pedra

Oxides Analyzed (%)	PP 01 (Flowstone)	PP 02 (Paleo fluvial level)	PP 03 (Cave Floor)	PP 04 (Stalagmite)
SiO_2	15,94	51,89	34,19	2,61
$Al2O_3$	0,54	2,53	0,97	0,16
FeO_3	0,37	2,04	0,72	0,11
MgO	4,91	5,05	5,89	2,89
CaO	41,54	17,06	29,10	50,98
LOI[1]	36,97	19,89	28,39	43,65
Other oxides	< LQ[2]	1,54	0,74	< LQ

[1] Loss in Ignition; [2] Below the quantifiable limit;

5. Discussion

5.1. Serra das Galés

Serra das Galés is part of the Itararé Group, and our sample analyses indicate that the rocks from this unit are predominantly quartz sandstones, with scarce carbonate minerals (Table 1). In this context, the features observed in the Serra das Galés may be associated with non-traditional karst processes developed in siliciclastic rocks. Hardt et al. (2022) report significant occurrences of sandstone karst in Brazil, highlighting Vila Velha State Park in Ponta Grossa, Paraná, as a case particularly similar to Serra das Galés. As in Serra das Galés, the Ponta Grossa sandstone exhibits lithological homogeneity and exokarst features characteristic of ruiniform relief.

According to Pontes et al. (2022), the origin of these landforms is related to a non-traditional karst initially formed by small underground conduits, which were later modified by mechanical processes and surface dissolution. Silva and Maia (2024) emphasize that the development of karst in sandstone is associated with two fundamental processes: (1) intragranular dissolution of the cementing material, a process known as arenization (Martini, 1979; Wray and Sauro, 2017); and (2) mechanical collapse of the altered grains through the piping process (Martini, 1979; Galán, 1991).

Given the absence of carbonates in the Serra das Galés (Table 1), the sandstone formation process offers the most plausible explanation for the morphogenesis of its ruiniform relief. In this context, the high silica homogeneity and the absence of calcium and magnesium oxides (Table 1) limit classical dissolution processes, while favouring sandstone arenization followed by mechanical grain collapse through piping. This collapse was more intense in the less cemented portions of the sandstone—typically cemented by iron oxides—but did not affect the entire rock mass, thereby preserving sections of sandstone above the surface in the form of 'ruins,' which characterizes the ruiniform aspect of the landscape.

5.2. Ponte de Pedra

In Ponte de Pedra a traditional karst system can be observed, in which the local geological map (CPRM, 2008) and laboratory analysis (Table 2) confirm the presence of carbonate layers interbedded with sandstone facies. The development of caves began through dissolution within these layers. As the calcium content decreased in the subsequent strata, water flow began to act predominantly through mechanical processes, widening the conduits and later connecting to new carbonate layers, which favors the progressive expansion of the cavities. This evolutionary pattern is similar to that described by Rodet, Willems, and Pouclet (2015) in the fluviokarst of Peruaçu, in Minas Gerais, Brazil. This formation process demonstrates a polyphasic evolution, which may occur over extended geological time scales (White, 2009). The concentrated hydrological recharge observed at Ponte de Pedra corresponds to the studies by Souza, Salgado, and Auler (2019), which highlight the importance of the origin and volume of infiltrating water in the pace of karstification.

Breitenbach et al. (2010) describe how caves in sandstone tend to develop preferentially along zones of weakness and structural faults, directly aligning with the case observed at Ponte de Pedra, where carbonate layers function as zones of weakness concerning dissolution processes. The presence of speleothems reinforces the role of calcite layers as conduits for the dissolution process, in which pressurized water beneath silicified layers can dissolve underlying carbonate units, resulting in structural collapse and the formation of conduits, with subsequent roof collapse in the caves (Orndorff, Weary, and Harrison, 2006). The settling of blocks on the bed of the Ponte de Pedra River appears to represent this stage of instability.

In the effort to understand the landform evolution of the Chapada das Mesas (Maranhão and Tocantins states), Martins et al. (2017) proposed a similar hypothesis: there is a predominantly subsurface drainage system, in which the karstification process at more advanced stages leads to the collapse of cave roofs, exposing canyons and waterfalls. The similarity between Ponte de Pedra and the features of Chapada das Mesas highlights the recurrence of geomorphological patterns associated with karstification in sandstone, even when occurring in distinct depositional contexts.

This example of morphogenesis reveals an intermediate conceptual zone in which traditional karst classification categories become insufficient. In this sense, understanding the karstification process as a spectrum, rather than a binary phenomenon, may be essential to incorporate the complexity of systems developed in lithologies of varying solubility, such as sandstone with occurrences of carbonate lenses or cementation.

This interpretation reinforces the importance of lithological variability in shaping karst evolution in sandstone environments. Considering these contrasting cases, we now turn to a broader conceptual discussion on the adequacy of current karst classifications and their applicability to mixed lithological contexts.

5.3. *Traditional or Non-Traditional Karst: Rethinking Conceptual Boundaries*

The diversity of morphogenetic processes observed in Serra das Galés and Ponte de Pedra raises important questions regarding the current classification of karst. The current prevailing view is that the concept of karst extends beyond carbonate rocks. In this revised framework, if the morphological features are typical and chemical dissolution played a significant role in their genesis—even if not the dominant one—the system may already be characterized as karst (Bento, Travassos, and Rodrigues, 2015). Thus, karst can be understood as a hydrogeological system whose morphogenesis is associated with porosity and permeability in soluble rocks, not limited to carbonates. This new karst paradigm prioritizes speleogenetic processes over lithology as the defining criterion (Klimchouk, 2015). Nevertheless, due to the higher solubility of carbonate rocks, karst is subdivided into two categories: traditional—primarily associated with carbonates—and non-traditional, which includes siliciclastic rocks such as sandstone. This perspective is essential for classifying Ponte de Pedra as a karst-related area that falls outside the classical definitions of traditional and non-traditional karst.

When comparing the ruiniform relief of Serra das Galés with the fluviokarst of Ponte de Pedra, distinct morphogenetic processes are observed, ranging from karst initiated by dissolution but sustained by mechanical processes, to karst directly driven by carbonate dissolution. While Serra das Galés can be classified as a case of non-traditional karst, Ponte de Pedra exhibits intermediate characteristics, lying within a transitional zone between traditional and non-traditional karst. Its morphogenesis involved both carbonate dissolution and mechanical erosion, as cavity development could proceed only through sandblasting and/or classical erosive processes once the carbonate lenses were depleted.

Therefore, the distinction between traditional karst—commonly associated with carbonate rocks such as limestone and dolomite—and non-traditional karst—developed in non-carbonate rocks—proves insufficient in light of the empirical evidence recorded in this study. The Ponte de Pedra Private Natural Reserve (RPPN) exemplifies features typically associated with traditional fluviokarst, such as caves and speleothems. Yet, it formed in sandstone with localized carbonate lenses interbedded between its layers. While some of its features contain significant amounts of calcium oxide, others are largely dominated by silicon (Table 2). From an epistemological standpoint, these results reinforce the need to move beyond the dichotomy between traditional and non-traditional karst. In nature, as illustrated by the case of Ponte de Pedra, processes are often too complex to be fully captured by rigid classification schemes. Therefore, new conceptual approaches are needed—ones that acknowledge the complexity of karst system morphogenesis.

5. Conclusion

The results of this study contribute to a deeper understanding of the conceptual boundaries between traditional and non-traditional karst, demonstrating that karst systems in sandstone can originate from a typical sandblasting process—as observed in Serra das Galés—but may also have a genesis associated with carbonate dissolution combined with sandblasting and mechanical erosion, as in the Ponte de Pedra. In Serra das Galés, although the high degree of degradation of certain landforms makes it difficult to confirm their origin, their geometry and chemical composition directly suggest a morphogenesis linked to intragranular dissolution and successive collapse. In contrast, at Ponte de Pedra, the presence of caves, speleothems, and evidence of chemical dissolution in carbonate lenses interbedded within sandstone reveals landforms characteristic of traditional karst, albeit developed in siliciclastic rocks.

This condition challenges the binary classification between traditional and non-traditional karst, prompting epistemological reflections on classical karst concepts. The study highlights the need to reconsider the dichotomy of karst categories and to adopt a more integrative framework capable of recognizing transitional forms in complex lithological settings. Such an approach may be particularly relevant for geomorphological mapping, geoheritage inventories, and the environmental management of karst terrains developed in mixed or atypical substrates.

In this context, future studies could benefit from applying this interpretative model to other sandstone karst systems in Brazil and globally, contributing to a refined understanding of karstification as a spectrum rather than a fixed typology.

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