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Research article

Geomorpho-pedological context of the landscape units with open-air archaeological sites in the Currais de Pedra region, Northern Minas Gerais

Contexto geomorfo-pedológico das unidades de paisagem com sítios arqueológicos a céu aberto na região dos Currais de Pedra, Norte de Minas Gerais

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Abstract: The Karst Region of Currais de Pedra, located in northern Minas Gerais, Brazil, holds a significant archaeological and speleological heritage, with sites containing rock art, ceramic fragments, and lithic remains. Despite its recognized importance, the region remains little known, being gradually revealed through geomorphological and geoarchaeological studies. This study focuses on the landscape units known as Limestone Massifs and Intermassif Slopes, which are conducive to past human occupation and host the open-air archaeological sites of Ressurgência and Conceição Caetano. We aimed to detail the physical-environmental framework of these units, emphasizing the organization of landforms at the fourth taxonomic level and characterizing the main soils that constitute the surficial deposits of the sites. Field and laboratory procedures were employed, including aerophotogrammetric surveys, landform mapping, and soil sampling and analysis. The results indicate that human groups appropriated the landscape by favoring geomorphological features such as intermediate plateaus and limestone slabs within the massifs, as well as colmated valleys. These areas were identified as the most favorable for the formation of open-air archaeological sites. Soil analyses revealed anomalies of phosphorus enrichment with distinct origins. At sites like Conceição Caetano, these anomalies are associated with more permanent or long-term human occupations. In contrast, at areas such as Ressurgência, the enrichment is linked to more sporadic occupations and the activity of local fauna, attracted by fertile soils and the presence of forest patches.

Keywords: Geoarchaeology; Karst; Geomorphological Mapping; Archaeoanthrosols.

Resumo: A Região Cárstica dos Currais de Pedra, no norte de Minas Gerais, abriga um valioso patrimônio arqueológico e espeleológico, com sítios contendo grafismos rupestres, fragmentos cerâmicos e vestígios líticos. Apesar de sua relevância, a região permanece pouco conhecida, sendo gradualmente revelada por meio de estudos geomorfológicos e geoarqueológicos. Destacam-se as unidades de paisagem Maciços Calcários e Vertentes Inter-maciços, propícias à ocupação humana pretérita e onde se localizam os sítios arqueológicos a céu aberto investigados neste estudo: Ressurgência e Conceição Caetano. O objetivo da pesquisa foi detalhar o quadro físico-ambiental dessas unidades, com ênfase na organização das geoformas em quarto nível taxonômico e na caracterização dos principais solos que compõem as coberturas superficiais dos sítios. Foram empregados procedimentos de campo e gabinete, como levantamentos aerofotogramétricos, mapeamento das formas de relevo e coleta e análise de solos. Os resultados indicam que a apropriação da paisagem pelos grupos humanos privilegiou geoformas como patamares intermediários e lajedos nos maciços calcários, além dos vales colmatados, identificados como as áreas mais favoráveis à formação de sítios arqueológicos a céu aberto. As análises de solo revelaram anomalias de enriquecimento em fósforo com distintas origens: em sítios como Conceição Caetano, associadas à presença humana mais permanente ou de longa duração, e em locais como o Sítio Ressurgência, relacionadas a ocupações mais esporádicas e à ação da fauna, favorecida pela atratividade de solos férteis e pela presença de capões florestais.

Palavras-chave: Geoarqueologia; Carste; Mapeamento Geomorfológico; Arqueoantrossolos.

1. Introduction

Karst areas located along the São Francisco River Basin in Brazil host an important archaeological heritage. In the northern region of Minas Gerais State, a substantial number and variety of archaeological sites have been identified, with particular emphasis on the Peruaçu River Basin. Research initiated in the 1970s in this area revealed "the occurrence of different periods of occupation, with the earliest dating to approximately 12,000 years BP" (PROUS, 1992). In the same region, another area has proven equally promising, situated along the Riacho Fundo Basin, within a cluster of limestone massifs known as the Currais de Pedra Karst Region (RCCP).

The archaeological potential of the RCCP was first noted in 1978, when a multidisciplinary team from the former Geological Research Center (CPG) conducted an expedition to assess the natural resources of the region. At that time, the area was already experiencing significant environmental degradation due to charcoal production, extensive cattle ranching, and Extraction of wood for railway sleeper construction on the Estrada de Ferro Norte de Minas (North Minas Railway). According to the CPG report (1978, p. 08), the region contains "sites of great interest due to the presence of rock paintings, engravings, and a large number of lithic industry remains." Nearly 30 years later, this potential was reaffirmed through surveys conducted by the Archaeology Division of the Natural History Museum and Botanical Garden of UFMG (RODET, 2018). Since 2009, research efforts have focused on systematically documenting and analyzing the sites in the region, identifying new occurrences, and integrating them into broader studies of the Sanfranciscana Depression (TOBIAS JR., 2013). One such study, developed by Coeli (2020), aimed to analyze the systems of objects and actions that shaped the (archaeo)geographic spaces of the RCCP.

Based on a multiscale analysis, the author proposed a compartmentalization of landscape units and highlighted the role of specific units in prehistoric human occupation processes. According to the study, the "Limestone Massifs" and "Intermassif Slopes" units were particularly favorable environments for human settlement, as they offered a range of opportunities in terms of mobility, presence of rock shelters, availability of natural resources, and scenic attributes that likely encouraged territorial use. In fact, these are the areas where the highest concentration of archaeological sites has been recorded to date, including open-air sites and zones with the greatest surface evidence density, such as lithic and ceramic artifacts and rock art.

The results presented by Coeli (2020) raised a new question: if, at the regional scale, these landscape units stand out due to the opportunities they offer, how can their internal morphological compartmentalization — at the local scale — along with soil characteristics, contribute to the understanding of prehistoric human occupation in the RCCP and the formation of open-air archaeological sites? This question aligns with the growing interest in expanding geoarchaeological research in the region, based on the premise that such studies provide valuable insights into the environmental contexts inhabited by past human groups, as well as into the formation processes of the sites that materialize those ways of life — even though each site represents only a fragment of those broader human experiences. In this regard, morphometric landform compartmentalization and pedological analyses are essential tools.

The geomorphological compartmentalization of landforms hosting one or more archaeological sites is a fundamental tool for interpreting the landscapes encountered and experienced by past human groups. In addition to aiding the reconstruction of occupation settings, this approach can reveal landscape modifications resulting from human activities, including the construction of anthropogenic features. Within this context, the systematic description of altitudinal levels —supported by appropriate analytical tools — is essential for understanding terrain morphology, site distribution, and their key characteristics. Studies such as those by Rodet (2007), Araujo et al. (2017), and Villagrán et al. (2021) demonstrate the critical role of geomorphological approaches in explaining the dynamics of human occupation across diverse environments, reinforcing their importance within the scope of geoarchaeological research.

Pedogenetic processes and their resulting products — soils — also play a central role in reconstructing past human occupations. Pedological studies in Archaeoanthrosols allow for interpretations regarding the origin of deposited materials and the post-depositional transformations occurring within archaeological contexts (SOUSA et al., 2015; SOUSA et al., 2017). As noted by Corrêa (2007, p. 26), “the pedological study of archaeological soils provides a new perspective on the site, enabling additional lines of inquiry,” with analytical scales ranging from macroscopic to microscopic, and encompassing morphological, physical, chemical, and mineralogical attributes directly associated with past human activity (ARROYO-KALIN, 2009; KERN et al., 2017; MACPHAIL & CROWTHER, 2007).

In tropical environments, the integration of archaeological and soil analyses becomes essential for interpreting site formation processes. Studies such as those by Corrêa et al. (2013) and Chu et al. (2008) demonstrate that examining the composition and transformation of phosphates and carbonates in soils constitutes a valuable tool for understanding human-environment interactions. Deeper soils enriched in phosphorus frequently indicate zones of anthropogenic activity, with this element serving as a key proxy in pedoarchaeological investigations and a major diagnostic attribute in soil classification systems such as the Soil Taxonomy (SSS, 2014) and the World Reference Base for Soil Resources (IUSS Working Group WRB, 2015).

Moreover, research by Sousa et al. (2018) suggests that magnetite formation linked to human actions such as prehistoric hearths can serve as an important marker in the interpretation of archaeological deposits. Studies like that of Morgan Schmidt (2016), published in the volume *Anthropogenic Amazonia*, also illustrate how detailed pedostratigraphic analysis and investigations of anthropogenic soil formation can shed light on patterns of occupation and landscape management. In the Brazilian context, research at sites such as Lapa do Santo, in Minas Gerais (VILLAGRÁN et al., 2017), further underscores the importance of understanding site formation through the interplay among sedimentary deposition, pedogenesis, anthropic activity, and natural processes.

Given the need to expand geoarchaeological investigations in the Currais de Pedra Karst Region, and building on recent contributions by Coeli (2020) and Sousa et al. (2022), this study aims to contribute by systematically integrating geomorphological and pedological analyses to interpret prehistoric human occupation in this still underexplored area.

This article presents a study aimed at characterizing the physical and environmental framework of the "Limestone Massifs" and "Intermassif Slopes" landscape units within the Currais de Pedra Karst Region, with a particular focus on landform organization and its potential relationship, alongside soil characteristics, to past human occupation and the formation of open-air archaeological sites. The results presented here advance the geoarchaeological knowledge of the study area and contribute to a broader understanding of the processes involved in the formation of such sites, which remain among the least understood.

2. Study area

The karst formations known as Currais de Pedra are located between the municipalities of Jequitaí, Lagoa dos Patos, and São João da Lagoa, in northern Minas Gerais, within the Riacho Fundo sub-basin — a tributary of the Jequitaí River, which flows into the right bank of the São Francisco River. These features are defined as "areas with predominantly flat topography, surrounded by carbonate rock massifs that display ovoid or rectangular shapes in plain view" (GONÇALVES, 2013). The local population associates these landforms with traditional cattle enclosures, hence their name. Approximately six isolated formations — or six Currais — can be identified in the region, among which Currais V and VI were selected for this study (Figure 1).

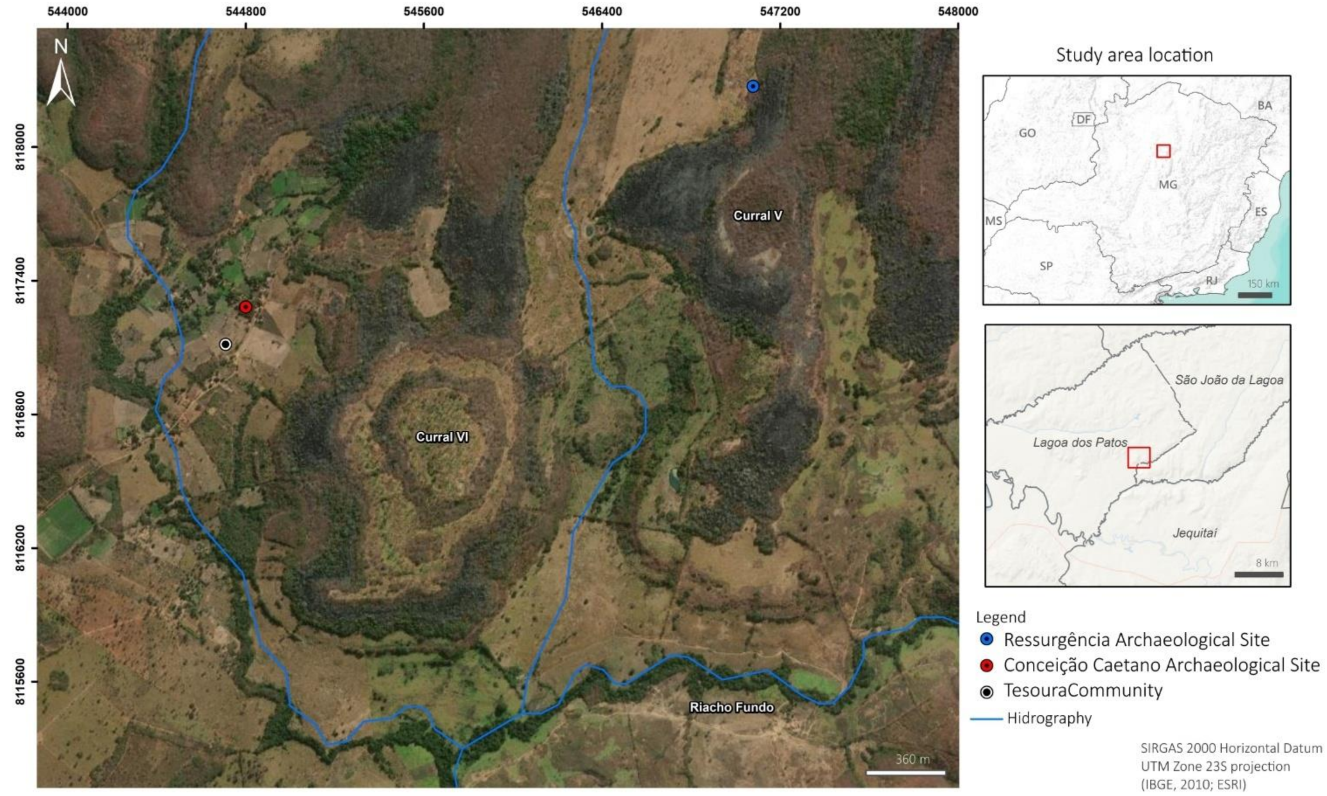

Figure 1. Location of the Currais de Pedra in the northern region of Minas Gerais State and of the archaeological sites Ressurgência and Conceição Caetano within Currais V and VI.

The Currais de Pedra are composed of limestone outcrops exposed by the erosion of overlying siliciclastic rocks (CPG, 1978). Between the massifs and their margins, gray calcarenites predominate, featuring oolitic textures and intraclasts, interbedded with marl and siltstone layers (COELI, 2020). These limestones are of Neoproterozoic age and belong to the Bambuí Group (CHAVES & BENITEZ, 2007), specifically the Lagoa do Jacaré Formation.

The area also includes the Serra de Santa Helena Formation — composed of siltstone, argillaceous siltstone, shale, fine sandstone lenses with calcitic cement, and calcilutite laminations — and the Areado Group, which consists of shale and medium- to coarse-grained sandstones with frequent conglomerate lenses. Detrital eluvio-colluvial deposits and undifferentiated alluvium, associated with the Cenozoic, occur in the depressions between the limestone massifs (CODEMIG/UFMG, 2014).

The RCCP lies within the Sanfranciscana Depression and is representative of the residual plateau landforms typical of northern Minas Gerais. Geomorphologically, it is classified as a perched karst (GONÇALVES et al., 2017), disconnected from the regional base level. Infiltration is the dominant process of current karstification, with rainwater penetrating the massifs more vertically than horizontally. Perched karst systems "typically occur in tabular morphologies overlying limestone, with a basal layer of rocks less susceptible to dissolution, and positioned above epigenic thalwegs" (LLOPIS-LLADÓ, 1970, apud GONÇALVES et al., 2017, p. 280) — precisely the case of the RCCP. Two distinct groups of water absorption features are present: (1) karren fields (fractures, fissures, and sinkholes) that feed underground conduits, and (2) closed depressions, such as dolines and mini-poljes. The development of this perched karst is closely linked to regional relief evolution, likely associated with uplift processes between the Middle Miocene and Late Pliocene that triggered drainage incision (GONÇALVES et al., 2017).

The landscape compartmentalization proposed by Coeli (2020) enhances the geomorphological interpretation of the RCCP. The author delineated 18 landscape units based on the morphological features of the Riacho Fundo sub-basin, aiming to understand past land use and settlement patterns. Among these, the Limestone Massifs and Intermassif Slopes stand out for their high potential for past human occupation.

The Limestone Massifs comprise areas of exposed rock, sometimes covered by thin soil layers and typically associated with Deciduous Seasonal Forest (Mata Seca). These areas exhibit characteristic exokarst features, such as exposed rock cavities and extensive karren fields (COELI, 2020). In contrast, the Intermassif Slopes are gently undulating areas shaped by erosional processes that disconnected the massifs. These zones often contain permanent drainage channels that feed into the Rio das Pedras, a tributary of the Riacho Fundo. Many slopes feature colluvial deposits derived from erosion of the surrounding rock formations. Around Curral de Pedra V, colluvial sediment accumulation is observed, resulting from disaggregated rock material transported by gravity (COELI, 2020). These slopes are directly connected to the Sanfranciscana Depression and the São Francisco Plateau and are considered relatively accessible compared to other landscape units. The massifs and slopes are interconnected within the landscape, as illustrated in Figure 2.

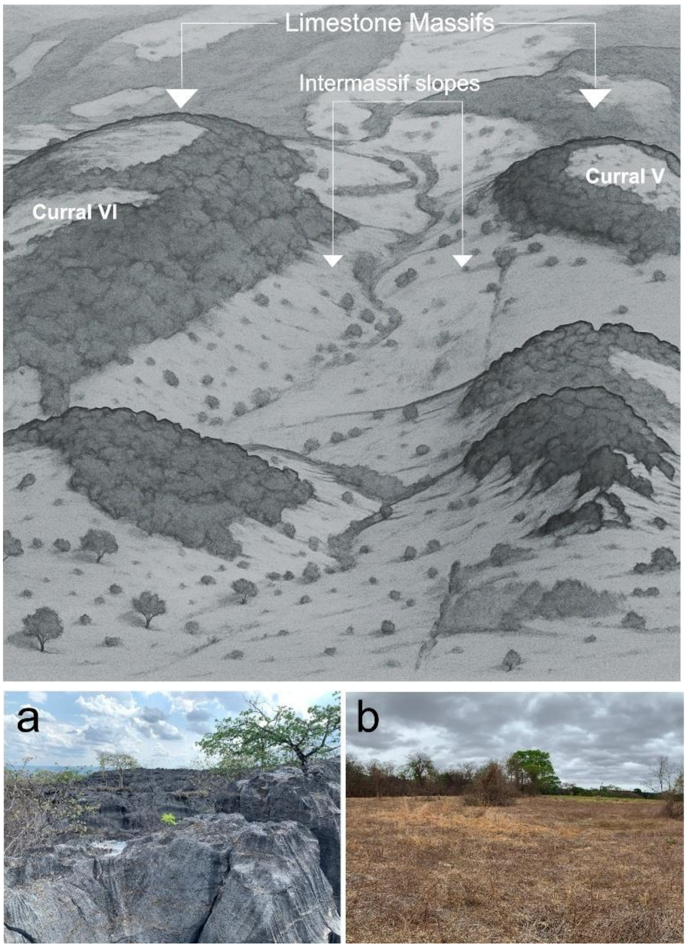

Figure 2. General view of the landscape units in the Currais de Pedra Karst Region, Northern Minas Gerais. At the higher elevations (left and right in the sketch and photograph a), the Limestone Massifs are visible, featuring outcrops with typical exokarst features such as karren fields, exposed cavities, and areas with shallow soils under Deciduous Seasonal Forest. Between them lie the Intermassif Slopes, gently undulating areas shaped by erosion, as shown in photograph b. These slopes separate and connect the massifs and are characterized by deeper soils or colluvial deposits, along with surface drainage. Relict vegetation indicates that these areas were originally forested but are now degraded and converted to pasture.

The climate of the RCCP is classified as Aw according to the Köppen-Geiger system, with dry winters and rainy summers from November to April. The average temperature of the coldest month is above 18°C, and annual rainfall ranges from 750 mm to 1800 mm. Lithology strongly influences soil formation and distribution. On limestone outcrops, Lithic Neosols predominate — extremely shallow soils formed directly over bedrock. In geomorphologically more stable areas, Eutrophic Cambisols are also present, likewise associated with limestone. Lower portions of the landscape, formed from colluvial and alluvial materials, host Latosols, Histosols (Organossolos) in wetland environments (veredas), and Chernozems in isolated spots, indicating more fertile edaphic conditions.

Native vegetation includes Deciduous Seasonal Forest (Dry Forest) on limestones and carbonate alluvium, typically associated with eutrophic soils, and Cerrado stricto sensu onLatosols and Quartzarenic Neosols developed over dystrophic siltstones and sandstones. In Gleysols and Histosols, Mauritia flexuosa palm swamps (veredas) and seasonally flooded grasslands are common, while gallery forests follow more incised drainage channels. Currently, native vegetation has been extensively degraded due to logging and livestock activity.

For the morphological compartmentalization undertaken in this study, Currais V and VI were selected, along with their associated landscape units. The selection was based on the following criteria: (i) these Currais contain the greatest number of identified archaeological sites to date (RODET, 2018); (ii) aerial photogrammetric surveys by drone are available for these areas; (iii) these Currais have undergone the highest number of field campaigns and are therefore better known by the authors; and (iv) they contain clearly demarcated and easily identifiable landscape units of interest.

Within these units, two open-air archaeological sites were selected for detailed soil analysis: the Ressurgência Site and the Conceição Caetano Site. Archaeological surveys at both sites included systematic sampling of surface lithic and ceramic artifacts (RODET et al., 2018). The Ressurgência Site, located at the foot of the Curral de Pedras V limestone massif (Figure 3a), lies in the transitional zone toward Curral de Pedras VI and is part of the Limestone Massifs unit. It has gently undulating topography at an average elevation of 650 meters. The area is currently degraded, with its original vegetation removed and used as pastureland. Surface collections yielded 135 lithic artifacts, including flaked quartzite pebbles and quartz crystals.

The Conceição Caetano Site is located in the Tesoura community (Lagoa dos Patos) (Figure 3b). Surface collections have yielded flaked quartzite, sandstone, and chert pebbles, totaling 56 lithic artifacts to date. According to a local resident, a ceramic urn containing human remains was uncovered during cassava planting approximately 10 to 20 years ago; it was removed and later reburied in the same location. In 2023, excavations revealed a significant assemblage of ceramic fragments, making this the only ceramic-bearing archaeological site identified in the region to date. The site is situated within the Intermassif Slopes unit.

Figure 3. Open-air archaeological sites selected for this study: (a) Ressurgência Site and (b) Conceição Caetano Site.

2. Materials and Methods

2.1 Study of landforms

The landforms were examined at a local scale by identifying their occurrence within the Limestone Massifs and Intermassif Slopes landscape units, resulting in a detailed geomorphological map at a scale of 1:500. Building upon the taxonomic classification system proposed by Ross (1992), this mapping focused on the fourth hierarchical level, given that the first three levels had already been addressed in Coeli (2020). For this scale of analysis, the term geoforms is used to designate patterns of morphologically similar terrain features, reflecting the spatial and formal coherence observed within the mapped units.

The landforms analysis involved the following steps: (i) Acquisition of secondary cartographic data relevant to the study area, including geological maps (CODEMIG et al., 2014) and high-resolution satellite imagery (RapidEye, 5 m spatial resolution); (ii) Drone-based aerial photogrammetry, conducted in the field using a DJI Phantom 4 Pro drone on October 22, 2021. The resulting imagery had a spatial resolution of 0.5 m; (iii) Digital image processing and generation of a Digital Elevation Model (DEM), along with derivative products such as drainage networks, slope maps, shaded relief models, and aspect maps. All processing was carried out using QGIS version 3.36.2; (iv) Manual photointerpretation of the terrain to delineate geoforms, using secondary thematic maps as initial references and refining the interpretation with DEM-based visualizations; (v) Field validation to verify, adjust, and finalize the boundaries of the identified landforms, as well as to define the legend based on observed terrain features; and (vi) Production of the final geomorphological map, integrating all verified and refined elements into a coherent spatial representation of landform distribution within the study area.

2.2 Study of soils

Soils were investigated at two selected open-air archaeological sites, Conceição Caetano and Ressurgência. This investigation comprised the collection and analysis of topsoil samples as well as soil horizons from pedological profiles. For surface sampling, at each site, topsoil was collected within the 0–10 cm depth range, following a regular grid pattern with sampling points spaced 2 meters apart. A total of 27 samples were collected at the Ressurgência Site and 34 at the Conceição Caetano Site. The objective of this sampling was to evaluate the spatial distribution of potential chemical and physical signatures that might indicate past human activities at these locations. Samples were stored in plastic bags, air-dried, sieved, and subsequently subjected to physical and chemical analyses.

Additionally, pedological profiles were described in situ within the same areas, with soil horizons identified and sampled for further physical and chemical characterization. Profile descriptions were performed following the guidelines of Santos et al. (2015), and horizon colors were determined using the Munsell Soil Color Chart (Munsell, 1994).

Physical analyses included particle-size distribution and texture classification. Particle-size analysis was conducted at the Soil Physics Laboratory of the Soil Department (DPS) – Federal University of Viçosa (UFV), following EMBRAPA (2011) protocols, and also at the laboratory of the Instituto Mineiro de Agropecuária (IMA). Sand, silt, and clay fractions were quantified to classify soil texture. Samples were chemically dispersed using 10 mL of 1 mol/L NaOH and gently agitated for 16 hours. The sand fraction was separated by sieving, while silt and clay fractions were determined by differential sedimentation and pipetting according to Stokes' Law. Texture classes were assigned based on a ternary diagram.

Routine chemical analyses were carried out at both the DPS-UFV Soil Department and the IMA laboratory, following EMBRAPA (2011) protocols. Soil pH was measured potentiometrically in water and in a 1 mol/L KCl solution, using a soil-to-solution ratio of 1:2.5. Exchangeable Ca and Mg were extracted with 1 mol/L KCl at pH 7.0 and quantified by atomic absorption spectrophotometry. Exchangeable K, Na, Cu, Fe, Zn, and Mn were extracted using a solution of 0.05 mol/L HCl and 0.025 mol/L H_2SO_4 (Mehlich-1); K and Na were determined by flame emission spectrophotometry, while the others were quantified by atomic absorption spectrophotometry. Exchangeable Al was extracted with 1 mol/L KCl and quantified by titration with 0.025 mol/L NaOH. Extractable acidity (H^+ + Al^{3+}) was determined by extraction with 0.5 mol/L calcium acetate adjusted to pH 7.0 and titrated with 0.06 mol/L NaOH. Organic carbon content was determined using the Walkley-Black method, and organic matter was estimated by multiplying organic carbon values by 1.724. Available phosphorus (P) was extracted with Mehlich-1 and quantified by molecular absorption spectrophotometry (colorimetry). Remaining phosphorus (P-rem) was determined by measuring the phosphorus concentration in solution after shaking soil samples for 1 hour in a 60 mg/L P solution with 0.01 mol/L $CaCl_2$, using a soil-to-solution ratio of 1:10. The following soil fertility indices were calculated: effective cation exchange capacity (CEC), potential CEC, base saturation (V), and aluminum saturation (m).

3. Results

3.1. The landforms

The taxonomic classification of the relief up to the fourth level is presented in Figure 4, while the landform mapping of the study area is shown in Figure 5. The morphostructural unit (taxon 1) corresponds to the São Francisco Craton, which includes the morphosculptural unit of the São Francisco Residual Plateaus (taxon 2). Within these plateaus lie the Limestone Massifs and the Intermassif Slopes, which constitute taxon 3 in this study. The Intermassif Slopes cover 63% of the mapped area and thus represent the predominant morphosculptural unit. For each unit, four landforms (taxon 4) were recognized and are described below.

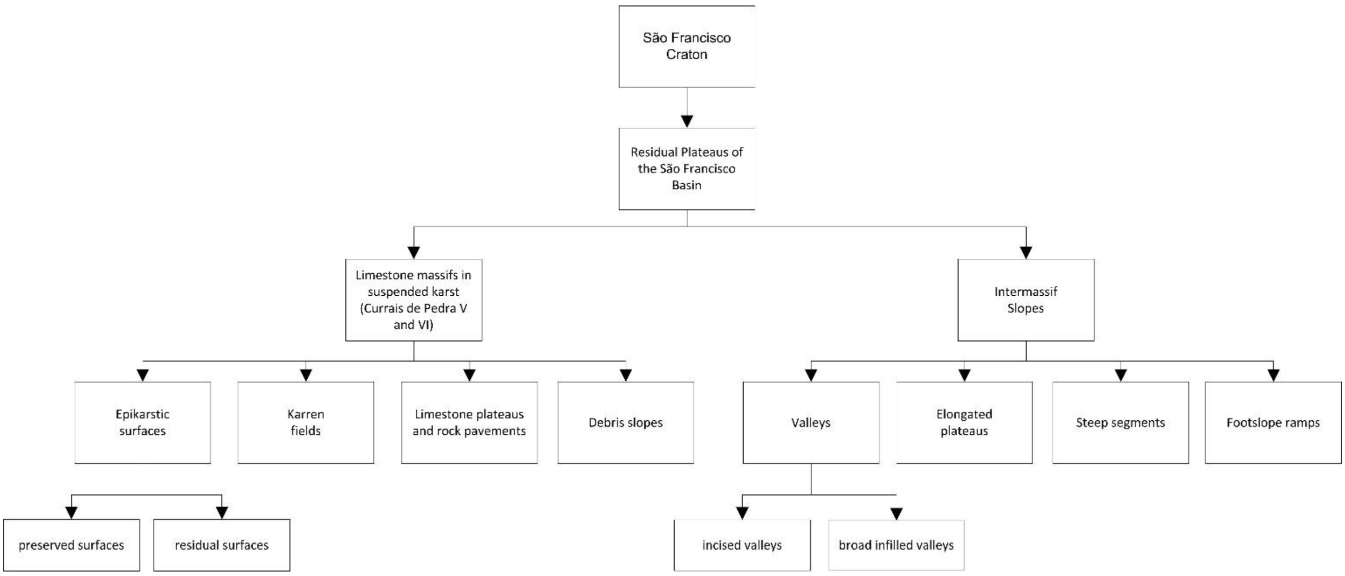

Figure 4. Taxonomic organization of the relief in the study area, from the first to the fourth taxon, arranged top-down in the flowchart.

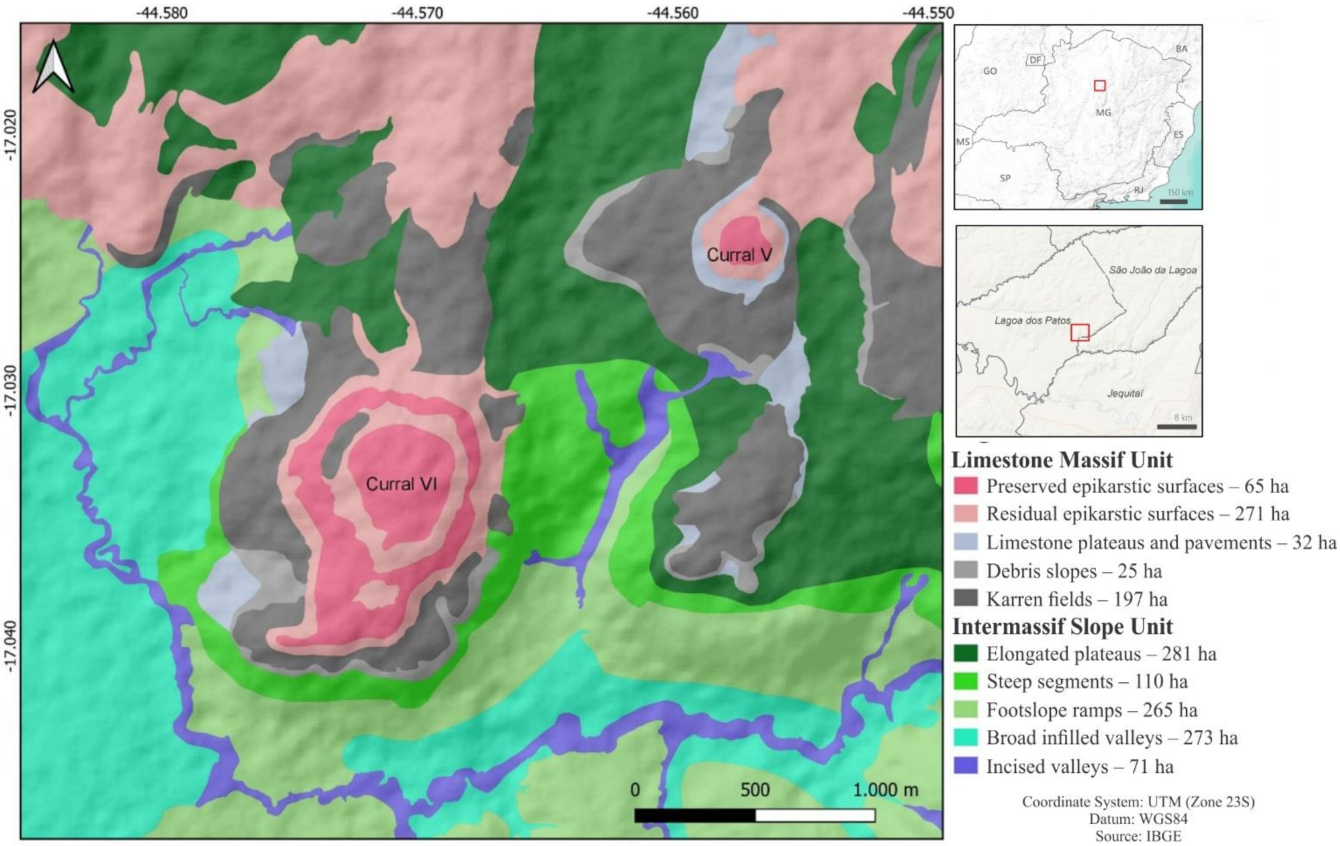

Figure 5. Landform map of Currais de Pedra V and VI – Lagoa dos Patos, Minas Gerais, Brazil.

Within the Limestone Massifs, the following landforms were identified: (i) Epikarstic surfaces, subdivided into (ia) preserved epikarstic surfaces and (ib) residual epikarstic surfaces; (ii) Karren fields; (iii) Limestone plateaus and rock pavements; and (iv) Debris slopes.

Epikarstic surfaces, the dominant landform in this unit (57% of the area), are characterized by flat to gently undulating topography, with slopes ranging from 2 to 20%, typically situated on the summits of the massifs above approximately 630 m elevation, reaching slightly above 700 m. They are distinguished by a pedological cover developed directly on the limestone substrate.

Two subtypes of epikarstic surfaces were identified based on soil cover characteristics: (a) Preserved epikarstic surfaces (Figures 5, 6a, and 6b), where the soil cover is relatively thick and rock outcrops are absent; (b) Residual epikarstic surfaces (Figures 5, 6c, and 6d), where erosion has partially or nearly completely removed the soil cover, exposing rock surfaces interspersed with discontinuous soil pockets. The soil cover typically exhibits reddish to yellowish-red hues and generally does not exceed one meter in thickness. These soils are derived from the limestone substrate, mainly consisting of well-drained Eutrophic Cambisols that sustain Deciduous Seasonal Forest vegetation. The erosion of the soil cover produces circular "halos" on the massifs, which impart a distinctive appearance reminiscent of traditional cattle enclosures, known locally as *currais*.

Karren fields (33.4% of the area), similarly influenced by surface morphogenetic processes, are characterized by a variety of dissolution features developed in the limestone substrate. These features are controlled by the hydrodynamics of the terrain and/or by the presence of fractures and other rock discontinuities (Figure 5). In the study area, karren fields correspond to exposed rock zones devoid of soil cover, exhibiting shallow dissolution forms and supporting rupestrian vegetation adapted to limestone. They are generally located near the massif summits, between 610 and 660 m in elevation, and are typically bordered by rock walls and debris slopes where cave entrances may be exposed.

The karren fields display a diverse array of dissolution features, including fractures, fissures, and vertical shafts. Among the more superficial forms are *rillenkarren* (grooved lapies; Figure 6e), which appear as narrow, parallel grooves that originate near the tops of outcrops and dissipate toward their bases. In steeper areas, deeper features such as *rinnenkarren* are common, while vertical dissolution forms on limestone walls — known as *wandkarren* — are also present. The fields additionally host *kluftkarren*, which are widened joints and fractures; *schichtfugenkarren*, which develop along horizontal bedding planes (a dominant structural feature in the area's limestone); and *kamenitzas* (Figure 6f) — circular to elliptical surface dissolution pans. These may occur in isolation or be interconnected and often retain water or accumulate sediment, including anthropogenic materials such as lithic flakes associated with rounded pebbles.

Limestone plateaus and rock pavements (5.4% of the area) occur adjacent to, above, below, or along the edges of the karren fields, often at the base of limestone walls or debris slopes (Figures 5 and 6g). These are flat to gently undulating rocky surfaces, either fully exposed or partially covered by sediment, and lack the rugged microrelief typical of exokarstic features. *Kamenitzas* are the only commonly observed dissolution forms on these surfaces, which may appear either dry or filled with sediment and vegetation. These rock pavements are distributed across a range of elevations, with the highest occurring at 660 m, though most are found between 640 and 645 m. Evidence of temporary water accumulation is frequent, particularly in shallow, closed depressions that form small to medium-sized ponds during the rainy season. These are indicated by hydromorphic sedimentary features, such as pale gray coloration, and by concentrations of aquatic shells. In contrast, depressions that have been breached and connected to the current drainage network tend to remain dry or show signs of sediment removal.

Debris slopes (4.2% of the area) are widespread landforms produced by the progressive collapse and downslope movement of blocks from the margins of the limestone massifs, where the exokarst disintegrates (Figures 5 and 6h). These slopes are closely associated with rock walls (not mapped at the fourth taxonomic level, but likely identifiable as linear features), as well as with adjacent karren fields and cave entrances. Characterized by steep gradients, typically exceeding 35%, the debris slopes consist of limestone blocks intermixed with fine-grained sediment. These environments support the growth of tall vegetation, similar to that found in the epikarst, often emerging between and over the blocks.

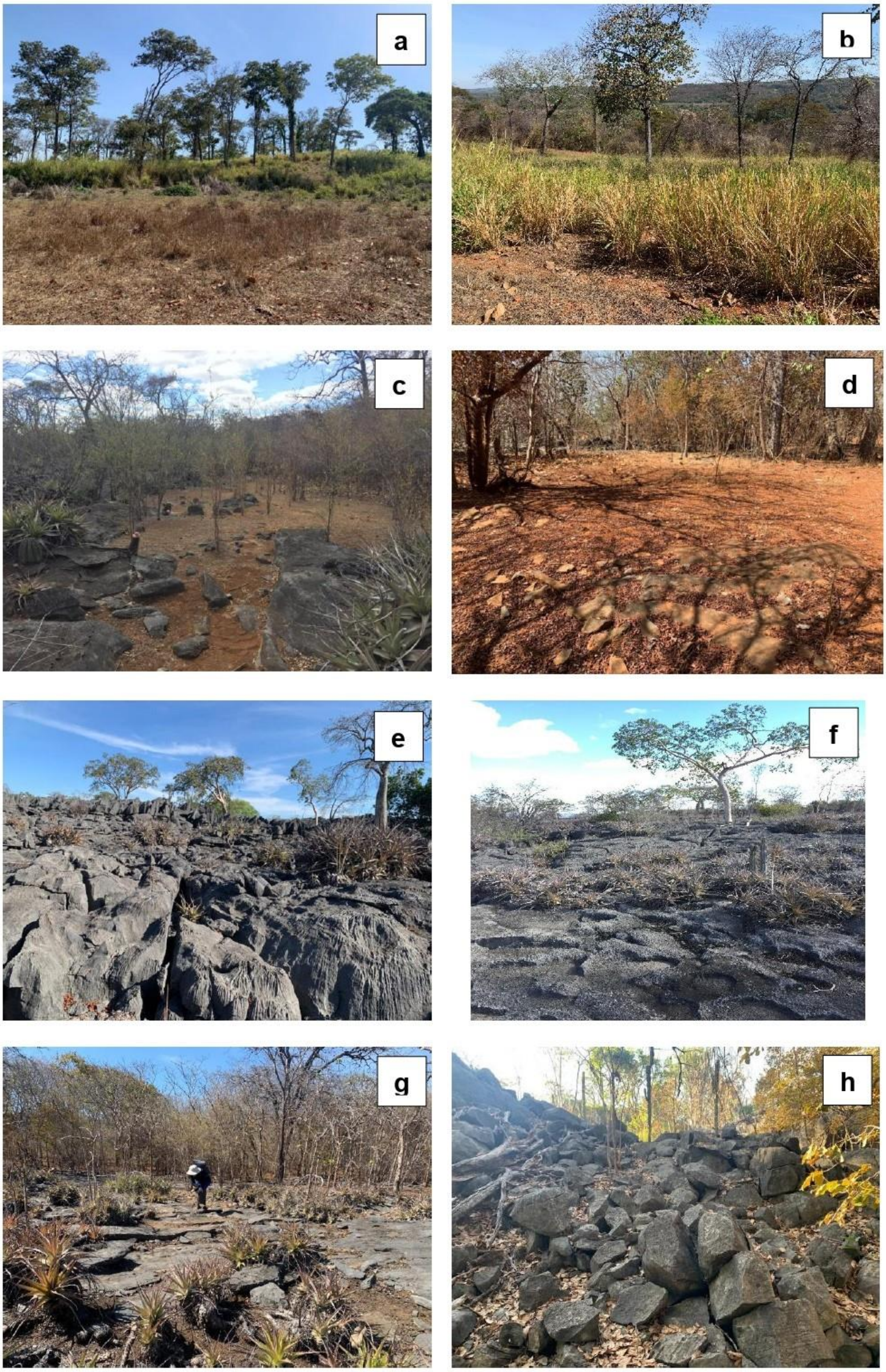

Figure 6. Representative images of the landforms within the Limestone Massifs, highlighting preserved epikarstic surfaces (a, b), residual epikarstic surfaces (c, d), karren fields (e, f), limestone plateaus (g), and debris slopes (h).

In the Intermassif Slopes, the following landforms were identified: (v) elongated plateaus; (vi) steep segments; (vii) footslope ramps; and (viii) valleys, which can be further divided into viii(a) – incised valleys and viii(b) – broad infilled valleys (Figure 5). Among these, three landforms dominate in terms of spatial extent: elongated plateaus (28%), broad valleys (27%), and footslope ramps (26%). Steep segments account for 11%, while incised valleys represent only 8% of the unit.

Elongated plateaus occur in the upper portions of the slopes to the south and southeast of the study area, as well as along the entire northern slope (Figures 5 and 7c). These plateaus consist of long, gently inclined ramps with gradients ranging from 5% to 12%, and are covered by moderately thick soils. However, existing studies are insufficient to determine whether these soils are primarily eluvial or colluvial in origin. In both the northern and southern sectors, these plateaus begin at elevations between 650 and 640 meters and descend to approximately 630–625 meters. They are connected to a variety of landforms, including limestone pavements and karren fields. A key distinction is that in the northern sector, the plateaus connect directly to the limestone massifs, whereas in the southern and southeastern sectors, this connection is disrupted by the presence of other landforms, as detailed below.

Steep segments correspond to sharply inclined slopes in the southern and southeastern sectors of the study area, predominantly occupying the middle portions of the slopes, with elevations ranging from approximately 630 meters to 580 meters (Figures 5 and 7d). These areas exhibit gradients exceeding 40%, classifying them as mountainous or escarped terrain. In aerial imagery, they often display a stepped or stair-like appearance, reflecting the structural influence of horizontally bedded carbonate and pelitic rock layers, which vary vertically in the stratigraphy. Some of these steep segments are dissected by incised fluvial channels forming ravines, where gallery forest vegetation develops within the narrow valley floors.

Footslope ramps occupy the lower portions of the slopes and are morphologically similar to the elongated plateaus in terms of gradient (Figures 5 and 7f). They are generally situated below steep slope segments, typically between 580 and 600 m in elevation, although they may also occur directly downslope from the elongated plateaus or limestone pavements in the northeastern sector. While no detailed analysis of the surface cover was conducted, these features resemble pediment-like slopes in morphology and may be associated with the lateral spread of colluvial material at the slope base, transitioning into colluvial–alluvial systems along the valley margins.

Valleys represent the lowest topographic position in the study area, with minimum elevations around 520 m. They were subdivided into two subtypes: viii(a) – incised valleys, and viii(b) – broad infilled valleys. Incised valleys correspond to the current river courses across all stream orders. These channels typically flow over exposed bedrock or exhibit minimal sediment accumulation in the form of sandy bars, a characteristic even reflected in local toponyms such as Riacho das Pedras (Figures 5, 7a, and 7b). Narrow riparian corridors of gallery forest are commonly associated with these channels.

Broad infilled valleys encompass all low-lying valley-floor areas with flat to gently undulating topography. These areas may be composed of fluvial terraces, relict floodplains, or mixed colluvial–alluvial deposits, although distinguishing among them based solely on morphology is challenging. These landforms are concentrated in the eastern to southwestern sector of the study area and include the rural community of Tesoura (Figures 5 and 7e). Presently, this is the most intensively cultivated landscape unit, which has obscured much of the native vegetation. The soils are generally deep, brown to very dark in color, and lack exposed bedrock.

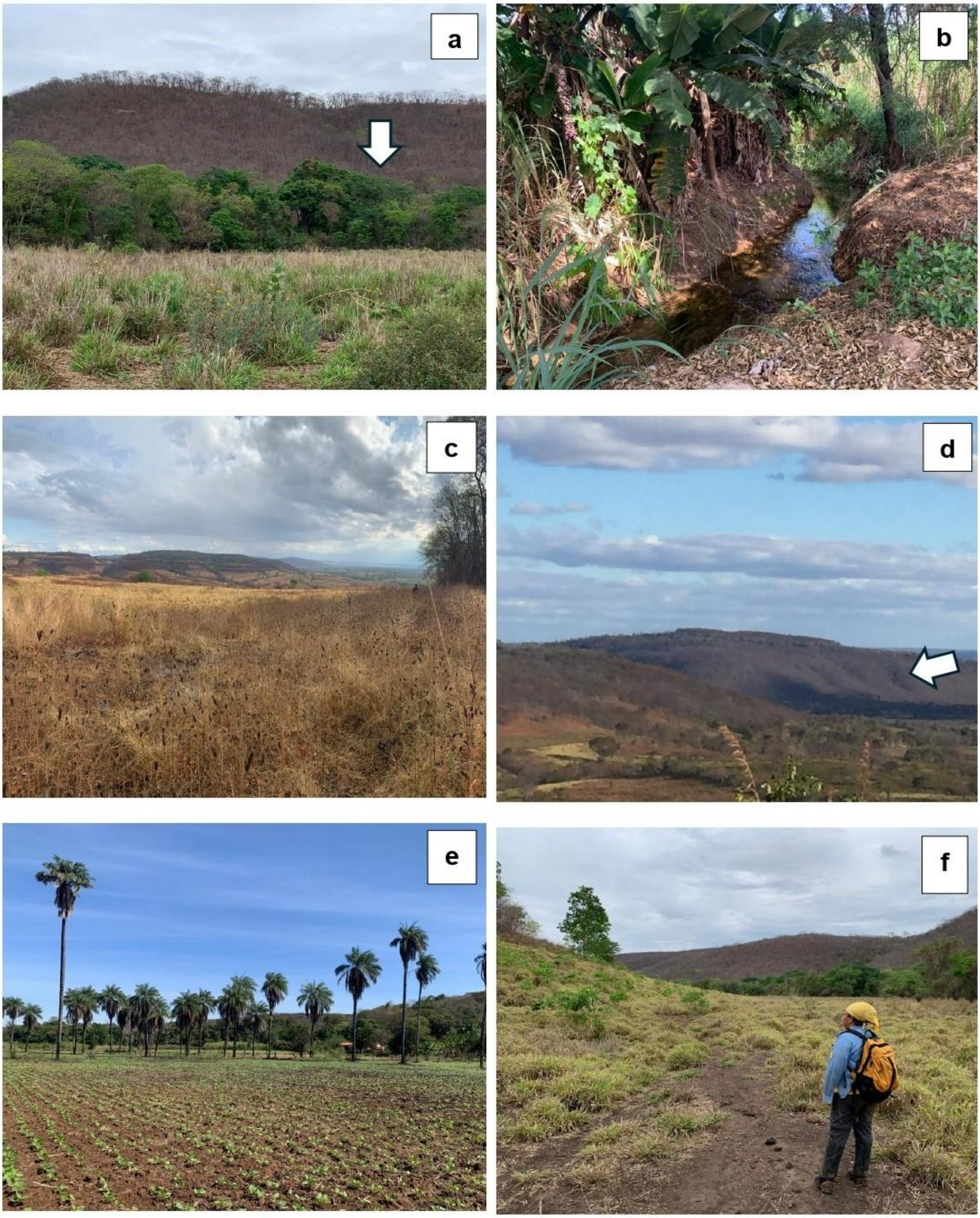

Figure 7. Representative images of the landforms that compose the Intermassif Slopes, highlighting incised fluvial valleys (a, b), elongated plateaus (c), steep segments (d), broad infilled valleys with palm wetlands (*veredas*) (e), and footslope ramps (f).

3.2. The soils

This section presents the results of the physical and chemical analyses conducted on soil samples from the open-air archaeological sites of Ressurgência and Conceição Caetano. The analyses include both the topsoils — defined here as the uppermost 10 cm of the soil, sampled at regular grid intervals — and the pedogenetic horizons described in representative soil profiles for each site.

3.2.1 – Topsoils

A total of 27 topsoil samples were collected from the Ressurgência site and 34 from the Conceição Caetano site. The results of physical (particle size distribution) and chemical analyses are summarized in Table 1.

At Ressurgência, the topsoils exhibit dark hues, ranging from dark brown to dark yellowish brown and very dark brown (10YR 2/2; 3/3; 4/6). The texture is predominantly clayey, with clay content consistently above 40%. Silt is the second most abundant fraction, varying between 30% and 38%, while sand is less abundant, ranging from 18% to 21%, and composed mostly of fine sand.

Soil pH ranges from 6.4 to 7.3, indicating a basic chemical environment. Both the effective (t) and potential (T) cation exchange capacities (CEC) are high, and due to the alkaline conditions, aluminum saturation (m) is effectively null (Table 1). As a result, base saturation (V) is consistently high, always above 80%, with a mean of 26.44%, classifying the topsoil as generally eutrophic. The exchange complex is dominated by calcium, with concentrations reaching up to 24.13 cmolc.dm^{-3}, reflecting the calcareous nature of the substrate. Magnesium is also a major component, with values ranging from 1.22 to 3.46 cmolc.dm^{-3} and a mean of 2.48 cmolc.dm^{-3}, consistent with calcareous soils. Organic matter, expressed as total organic carbon, is present in relatively high amounts, ranging from 4.70% to 7.79%. Available phosphorus, an important proxy for anthropogenic occupation, shows a mean value of 5.13 mg.dm^{-3}, with a range from 1.9 to 18.9 mg.dm^{-3}.

At the Conceição Caetano site, the topsoil is even darker, varying from very dark brown to black (10YR 2/2; 2/1). Its particle-size composition is dominated by sand, especially fine sand (FS), which ranges from 42% to 57%. Coarse sand (CS) accounts for 6% to 15% of the composition. Silt is the second most abundant fraction, with a mean of 22%, followed by clay at 19.33%. Consequently, the topsoil at Conceição Caetano is predominantly sandy loam in texture, occasionally grading into loamy sand or sandy clay loam.

The average pH is 7.3, indicating basic to alkaline reactions. These conditions result in null aluminum saturation (m), as shown in Table 1. Consequently, the high values of both effective and potential CEC reflect the presence of exchangeable bases, as evidenced by the base saturation (V), which exceeds 80% and reaches 100% in many samples. Similar to the Ressurgência site, the carbonate nature of the parent material leads to the dominance of Ca in the exchange complex, followed by Mg. However, the average calcium content is lower than that observed at the Ressurgência site (Table 1). A similar trend is observed in organic matter content, which ranges from 1.48% to 4.3%, with an average of 3.12%. In contrast, the available phosphorus content at Conceição Caetano is considerably higher, ranging from 15.2 to 151.7 mg·dm^{-3}, with a mean of 81.05 mg·dm^{-3}. Notably, the lowest values of P at this site are comparable to the highest values recorded at Ressurgência.

Table 1. Particle-size and chemical analyses of topsoil samples collected at the Ressurgência and Conceição Caetano Archaeological Sites, Currais de Pedra, Minas Gerais, Brazil.

	CS	FS	Silt	Clay	pH	P	Na	K	Ca	Mg	Al	H + Al	SB	t	T	V	m	MO
	%				H_2O	$mg.dm^{-3}$	cmolc.dm^{-3}									%		
	Ressurgência Site																	
Mean	8,67	10,33	35,33	45,67	6,74	5,13	0,02	0,35	19,11	2,48	0,00	3,41	21,94	21,94	25,35	86,44	0,00	5,90
Standard error	0,67	0,33	2,67	3,28	0,05	0,83	0,00	0,04	0,51	0,10	0,00	0,18	0,55	0,55	0,55	0,73	0,00	0,14
Median	8,00	10,00	38,00	44,00	6,80	4,00	0,01	0,30	19,17	2,56	0,00	3,63	21,56	21,56	25,40	85,60	0,00	5,51
Standard deviation	1,15	0,58	4,62	5,69	0,25	4,29	0,01	0,19	2,66	0,53	0,00	0,96	2,88	2,88	2,87	3,79	0,00	0,74
Sample variance	1,33	0,33	21,33	32,33	0,06	18,38	0,00	0,04	7,07	0,28	0,00	0,92	8,30	8,30	8,24	14,37	0,00	0,54
Minimum	8,00	10,00	30,00	41,00	6,40	1,90	0,00	0,16	13,87	1,22	0,00	1,32	16,90	16,90	20,35	80,90	0,00	4,70
Maximum	10,00	11,00	38,00	52,00	7,30	18,90	0,07	0,95	24,13	3,46	0,00	4,95	27,31	27,31	31,27	95,40	0,00	7,79
	Conceição Caetano Site																	
Mean	10,00	48,67	22,00	19,33	7,30	81,05	0,02	1,28	10,89	0,89	0,00	0,81	13,07	13,07	13,43	93,92	0,00	3,12
Standard error	2,65	4,41	4,36	0,67	0,10	7,56	0,01	0,10	0,46	0,05	0,00	0,13	0,43	0,43	0,54	1,01	0,00	0,12
Median	9,00	47,00	23,00	20,00	7,20	67,60	0,01	1,14	11,06	0,92	0,00	0,83	13,43	13,43	13,43	94,15	0,00	3,03
Standard deviation	4,58	7,64	7,55	1,15	0,61	44,10	0,03	0,61	2,69	0,31	0,00	0,77	2,50	2,50	3,18	5,91	0,00	0,71
Sample variance	21,00	58,33	57,00	1,33	0,37	1944,4	0,00	0,37	7,23	0,09	0,00	0,60	6,27	6,27	10,09	34,96	0,00	0,51
Minimum	6,00	42,00	14,00	18,00	6,50	15,20	0,00	0,56	5,95	0,39	0,00	0,00	8,19	8,19	1,16	82,60	0,00	1,48
Maximum	15,00	57,00	29,00	20,00	8,30	205,60	0,13	3,07	17,83	1,38	0,00	2,31	19,10	19,10	19,79	100,00	0,00	4,30

3.2.2 – Soil profiles and their horizons

Two soil profiles were described and analyzed at the Ressurgência site, and one profile at the Conceição Caetano site (Figure 8). The decision to analyze more profiles at the former was due to the observed lateral variability in the soil cover, whereas the latter site exhibited a more uniform pedological organization across the exposure. All profiles were described on exposed slopes that were cleaned prior to sampling to minimize edge effects.

The profiles were coded as follows: PR1 – Ressurgência Profile 1; PR2 – Ressurgência Profile 2; and PCC – Conceição Caetano Profile. Profiles PR1 and PR2 were classified as CAMBISSOLO HÁPLICO Carbonático típico (Typical Carbonatic Haplic Cambisol, equivalent to Cambisol (WRB)), while the PCC profile was classified as an LATOSSOLO VERMELHO-AMARELO Eutrófico cambissólico antropogênico (Anthropogenic Eutric Cambic Ferralsol (WRB equivalent)). The results of the physical and chemical soil analyses are presented in Table 2.

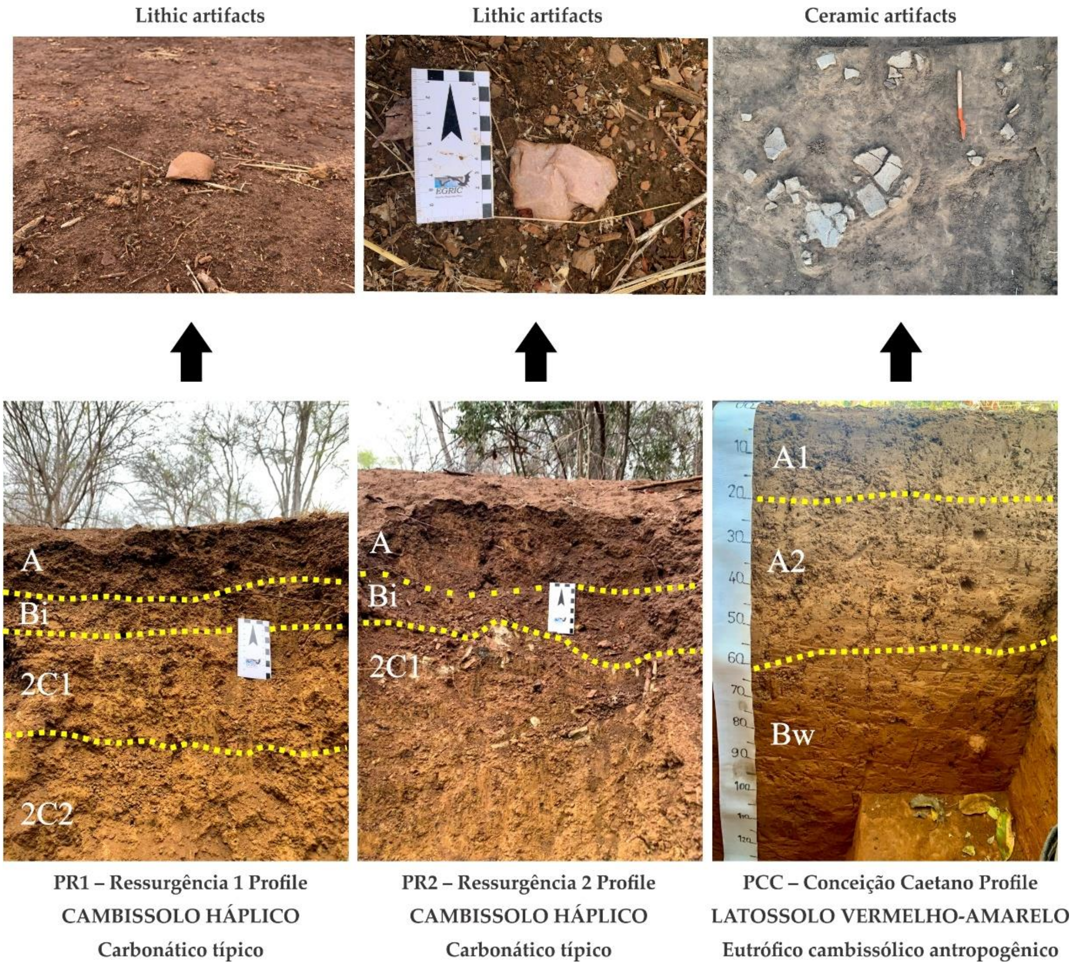

Figure 8. Representative images of the soil profiles described and sampled at the Ressurgência (PR1 and PR2) and Conceição Caetano (PCC) archaeological sites, as well as the main archaeological findings observed at the surface-lithic artifacts, and within the soil profile (ceramics) in the PCC.

Profile PR1 is 90 cm thick and is subdivided into four horizons: A, Bi, 2C1, and 2C2. The prefix "2" denotes a discontinuity in the parent material, marked by a stone line composed of platy fragments of highly weathered pelitic rocks, predominantly siltstones, with a greenish-purple hue. Horizon transitions range from clear and wavy to clear and smooth. The dominant soil structure is composed of weakly developed, small to medium subangular blocks, with a laminar structure also present at the profile base. Soil consistency is firm when dry, moderately friable when moist, and slightly plastic and sticky when wet, across all horizons. Subsurface coarse fragment content is marked at the level of the stone line.

A clayey texture is present in the A and Bi horizons, transitioning to silty clay and silty clay loam in the underlying 2C1 and 2C2 horizons. The matrix color varies from dark yellowish brown (10YR 3/6) in the upper layers to yellow (10YR 7/8) at depth. Chemically, all horizons exhibit alkaline conditions, with pH values ranging from 6.8 to 7.8. Exchangeable bases — particularly calcium — are present in high concentrations, with peak values of K = 0.10 cmolc·dm^3, Ca = 19.93 cmolc·dm^3, and Mg = 0.95 cmolc·dm^3. These data confirm calcium as the predominant cation in the exchange complex, even in horizons influenced by pelitic rock fragments. Base saturation remains consistently high throughout the profile, with values at or above 90%, indicating eutrophic conditions. Organic matter content is elevated in the surface horizon (4.43%) but declines markedly with depth, reaching just 0.81% in the lowest horizon. In contrast, available phosphorus follows an inverse pattern: surface values are relatively low (2.5 and 4.4 mg·dm^3 in the A and Bi horizons, respectively), while subsurface concentrations increase sharply, rising to 51.3 mg·dm^3 in horizon 2C1 and reaching 230.1 mg·dm^3 in 2C2.

Profile PR2 represents a lateral variant of PR1, distinguished primarily by a thinner stone line, though the lithological discontinuity remains evident. The profile comprises horizons A, Bi, and 2C, with morphological features largely mirroring those of PR1. Subangular blocky structure predominates, with medium-sized, weakly developed aggregates. Consistency is firm to slightly hard when dry, friable to slightly friable when moist, and slightly plastic and sticky under wet conditions. Transitions between horizons are clear, ranging from wavy to smooth.

Physically and chemically, PR2 shares many similarities with PR1. The surface horizons are dominated by clay, resulting in a clayey texture, while the deeper 2C horizon is classified as silty clay loam due to a marked increase in silt content, reinforcing the evidence for parent material discontinuity. Soil pH remains high throughout the profile (6.7–7.9), and base saturation levels indicate eutrophic conditions. The exchange complex is again dominated by calcium, independent of the presence of pelitic lithologies, with maximum exchangeable base concentrations recorded at K = 0.09 cmolc·dm³, Ca = 16.49 cmolc·dm³, and Mg = 0.50 cmolc·dm³. Organic matter is concentrated in the surface horizon (3.49%) and drops below 1% in the subsurface. As observed in PR1, available phosphorus levels are low at the surface (2.9 mg·dm³ in horizon A) and rise significantly in the 2C horizon, reaching 250.6 mg·dm³.

Table 2. Particle-size and chemical analyses of the horizon samples from the representative soil profiles of the Ressurgência and Conceição Caetano Archaeological Sites, Currais de Pedra, Minas Gerais, Brazil.

Hor.	Depth (cm)	Color	Sand	Silt	Clay	Textural class	pH	P[1]	Na[1]	K[1]	Ca[2]	Mg[2]	Al[3]	H + Al	SB[4]	CEC e[5]	CEC p[6]	V[7]	m[8]	OM[9]
			%				H_2O	mg.dm^{-3}					cmolc.dm^{-3}						%	
PR1 –Ressurgência 1 Profile – CAMBISSOLO HÁPLICO Carbonático típico																				
A	0-20	dark yellowish brown	22	36	42	Clay	6.8	2.5	0.02	0.10	19.93	0.95	0.0	2.64	21.00	21.00	23.64	88.8	0.0	4.43
Bi	20-28	dark yellowish brown	21	32	47	Clay	7.2	4.4	0.02	0.05	15.07	0.33	0.0	1.32	15.47	15.47	16.79	92.1	0.0	2.69
2C1	28-42	brownish yellow	15	40	45	Clayey silt	7.3	51.3	0.02	0.02	14.81	0.15	0.0	0.66	15.01	15.01	15.67	95.8	0.0	1.48
2C2	42-90	yellow	07	63	30	Silty clay loam	7.8	230.1	0.01	0.04	9.91	0.03	0.0	0.0	9.99	9.99	9.99	100.0	0.0	0.81
PR2 –Ressurgência 2 Profile - CAMBISSOLO HÁPLICO Carbonático típico																				
A	0-12	Dark brown	20	32	48	Clay	6.7	2.9	0.02	0.09	16.49	0.50	0.0	3.96	17.10	17.10	2.06	81.2	0.0	3.49
Bi	12-20	Yellowish brown	20	31	49	Clay	7.2	37.4	0.02	0.04	15.25	0.11	0.0	0.00	15.42	15.42	15.42	100.0	0.0	0.94
2C	20-60+	yellow	07	58	35	Franco-Clayey silt	7.9	205.6	0.02	0.04	9.97	0.04	0.0	0.00	10.07	10.07	10.07	100.0	0.0	0.81
PCC – Conceição Caetano Profile – LATOSSOLO VERMELHO-AMARELO Eutrófico cambissólico antropogênico																				
A1	0-20	Black	60.69	19.80	19.50	Sandy clay loam	7.2	206.4	1.07	9.42	1.17	0.02	1.07	11.67	11.67	12.74	1.07	91.63	0.18	4.86
A2	20-65	Black	54.24	17.53	28.24	Sandy clay loam	7.4	163.7	0.41	10.89	1.00	0.02	1.00	12.29	12.29	13.29	0.41	92.50	0.17	2.96
Bw	65-130+	brown	51.11	21.16	27.72	Sandy clay loam	8.0	200.8	0.36	9.65	0.52	0.01	0.69	11.23	10.54	11.23	0.36	93.85	0.10	1.37

[1]Extracted with Mehlich-1; [2]Extracted with 1 mol·L^{-1} KCl; [3]Extracted with 0.5 mol·L^{-1} calcium acetate at pH 7.0; [4]Sum of bases; [5]Effective cation exchange capacity (CECe); [6]Potential cation exchange capacity (CECp); [7]Base saturation; [8]Aluminum saturation; [9]Organic matter.

The soil profile described at the Conceição Caetano site (PCC) is deeper and more homogeneous than those at the Ressurgência site, with no observed discontinuities such as stone lines or lithological breaks. This profile reaches a depth of 130 cm, and three horizons were identified: A1, A2, and Bw. The A1 horizon is 20 cm thick and exhibits a weak to moderate subangular blocky structure, some of which disaggregate into small moderate granules. This granular structure is particularly common in areas affected by bioturbation. Below this horizon, the A2 horizon presents a denser structure. The consistency also changes with depth, ranging from slightly hard to hard when dry, firm to very firm when moist, and slightly plastic and non-sticky when wet, with increasing firmness observed from horizon A1 downward. Bioturbation features are abundant throughout the entire profile, as evidenced by the presence of infilled channels containing material differing in texture and color from the surrounding matrix. A clear chromatic change is observed from surface to subsurface: the color is black in the A1 and A2 horizons, transitioning to yellowish-red in the Bw horizon. Horizon transitions are gradual and smooth.

The physical analysis results (Table 2) show that this profile has a higher sand content compared to the other particle-size fractions (silt and clay), resulting in a predominantly sandy clay loam texture. Chemically, the pH in water [pH(H_2O)] ranged from 7.2 to 8.0, indicating a neutral to slightly alkaline environment. The highest concentrations of exchangeable bases were found in calcium and magnesium, at 10.89 and 1.17 cmolc.dm^3, respectively. Aluminum saturation (m%) ranged from 0.10 to 0.18%, and base saturation (V%) varied between 91.63% and 93.85%. The highest organic matter content (4.86%) was recorded in the A1 horizon, progressively decreasing with depth to just 0.08% in the Bw horizon. Finally, available phosphorus (P), a key indicator of anthropogenic influence, showed high concentrations across all horizons—from surface to subsurface—measuring 206.4, 163.7, and 200.8 mg.dm^3, respectively.

4. Discussion

4.1. The physical–environmental framework of the investigated units based on landforms and soils

The results obtained in this study through morphological compartmentalization reinforce the role of stratigraphic control in shaping both landforms and soil development, a pattern also identified by Gonçalves et al. (2017). This control is exerted by the alternation of horizontally layered carbonate and pelitic rocks, which vary in their susceptibility to weathering — some layers are more prone to dissolution, while others are more resistant.

In the Limestone Massifs, several landforms indicate the presence of such litho-structural controls. On epikarstic surfaces, whether preserved or residual, the interbedding of pelitic lenses within the carbonate matrix plays a key role in promoting soil formation. This is because pure carbonate rocks, composed almost entirely of calcite, are generally unfavorable for soil development (RESENDE et al., 2007). Since the dissolution of calcite does not produce secondary mineral phases, the formation of soils depends on the presence of other minerals — sometimes referred to as “impurities”— such as clay minerals, quartz, and opaque minerals. In contrast, the development of karren fields is linked to limestones that are relatively pure and therefore more susceptible to dissolution. Once exposed, these rocks allow water to circulate over their surfaces and through fractures, forming a variety of dissolution features, as described by Travassos (2019). Another landform that reflects litho-structural control is the limestone pavement (*lajedo*), whose horizontal surfaces are likely aligned with bedding planes in the stratigraphic sequence.

On the Intermassif Slopes, the diversity of landforms itself signals varied litho-structural controls. The elongated plateaus found on upper slope positions appear to be influenced by horizontal rock layering. The steeper slope segments likely correspond to lithological contacts, where a transition occurs from carbonate rocks to pelitic formations. These contacts are associated with abrupt changes in erosive capacity, as the two rock types have differing mechanical resistance. As a result, slope gradients increase. The footslope ramps indicate reworking at the base of these lithological contacts, where steep segments have retreated to form pediments. In this way, the slope zone reflects the transition from one rock type to another, and whether the landscape appears smooth or abrupt depends on how carbonate and siltstone layers are arranged and exposed.

Other landforms also contribute to the ongoing morphological evolution of the *Currais*, each illustrating distinct processes of landscape transformation. For example, debris slopes mark zones of erosional dismantling (via blockfall and toppling) from the escarpments of the Limestone Massifs. These features suggest a shift from active karstification to karst collapse and degradation processes. Broad, infilled valleys represent ancient drainage incision zones that were later opened and filled with sediments, likely of colluvial–alluvial origin. Finally, incised valleys indicate the influence of the current base level. The opening of the Sanfranciscana Depression provided energy for river downcutting, which not only deepened the channels but also intensified headward erosion along the surrounding slopes, especially in the steeper segments.

Soil analysis complements the physical–environmental characterization of the investigated units. The first archaeological site is located on a limestone pavement, where results indicate a strong influence from metapelitic rocks in the composition of the soils, as evidenced by the predominance of clayey to silty textures. A stone line composed of weathered siltstone fragments further suggests the contribution of allochthonous material. Despite this input, the chemical attributes, such as pH, sum of bases, base saturation, and CEC, reveal a strong carbonate influence, reinforcing the presence of calcareous sediments in the genesis of these soils.

At the Conceição Caetano site, situated in a broad, infilled valley, the predominance of sandy textures suggests a different sediment source, with significantly less contribution from pelitic rocks. Even so, the chemical parameters also reflect the influence of carbonate systems, indicating that these soils likely formed from colluvial–alluvial sediments with a strong input from the regional calcarenites. Unlike the first site, no clear evidence of profile discontinuities was identified, at least based on preliminary field observations.

Soils developed from distinct parent materials — though strongly shaped by the surrounding carbonate system and derived from sediments — are directly linked to the erosional dismantling processes of the perched karst. These soil profiles are associated with epikarstic depletion, marked by the downward transport of material originally generated in upper slope positions, either through surface erosion or internal flow within karst conduits, eventually leading to deposition on pavements, elongated plateaus, footslopes, and valley bottoms.

These patterns highlight a close relationship between epikarst disintegration, interpreted as the remnant of a once more extensive karst surface, as proposed by Gonçalves et al. (2017), and the redistribution of carbonate sediment across various landforms. In other words, the relationship between soils and landforms reveals an integrated dynamic in which the erosion of a primary carbonate surface, the incision of slope- and valley-forming drainages, the exposure of limestone interbedded with pelitic rocks, the development of karren fields and pavements, and the formation of caves and escarpments all constitute a continuous process of landscape reconfiguration and sediment redistribution.

Although the precise chronology of this evolution and the complex interactions among these processes require further investigation, the available data already support the conclusion that a strong interrelationship exists between landforms, soils, and the physical–environmental organization of the analyzed units.

4.2. The role of the investigated units in past human occupation at open-air archaeological sites

The Currais de Pedra karst region presents a high diversity of environments, offering different possibilities for land use and occupation by past human groups. Among these, the environments associated with the Limestone Massifs and Intermassif Slopes stand out. Fragmented limestone massifs, separated by slopes shaped by karst dynamics, form the landscape that Coeli (2020) interpreted as favorable to human occupation, especially in the transitional zone between the Sanfranciscana Depression and the São Francisco Plateau. Her analysis, grounded in the concept of territorial opportunities, considered factors such as accessibility, mobility, hypothetical pathways, annual insolation, potential for horticulture, and availability of resources for hunting, fishing, and gathering.

Coeli (2020) identified Currais V and VI as the most favorable access points to both the São Francisco Plateau and the Riacho Fundo Depression, a route regarded as significant for regional human occupation. In the associated Intermassif Slopes, she found no slope breaks that would hinder movement, characterizing them as more accessible compared to Currais I through IV. These slopes were also highlighted for their high horticultural potential, due to water availability and the presence of deeper, more fertile soils. Although hunting, fishing, and gathering were concentrated mainly in these slope areas, they could also occur within the massifs depending on the distribution of endemic fauna.

While Coeli's macroregional approach already emphasized the relevance of these units for human occupation, the fourth-level morphological compartmentalization performed in this study reinforces and expands on her findings, offering greater detail. Two key observations emerge: (i) mobility likely occurred not only between but also within the massifs, facilitated by specific landforms; and (ii) preferential circulation routes likely existed between the massifs, shaped by the diversity of landforms.

Regarding the first point, various archaeological sites containing rock art and lithic artifacts (RODET, 2018) are concentrated mainly along the edges of the massifs, where erosion has formed cliffs and exposed cave entrances. Movement between these sites appears to have occurred primarily across relatively flat surfaces, such as the limestone pavements, which are structured along horizontal geological bedding planes. These pavements, located at different elevations, serve to connect occupation areas. In contrast, karren Fields, also present in the massifs, are areas of difficult access due to their rugged surface topography. The pavements themselves may have been occupied, as evidenced by the Ressurgência site, located directly on one such landform. Therefore, limestone pavements appear to offer favorable conditions for the establishment of open-air sites.

For the second point, detailed analysis of the Intermassif Slopes revealed a mosaic of landforms. Upper-slope elongated plateaus, along with footslopes and infilled valleys in lower areas, facilitated movement and resource access, while steep slope segments acted as natural obstacles. The northern sector, dominated by elongated plateaus, likely functioned as a preferential corridor connecting Currais V and VI. In contrast, the southern sector, with more abrupt segments, would have presented mobility challenges. Footslopes and infilled valleys not only enabled easier movement but also provided water sources, thicker soils, and denser vegetation, conditions favorable for more stable and longer-term occupations. The Conceição Caetano site, situated in an infilled valley, exemplifies the suitability of such features for the establishment of open-air settlements.

Archaeological evidence further reinforces these interpretations. At the Ressurgência site, lithic artifacts predominate, many of them lacking signs of abrasion, suggesting in situ production. Pebble processing was mainly carried out using unipolar centripetal and frontal techniques, typical of the "pebble slicing" method (RODET et al., 2009; INIZIAN et al., 2017). Soil analyses at the site showed no anomalies in available phosphorus at the surface; anomalies were only found at depth, below a stone line composed of weathered siltstone fragments. In contrast, the Conceição Caetano site yielded both lithic artifacts and ceramic fragments, especially from pots (TOJA, 2021). Since systematic excavations began only in 2023, the site's archaeological potential remains largely untapped. Its soils display elevated phosphorus levels throughout the profile, suggesting long-term or repeated human occupation.

These findings point to distinct intensities and modes of occupation at the two sites. Ressurgência appears to have functioned as a transient camp or short-term activity area, likely related to lithic tool production and hunting. Meanwhile, Conceição Caetano suggests more prolonged or even semi-permanent occupation, with possible settlement structures. The phosphorus data further support this distinction. At Ressurgência, deep phosphorus enrichment is likely natural, resulting from sediment input enriched with bat guano inside caves (ANDRADE, 2017), which may have promoted the development of forest patches, attracting fauna and, consequently, human hunters. It is important to note that due to the clayey texture of the soils at Ressurgência, vertical leaching of phosphorus is improbable.

At Conceição Caetano, phosphorus anomalies throughout the profile are most likely anthropogenic, potentially resulting from the introduction of organic matter such as bones, feces, and burial residues. The hypothesis of guano-related enrichment is ruled out due to both the extent of the site and the alluvial origin and sandy texture of its soils—markedly different from the clayey soils of the massif edges. Additionally, organic matter preservation in these soils may be associated with the presence of calcium, which slows microbial decomposition, or with the formation of biochar from fire-related human practices. Further pedoarchaeological investigations will be essential to clarify these processes.

5. Conclusions

Brazilian geoarchaeology still lacks integrated studies of soils and landforms in open-air archaeological sites, particularly within the Cerrado biome. The absence of research dedicated to identifying and mapping these physical components of the landscape — and their interactions with past human occupations — was the central motivation for this study. The results and discussions presented here aim to contribute to the strengthening of geoarchaeological research in northern Minas Gerais, especially in the Currais de Pedra region.

By analyzing soils and landforms, we sought to reconstruct the landscape dynamics of Currais de Pedra and provide a foundation for future studies on regional patterns of human settlement. The geomorphological compartmentalization into Limestone Massifs and Intermassif Slopes enabled a more refined understanding of local landscape features. Within the massifs, we identified epikarstic surfaces, karren fields, stepped topography, limestone pavements, and debris slopes. In the intermassif areas, features such as incised or broad valleys, elongated plateaus, abrupt slopes, and footslope ramps were observed.

Among the open-air archaeological sites studied, the Ressurgência Site, located on limestone pavements and plateaus, is geomorphologically connected to surrounding features. In contrast, the Conceição Caetano Site is set within broad, sediment-filled valleys that provide abundant resources and favorable conditions for long-term or even permanent settlement.

Soil analyses revealed different sources of phosphorus enrichment at each site. At Ressurgência, the enrichment is likely linked to the breakdown of guano-rich cave sediments, which may have acted as an ecological attractor by enhancing soil fertility and supporting a diverse forest ecosystem. At Conceição Caetano, phosphorus enrichment appears to result from anthropogenic activity. Further research is needed to determine whether this reflects horticultural practices, waste accumulation, burial activity, or other factors.

These findings underscore the need for deeper and more targeted investigations. Complementary methodologies, such as geochemical profiling, organic matter analysis, soil micromorphology, and chronological dating, are essential for refining our understanding of past human presence in the region. Ultimately, this study reinforces the importance of geomorpho-pedological analysis as a key tool for reconstructing ancient landscapes and interpreting settlement processes in northern Minas Gerais, especially within the karst environments of the Currais de Pedra.

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References

1. ANDRADE, P. B. de. **Caracterização bioespeleogênica dos compostos fosfatados em cavernas e seu papel ecológico no geossistema ferruginoso da Serra dos Carajás, Pará, Brasil**. Dissertação (Mestrado em Agronomia) – Programa de Pós-Graduação em Solos e Nutrição de Plantas, Universidade Federal de Viçosa, Viçosa, 2017.
2. ARAUJO, A. G. M.; PAISANI, J. C.; SCHRAGE, T. J.; FEATHERS, J. K.; HARTMANN, G. A.; RICCI, O. The "Lagoa do Camargo 1" Paleoindian site: Some implications for tropical geomorphology, pedology, and paleoenvironments in southeastern Brazil. *Geoarchaeology*, v. 32, n. 6, p. 662–677, 2017. DOI: https://doi.org/10.1002/gea.21628.
3. ARROYO-KALIN, M. Steps towards an ecology of landscape: The pedo-stratigraphy of anthropogenic dark earths. In: WOODS, W. I.; TEIXEIRA, W. G.; LEHMANN, J.; STEINER, C.; WINKLERPRINS, A.; REBELLATO, L. (Eds.). **Amazonian Dark Earths: Wim Sombroek's Vision**. Dordrecht: Springer, 2009. p. 33–83.
4. CENTRO DE PESQUISAS GEOLÓGICAS. **Relatório de pesquisas realizadas na região denominada Curral de Pedras**. Belo Horizonte, 1978. 18 p. (CPG. Relatório interno).
5. CHAVES, M. L. de S. C.; BENITEZ, L.; ANDRADE, K. W.; QUEIROGA, G. N. Estratigrafia e evolução geomorfológica do grupo Bambuí na região Morro da Garça (MG). *Geonomos*, UFMG, p. 43–52, 2007.
6. CHU, V.; REGEV, L.; WEINER, S.; BOARETTO, E. Differentiating between anthropogenic calcite in plaster, ash and natural calcite using infrared spectroscopy: Implications in archaeology. *Journal of Archaeological Science*, v. 35, p. 905–911, 2008.
7. CODEMIG/UFMG. Mapa Geológico e Relatório. **Folha Pirapora - SE.23-X-CI**. Belo Horizonte: CODEMIG, 2014. Escala 1:100.001.
8. COELI, L. **O Arqueoespaço Geográfico: análise multiescalar – Currais de Pedras, Brasil Central**. Tese (Doutorado em Geografia) – Programa de Pós-Graduação em Geografia, Universidade Federal de Minas Gerais, Belo Horizonte, 2020. 321 p.
9. CORRÊA, A. M. R. da C. **Geoarqueologia da Bacia do Rio Pardo: aplicações e perspectivas**. Tese (Doutorado em Geografia) – Universidade Estadual Paulista, Presidente Prudente, 2007. 222 p.
10. CORRÊA, G. R.; SCHAEFER, C. E. G. R.; GILKES, R. J. Phosphate location and reaction in an archaeoanthrosol on shell-mound in the Lakes Region, Rio de Janeiro State, Brazil. *Quaternary International*, v. 315, p. 16–23, 2013.
11. GONÇALVES, F. A. A. **Morfodinâmica e morfogênese de um carste suspenso e evolução geomorfológica de longo termo: uma aproximação com base no caso do setor oeste do Curral de Pedras I/Jequitaí**. Dissertação (Mestrado em Geografia) – Programa de Pós-Graduação em Geografia, Universidade Federal de Minas Gerais, Belo Horizonte, 2013. 162 p.
12. GONÇALVES, F. A. A.; RODET, J. G. M. A.; JÚNIOR, A. P. M. Carste suspenso e geomorfologia de longo termo: A Região Cárstica dos Currais de Pedras, Jequitaí – Minas Gerais. *Revista Brasileira de Geomorfologia*, v. 18, n. 2, p. 279–293, 2017. DOI: http://dx.doi.org/10.20502/rbg.v18i2.817.
13. INIZAN, M.-L.; REDURON-BALLINGER, M.; ROCHE, H.; TIXIER, J. **Tecnologia da pedra lascada**. Edição traduzida, revisada e ampliada com definições e exemplos brasileiros por RODET, M. J.; MACHADO, J. R. Belo Horizonte: Museu de História Natural e Jardim Botânico/UFMG, 2017. 211 p.
14. IUSS WORKING GROUP WRB. World Reference Base for Soil Resources. Update 2015. International soil classification system for naming soils and creating legends for soil maps. *World Soil Resources Reports*, n. 106. Rome: FAO, 2015. 192 p.
15. KERN, D. C.; KÄMPF, N. Antigos assentamentos indígenas na formação de solos com terra preta arqueológica na Região de Oriximiná, Pará. *Revista Brasileira de Ciência do Solo*, v. 3, p. 219–225, 1989.
16. KERN, D. C.; LIMA, H. P.; COSTA, J. A.; LIMA, H. V.; BROWNE RIBEIRO, A.; MORAES, B. M.; KÄMPF, N. Terras pretas: Approaches to formation processes in a new paradigm. *Geoarchaeology*, v. 32, p. 694–706, 2017. DOI: https://doi.org/10.1002/gea.21647.
17. LLOPIS-LLADÓ, N. **Fundamentos de hidrogeologia cárstica: introducción a la geoespeleologia**. Madrid: Blume, 1970.
18. MACPHAIL, R. I.; CROWTHER, J. Soil micromorphology, chemistry and magnetic susceptibility studies at Huizui (Yiluo Region, Henan Province, Northern China), with special focus on a typical Yangshao floor sequence. *Bulletin of the Indo-Pacific Prehistory Association*, v. 27, p. 103–113, 2007. DOI: https://doi.org/10.7152/bippa.v27i0.11981.
19. MUNSELL COLOR. **Soil Color Charts**. New Windsor: Macbeth, Division of Kollmorgen Instruments Corporation, 1994.
20. PROUS, A. **Arqueologia brasileira**. 1. ed. Brasília: UnB, 1992. 613 p.
21. RESENDE, M.; CURI, N.; REZENDE, S. B.; CORRÊA, G. F. **Pedologia: base para distinção de ambientes**. 5. ed. Lavras: UFLA, 2007. 322 p.
22. RODET, J.; RODET, M. J.; WILLEMS, L.; POUCLET, A. Abordagem geomorfológica da bacia do rio Peruaçu e implicações geoarqueológicas. *Arquivos do Museu de História Natural*, v. 19, p. 75–103, 2009.

23. RODET, M. J. **Étude technologique des industries lithiques du nord de Minas Gerais, Brésil**. Depuis le passage Pléistocène/Holocène jusqu'au contact – XVIIIème siècle. Tese (Doutorado) – University of Paris X, Nanterre, França, 2007.
24. RODET, M. J. **Arqueologia e etnografia da região do alto médio rio São Francisco (Jequitaí, Lagoa dos Patos, Barra do Guacuí e Buritizeiro MG)**. Relatório Final do Projeto MCTI/CNPq Nº14/2014. Belo Horizonte, fevereiro, 2018.
25. RODET, M. J.; TALIM, D. D.; SANTOS JUNIOR, V. Cadeia operatória e análise tecnológica: uma abordagem metodológica possível mesmo para coleções líticas fora de contexto (exemplo das pontas de projétil do nordeste do Brasil). *Cuadernos del Instituto Nacional de Antropología y Pensamiento Latinoamericano*, n. 1, p. 264–278, 2013.
26. ROSS, J. L. S. O registro cartográfico dos fatos geomorfológicos e a questão da taxonomia do relevo. *Revista do Departamento de Geografia*, v. 6, p. 17–29, 1992. DOI: https://doi.org/10.7154/RDG.1992.006.0002.
27. SCHMIDT, M. J. Landscapes of movement: The anthropology of roads, paths, and trails. In: NEVES, E. G.; SCHMIDT, M. J. (Eds.). **Amazônia Antropogênica: um estudo interdisciplinar**. Manaus: Universidade Federal do Amazonas, 2016. p. 123–150.
28. SOIL SURVEY STAFF. Keys to Soil Taxonomy. 12. ed. Washington, DC: USDA, Natural Resources Conservation Service, 2014.
29. SOUSA, D. V.; KER, J. C.; PROUS, A.; SCHAEFER, C. E. G. R.; RODET, M. J.; OLIVEIRA, F. S.; SILVA, R. C. Archaeoanthrosol formation and evolution of the "Santana do Riacho" archaeological shelter: An old burial site in South America. *Geoarchaeology*, v. 32, p. 678–693, 2017. DOI: https://doi.org/10.1002/gea.21645.
30. SOUSA, D. V.; KER, J. C.; RODET, M. J.; SCHAEFER, C. E. G. R.; TEIXEIRA, W. G. Pedoarqueologia em abrigo quartzítico, Sítio Bibocas II, Jequitaí: ocupação humana no Holoceno inicial na bacia do São Francisco. *Revista Teoria & Sociedade*, v. 23, p. 167–197, 2015.
31. SOUSA, D. V.; KER, J. C.; SCHAEFER, C. E. G. R.; RODET, M. J.; GUIMARÃES, L. M.; FELIX, J. F. Magnetite originating from bonfires in a Brazilian prehistoric Anthrosol: A micro-Raman approach. *Catena*, v. 171, p. 552–564, 2018.
32. SOUSA, D. V.; RODET, M. J.; DUARTE-TALIM, D.; TEIXEIRA, W. G.; PROUS, A.; VASCONCELOS, B. N.; PEREIRA, E. Linking anthropogenic burning activities to magnetic susceptibility: Studies at Brazilian archaeological sites. *Geoarchaeology*, v. 38, n. 1, p. 89–108, 2022. DOI: https://doi.org/10.1002/gea.21941.
33. TOBIAS JUNIOR, R. Arte rupestre de Jequitaí/MG: suas relações internas em oposição ao contexto arqueológico do Centro Norte Mineiro. *Revista Espinhaço*, n. 3, p. 132–146, 2013. DOI: https://doi.org/10.5281/zenodo.3967845.
34. TOJA, S. **Análise de Cerâmicas Arqueológicas, limites e possibilidades: O caso do sítio Arqueológico Conceição Caetano (Lagoa dos Patos, MG)**. Monografia (Graduação em Antropologia, habilitação em Arqueologia) – Universidade Federal de Minas Gerais, Belo Horizonte, 2021. 166 p.
35. TRAVASSOS, L. E. P. **Princípios de carstologia e geomorfologia cárstica**. Brasília: ICMBIO, 2019. 242 p.
36. VALADÃO, R. C. **Evolução de longo-tempo do relevo do Brasil Oriental: desnudação, superfícies de aplainamento e soerguimentos crustais**. Tese (Doutorado em Geologia) – Universidade Federal da Bahia, Salvador, 1998. 240 p.
37. VILLAGRÁN, X.; HARTMANN, G. A.; STAHLSCHMIDT, M.; HEINRICH, S.; GLUCHY, M. F.; HATTÉ, C.; LAHAYE, C.; GRIGGO, C.; PÉREZ, A.; RAMOS, M. P. M.; STRAIOTO, H.; SANTOS, J.; TRINDADE, R. I. F.; STRAUSS, A.; GUIDON, N.; BÖEDA, E. Formation processes of the Late Pleistocene Site Toca da Janela da Barra do Antonião – Piauí (Brazil). *PaleoAmerica*, v. 7, p. 260–279, 2021. DOI: https://doi.org/10.1080/20555563.2021.1931744.
38. VILLAGRÁN, X.; STRAUSS, A.; MILLER, C.; LIGOUIS, B.; OLIVEIRA, R. Buried in ashes: Site formation processes at Lapa do Santo rockshelter, east-central Brazil. *Journal of Archaeological Science*, v. 77, p. 10–34, 2017.