

Artigo de Pesquisa

Structural Geomorphology of Rock Shelters in Metasedimentary Rocks of the Lagoa da Velha Archaeological Complex, Morro do Chapéu, Bahia

Geomorfologia estrutural de abrigos rochosos em rochas metassedimentares do Complexo Arqueológico Lagoa da Velha, Morro do Chapéu, Bahia

Rafael Oliveira de Araújo¹, Thaysa Gisella Mendes de Araújo Silva², Bruno de Azevedo Cavalcanti Tavares³
João Rhannyé Brito de Araújo²,

¹ Universidade Federal de Pernambuco, Programa de Pós-Graduação em Geografia, Recife, Brasil.

rafael.oliveiraaraujo@ufpe.br

ORCID: <https://orcid.org/0009-0005-5842-4230>

² Universidade Federal de Pernambuco, Programa de Pós-Graduação em Arqueologia, Recife, Brasil.

thaysa.gisella@ufpe.br.

ORCID: <https://orcid.org/0009-0001-2486-0844>

³ Universidade Federal de Pernambuco, Departamento de Arqueologia, Recife, Brasil. bruno.tavares@ufpe.br

ORCID: <https://orcid.org/0000-0003-1823-3016>

² Universidade Federal de Pernambuco, Programa de Pós-Graduação em Arqueologia, Recife, Brasil

joao.rhannye@ufpe.br

ORCID: <https://orcid.org/0009-0003-1403-6813>

Received: 25/03/2026; Accepted: 17/09/2026; Published: 30/09/2026

Abstract: This study investigates the genesis and morphology of rock shelters in the Lagoa da Velha Archaeological Complex (Morro do Chapéu, Bahia, Brazil) through a structural geomorphology lens, using aerial photogrammetry techniques, field fracture measurement, and digital elevation models. The analysis uses a cantilever beam mechanical model to explain the projection of competent rock layers over voids created by preferential basal retreat. Situated within the São Francisco Craton, the study area contains siliciclastic rocks of the Morro do Chapéu Formation, deformed during the Brasiliano Orogeny. The research establishes a hierarchy of controls: morphostructural (large-scale folds), lithostructural (binary mechanical stratigraphy), and internal geometric (fracture networks). Results indicate that alternating layers of silicified sandstones and less resistant pelitic levels drive shelter formation. Roof instability is governed by negative bending moments that lead to slab falls, triggered by either catastrophic failure or subcritical stress corrosion cracking. The study concludes that the resulting morphology results from Proterozoic structural heritage interacting with contemporary surface processes, showcasing the principle of geomorphological equifinality.

Keywords: Rock mechanics, Cantilever beam, Morro do Chapéu, Rock Shelter.

Resumo: O estudo investiga a gênese e a morfologia dos abrigos rochosos do Complexo Arqueológico Lagoa da Velha, em Morro do Chapéu, Bahia, sob a ótica da geomorfologia estrutural, utilizando técnicas de aerofotogrametria, medição de fraturas em campo e modelos digitais de elevação. A análise fundamenta-se no modelo mecânico de viga em balanço (*cantilever beam*), que descreve a projeção das camadas competentes sobre os vãos gerados pelo recuo basal preferencial. Localizada no Cráton do São Francisco, a área apresenta rochas da Formação Morro do Chapéu deformadas durante a Orogênese Brasileira. A pesquisa propõe uma hierarquia de controles: o morfoestrutural (dobras de grande raio), o litoestrutural (estratigrafia mecânica binária) e o geométrico interno (redes de fraturas). Os resultados indicam que a alternância entre arenitos silicificados e níveis pelíticos menos resistentes permite a formação de abrigos, cuja estabilidade é regida por momentos fletores que levam ao colapso do teto (*slab fall*). Tais colapsos ocorrem devido a falhas catastróficas ou a processos subcríticos

assistidos por agentes químicos. Conclui-se que a morfologia atual resulta da convergência entre heranças estruturais proterozóicas e processos superficiais ativos, exemplificando o conceito de equifinalidade geomorfológica.

Palavras-chave: Mecânica de Rochas; Modelo de Viga em Balanço; Morro do Chapéu; Abrigos Rochosos

1. Introduction

The study of rock shelters in siliciclastic sedimentary rocks represents a thematic frontier where structural geomorphology, historical geology, and geoarchaeology converge in a singular way. In Brazil, this convergence has been systematically explored in the major sedimentary units of the Northeast, such as Serra da Capivara (Piauí), Chapada Diamantina (Bahia), and Vale do Catimbau (Pernambuco), where the recurrence of shelters with rock art has endowed the bedrock with an archaeological dimension that transcends the geomorphological record (Etchevarne, 2007). Despite this relevance, the formation mechanisms of these shelters remain subject to conceptual debates that involve both the validity of the descriptive models applied and the epistemological limits of genetic inference from observed morphology.

The cantilever beam model has been progressively recognized as an appropriate analytical tool to interpret the geometry of shelters in stratified sedimentary rocks (Young and Young, 1992; Young et al., 2009; Gleadow et al., 2025). Its mechanical basis is supported by the models of unsupported rock cantilever instability developed by Wu et al. (2018), who, through numerical modeling and physical experiments, demonstrated that gravitational loading on unsupported cantilevers induces tensile stresses on the upper face and compressive stresses on the lower face.

In its most elementary form, the model describes the projection of a competent layer over an underlying void, generated by the preferential removal of horizons of lower strength, resulting in the characteristic morphology of a projecting roof, recessed wall, and free span. The studies by Young et al. (2009) consolidated understanding of the morphology and geometry of features in sandstones across distinct lithological (with variations in cementation and porosity) and climatic contexts, and Gleadow et al. (2025) contribution expanded this empirical basis by documenting the genesis and life cycle of shelters in the Kimberley Basin, northwestern Australia, a context of sub-horizontal sequences over an exhumed lateritized landscape, mechanically analogous to the model proposed for the Morro do Chapéu Formation.

Morphological consistency of the model, however, does not necessarily imply genetic consistency. Equifinality, understood as the convergence of distinct processes into morphologically equivalent forms, is a property of open systems, systematized by Bertalanffy (1969) in the mid-twentieth century and incorporated into geomorphology by Chorley (1962); its relevance for process inference from form was systematized by Schumm (1991). This epistemological limit imposes rigor on the inference of mechanisms from form. In this context, the Lagoa da Velha Archaeological Complex constitutes a relevant case study, in which folded structures and the mechanical stratigraphy of the Morro do Chapéu Formation enable investigation of the hierarchy of controls on shelter morphology (Figure 1).

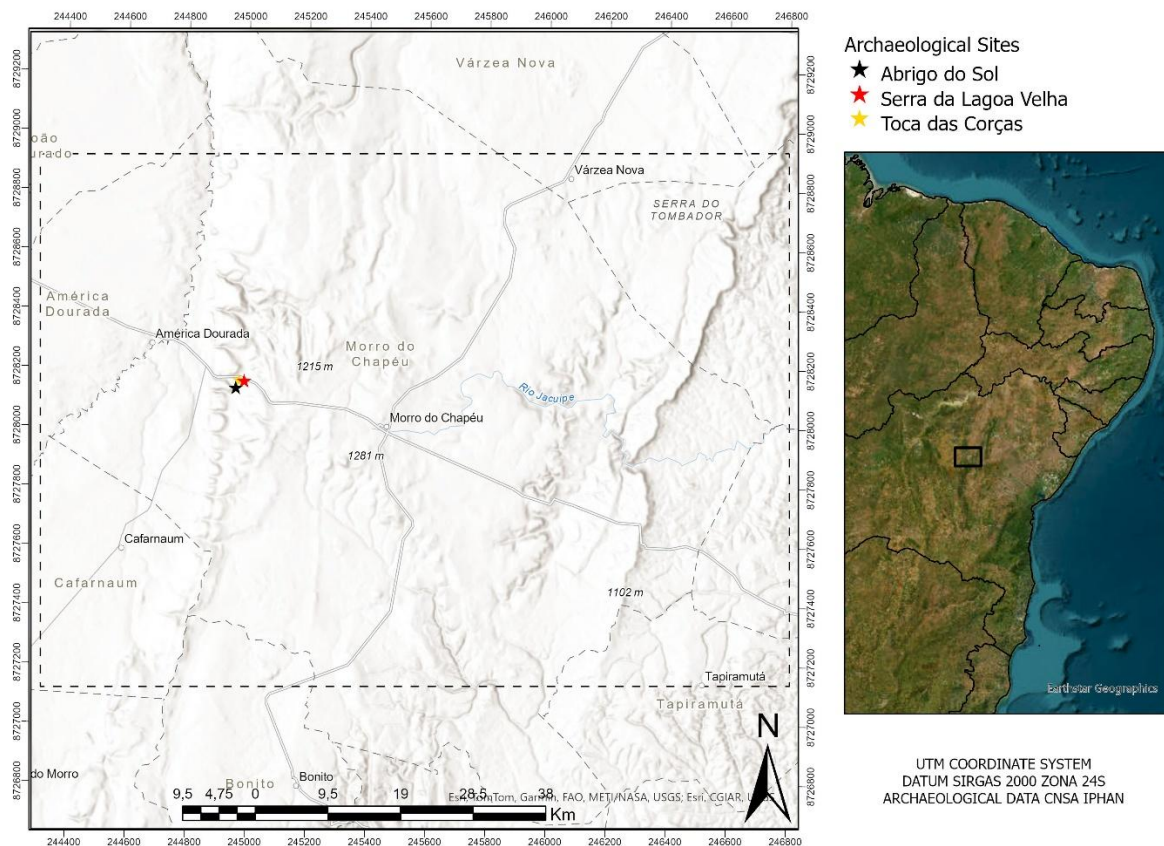


Figure 1. Location map of the Lagoa da Velha Archaeological Complex, municipality of Morro do Chapéu, Bahia, Brazil. Source: Araújo et al, 2026.

The area is situated within the geotectonic context of the São Francisco Craton (SFC), whose basement was amalgamated during the Transamazonian Orogeny (~2.0–2.1 Ga), with full cratonization completed around 1.8–1.9 Ga (Teixeira & Figueiredo, 1991). On this stabilized basement, during the Mesoproterozoic, the thick sedimentary cover of the Espinhaço Supergroup was deposited (Heilbron et al., 2017). The top of this cover is represented by the Chapada Diamantina Group, formed by the Tombador, Caboclo, and Morro do Chapéu formations, which were deformed during the Brasiliano Orogeny between 640 and 490 Ma (Alkmim et al., 2006).

The area is located at the contact between the Chapada Diamantina units, the Northern Espinhaço (Neoproterozoic) and the Gavião Block, which is structured by Neoproterozoic thrust-fault systems and contractional shear zones (Figure 2).

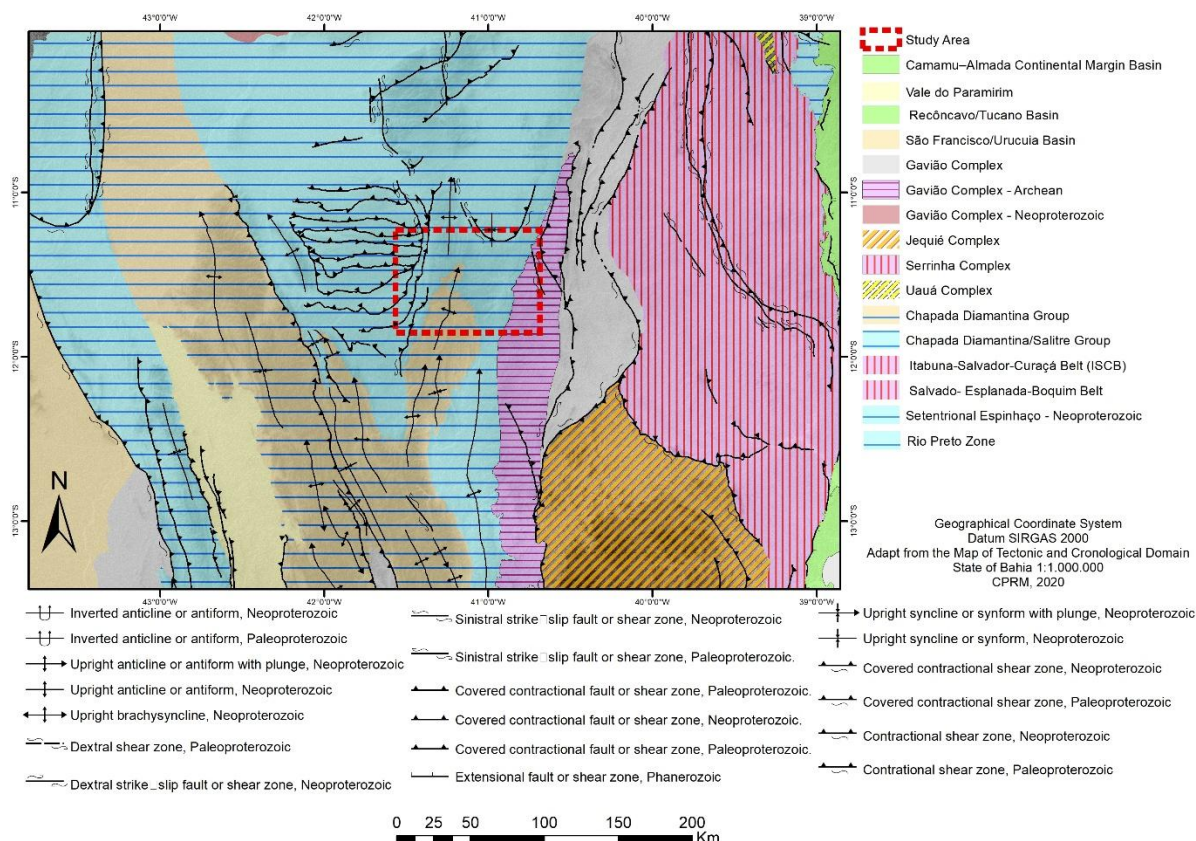


Figure 2. Map of tectonic and chronological domains of the São Francisco Craton and surrounding areas. Source: Adapted from CPRM, 2000.

The study aims to analyze the morphology of the rock shelters of the Lagoa da Velha Complex, using the cantilever beam mechanical model, and to contextualize the morphostructural and lithostructural controls in a hierarchical framework. The central hypothesis suggests that binary mechanical stratigraphy, conditioned by sedimentary deposition and by the Brasiliano folds resulting from deformation of the Morro do Chapéu Formation, acts as a necessary conditioning factor for the genesis of cantilever morphology. The field evidence supporting this hypothesis includes the position of the shelter complex on the flank of the anticline, the structural control documented in the geological section, and the rock-art records preserved on the rock panels. However, this geological framework is not self-sufficient for the genetic characterization of the shelters and requires the associated action of complementary surface agents, such as climate, which controls the physical, chemical, and biological weathering dynamics (Figure 3).

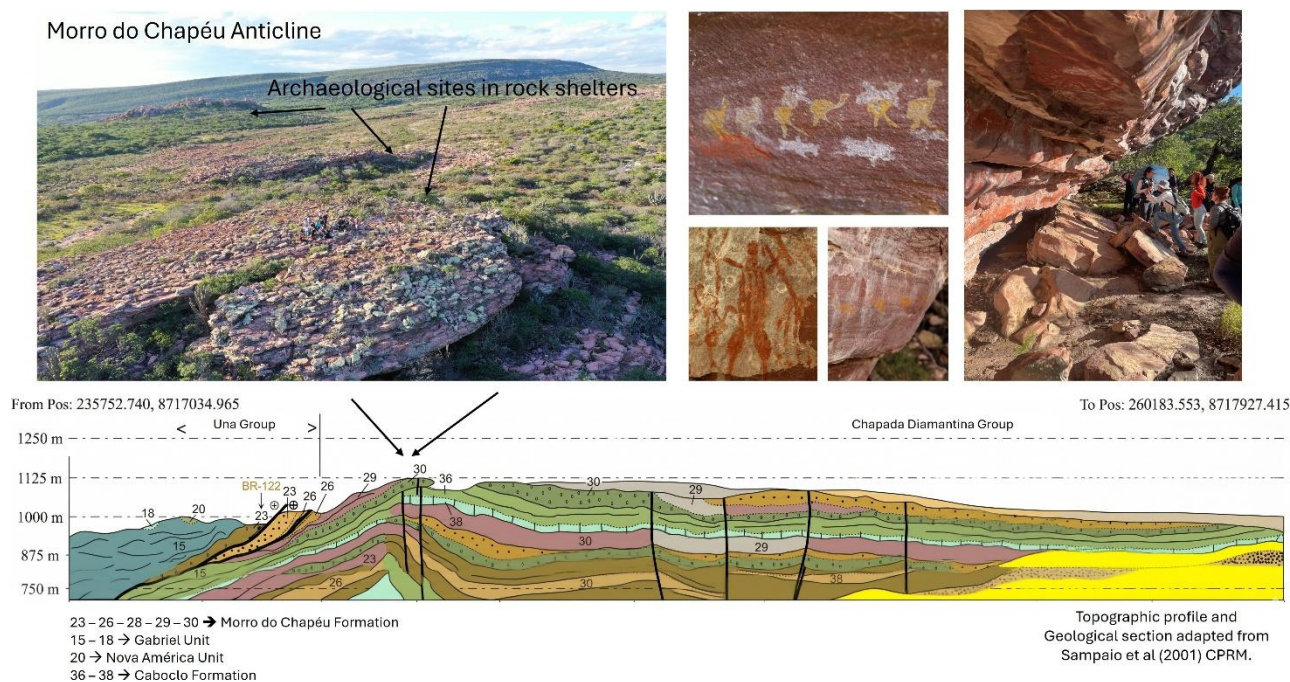


Figure 3. Lagoa da Velha Archaeological Complex. Location of the shelters in metasedimentary rocks on the western edge of the plateau escarpment, at the contact between the Anticline and the Irecê Basin. (a) View of the complex of rock shelters situated on the edge of the Morro do Chapéu Anticline, showing the shelters associated with archaeological sites. (b) W-E geological section displaying the units of the Una Group and the Chapada Diamantina Group, with a system of thrust faults. (c) Panels of rock-art motifs with zoomorphic and anthropomorphic figures preserved on the rock walls of the shelters. Source: Araújo et al, 2026.

2. Theoretical framework and state of the art

2.1. The Cantilever Beam Model: Mechanical Nature and Genetic Limits

The cantilever beam theory has its roots in the mechanics of deformable solids and was formally incorporated into the analysis of rock masses through studies on the stability of openings in mines and tunnels (Brady & Brown, 1985). In geomorphology, this criterion is applied to the basal retreat of lithology with the projection of the roof over a void, which exhibits collapse cycles by slab fall. The analogy is, however, of limited scope because, unlike tunnels—which are governed essentially by lithostatic stresses—natural shelters are shaped by surface processes (thermal and moisture variations are part of physical and chemical weathering) that alter material strength over time.

From the mechanical perspective of Wu et al. (2018), cantilever instability is governed by a negative bending moment along the entire free span. The represented model shows that the more competent layer acts as the projecting roof (Figure 4). In this configuration, the imposed curvature produces extension of the fibers on the tensile upper face and shortening of the fibers on the compressed lower face. Fracture nucleation occurs according to a mixed Mode I–II criterion, integrating opening by tensile normal to the crack plane and displacement by shear. The propagation of these discontinuities is governed by the interaction of the stress intensity factors at the crack tip, reinforcing the idea that structural failure is not a purely tensile event but the result of the combination of bending and shear stresses acting on the shelter geometry.

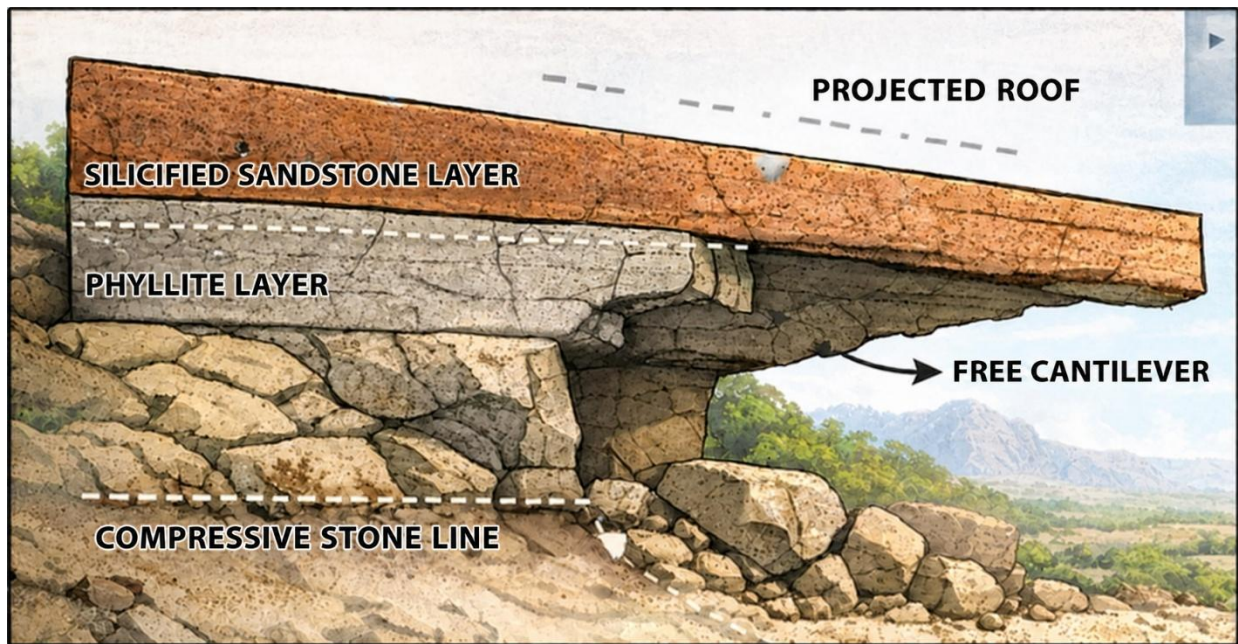


Figure 4. Schematic model of a cantilever beam applied to shelters in stratified sedimentary rocks. Source: Araújo et al, 2026.

The silicified sandstone layer (competent) acts as the projecting roof over the free span, supported by the underlying pelitic layer (incompetent). The compression line at the base indicates the structural fulcrum from which the negative bending moment that governs the instability of the system develops.

Different mechanisms of basal removal — such as differential dissolution, haloclasty weathering, fluvial erosion, and subsurface piping — can, by equifinality, produce the same cantilever morphology (Schumm, 1991). The model accurately describes what is observed in the contemporary landscape but does not determine the process responsible for basal retreat. Young & Young (1992) and Young et al. (2009) demonstrate that the stratigraphy of siliciclastic formations reveals the juxtaposition of resistant and friable layers in the vertical succession. This principle converges with the concept of mechanical stratigraphy (Narr & Suppe, 1991; Fischer et al., 1995), which describes the vertical variation of elastic and strength properties along stratigraphic columns, providing one of the processes responsible for shelter formation.

2.2. Morphostructure, Space-Time Hierarchy and Systemic Complexity

Morphostructure, as a synthesis of a spacetime hierarchy of controls, represents one of the most significant contributions to contemporary systemic geomorphology. Chorley and Kennedy (1971) defined landscape as an open system in which inputs of energy and matter, processed across different spacetime scales, generate the observable forms. Schumm (1991) systematized this problem by identifying sources of uncertainty in space-time extrapolation in geomorphology. The concept of a geomorphological threshold (Schumm, 1979) is particularly relevant for shelters: the system progressively accumulates bending moment through the deepening of basal retreat until an intrinsic mechanical threshold is exceeded and an episodic collapse event rebalances the span. This dynamic corresponds to the system's internal evolution without the need for changes in external controls, such as climate, and therefore characterizes a mechanism of mechanical self-regulation.

Complexity in geomorphological studies produces a transition between equilibrium analysis and nonlinear dynamics. Brunsden and Thornes (1979) introduced the concept of landscape sensitivity, defining it as the temporal relationship between the system's relaxation time after a disturbance and the frequency of new perturbing events. Later, Phillips (1992) advanced this discussion by applying nonlinear dynamical systems methods, characterizing relief as an open dissipative structure in which deterministic complexity and sensitivity to initial conditions make current forms contingent inheritances of past processes. In the early twenty-first century, Brunsden (2001) revisited the concept of landscape sensitivity, introduced with Thornes in 1979, to test its validity considering new process rates and contemporary environmental changes. Consolidating this trajectory, Phillips (2003) deepened the

typology of nonlinearity sources, establishing mechanisms such as competitive feedback and self-organization as pillars of the irreducible complexity of geomorphological systems. From this perspective, the model proposed in Figure 4 illustrates the projection limit of the roof up to its collapse, evidencing a temporal contingency relationship in which past processes determine the current rupture threshold. However, it must be acknowledged that the models of Brunsten and Thorne (1979) and Phillips (1992; 2003) were developed primarily for fluvial systems and slopes, and their transposition to shelters in crystalline and siliciclastic rocks should be undertaken with caution given the specificity of the mechanical thresholds involved.

Geomorphological analysis must integrate process intensity and recurrence frequency (Wolman & Miller, 1960; Chorley & Kennedy, 1971): large-magnitude, low-recurrence events can completely destabilize shelters by abrupt collapse, whereas low-energy, high-recurrence processes, such as progressive fatigue from wetting-drying cycles, can lead to the same outcome via distinct trajectories. This convergence of process trajectories toward a single final form is precisely the geomechanical equifinality that renders genetic inference from observed morphology ambiguous.

3. Geological Setting and Morphostructural Evolution

According to CPRM (2012), the municipality of Morro do Chapéu is in the north-central portion of the State of Bahia and lies within the geologic context of the São Francisco Craton (SFC), the oldest geotectonic unit of eastern Brazil. Geomorphologically, the morphostructure is conditioned by the lithostructure, exhibiting a tabular morphology composed of a folding system with gentle flanks, underlain by partially metamorphosed lithologies that are highly resistant to erosional processes, which characterizes a regional chapada (plateau) landscape. Heilbron et al. (2017) define the ensemble formed by the craton and its marginal belts as the most intensively studied portion of the Precambrian of the South American platform; the rock record spans from the Archean to the Cenozoic.

The SFC is bounded by Neoproterozoic orogenic belts: the Araçuá belts to the east and southeast; the Brasília belt to the west; and the Rio Preto and Riacho do Pontal belts to the north. These belts bordered the craton and shaped its present configuration during the amalgamation of Western Gondwana between 640 and 490 Ma (Alkmim et al., 2006; 2007; Heilbron et al., 2017). The SFC basement consists of an Archean core amalgamated during the Transamazonian Orogeny (2.1–2.0 Ga), resulting in a stabilized crust by the end of the Paleoproterozoic cycle, around 1.8–1.9 Ga (Teixeira & Figueiredo, 1991).

In the northern portion of the SFC, Barbosa & Sabaté (2004) identified four crustal segments: Gavião, Jequié, Serrinha, and the Itabuna–Curaçá–Salvador belt. The oldest is the Gavião Block, with remnants of TTG suites dated at 3.4 Ga. The Paleoproterozoic orogenic domain of eastern Bahia is detailed by Barbosa & Barbosa (2016), who interpret it as the western half of a Rhyacian–Orosirian orogen that contributed to the São Francisco–Congo cratonic bridge. Teixeira et al. (2010) document basement structures with preferred NNW–SSE and E–W orientations that, since the Paleoproterozoic, conditioned the initiation of subsequent rift systems and the development of Proterozoic sedimentary basins.

3.1. Meso and Neoproterozoic Evolution and the Brasiliano Cycle

Built upon that basement, the geological history of the SFC continued with a long phase of intraplate processes during the Meso- and Neoproterozoic. The São Francisco paleocontinent, joined to the Congo continental mass, experienced rifting and bimodal magmatism over the subsequent ~1.3 Ga (Heilbron et al., 2017). It was in this interval, in response to the extensional stresses associated with the assembly of the supercontinent Columbia (~1.8–1.5 Ga) and the rifting of Rodinia (~1.0–0.9 Ga), that the Paramirim Aulacogen and the intracratonic Espinhaço Basin were established. The Tonian tectonic evolution of this margin, investigated by Souza (2025), reinforces the interpretation of a passive-margin and intracontinental rift environment that persisted from the Stenian to the Tonian, creating the conditions for deposition of the Morro do Chapéu Formation.

The end of this intracratonic history occurred with the Brasiliano tectonic inversion. Alkmim et al. (2006; 2007) propose a nutcracker model in which the São Francisco and Congo cratonic blocks, acting as articulated cratonic pieces, moved in opposite directions under collisional forces; this model was originally published in Alkmim et al. (2006) and synthesized in Alkmim et al. (2007). The main event occurred around 580 Ma and resulted in large-wavelength folded structures that today condition the area's morphology (Figure 5). Phanerozoic data from

Dias et al. (2024) show that the SFC continued to record reactivations of Precambrian structures throughout the Phanerozoic, evidencing the longevity of these discontinuities as active morphostructural controls (Alkmim et al., 2007; Barbosa et al., 2012; Souza, 2025).

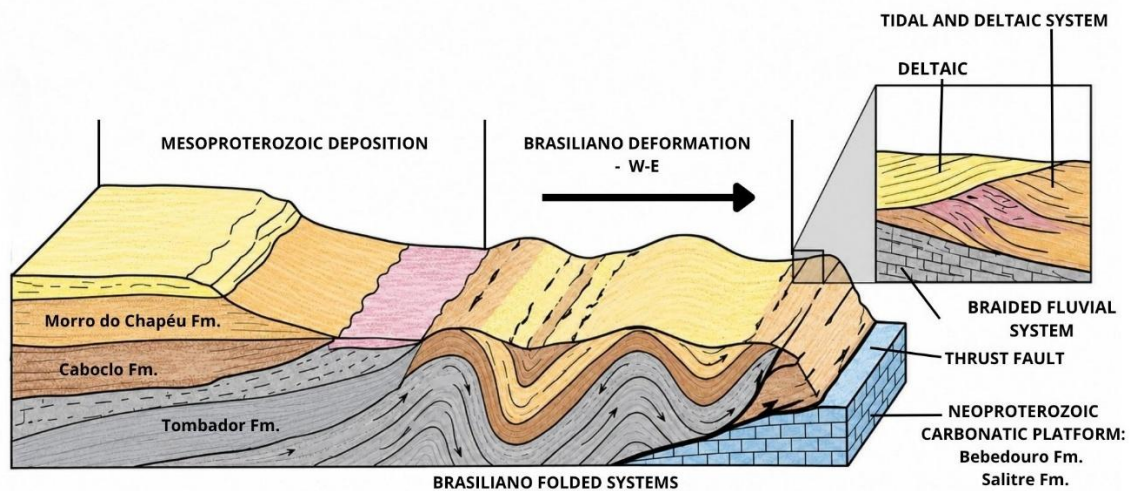


Figure 5. Explanatory model of the tectonic inversion of the Chapada Diamantina Group — Northeastern margin (Adapted from Sampaio et al., 2001; Guadagnin et al., 2015). Source: Araújo et al., 2026.

3.2 Stratigraphy and Depositional History of the Chapada Diamantina Group

The sedimentary lithology belongs to the Chapada Diamantina Group, whose deposition spans the Paleoproterozoic–Mesoproterozoic interval. Guadagnin et al. (2015) place the basal stages of the Espinhaço Supergroup in the Paleoproterozoic, while the tops of the sequences that include the Tombador, Caboclo, and Morro do Chapéu formations are consistently situated in the Mesoproterozoic (~1.4–1.1 Ga). These units form a cratonic sedimentary cover, more than 1,000 m thick, that underwent very low- to low-grade metamorphism, which allowed exceptional preservation of original sedimentary structures. The Tombador Formation reaches thicknesses greater than 400 m, comprising highly mineralogically mature sandstones and conglomerates (Pedreira, 1994; Guadagnin et al., 2015). The Caboclo Formation represents the subsequent marine transgressive event, recorded on a shallow platform in a mixed siliciclastic–carbonate setting, including stromatolites and oncolites described by Srivastava and Rocha (2002).

The Morro do Chapéu Formation, at the top of the Chapada Diamantina Group, was first described by Brito Neves (1967). Pedreira (1994) defined it as composed of siltstones, quartzose sandstones ranging from fine to coarse grain size, and conglomerates with intense authigenic silica cementation — a lithological character that directly underpins the binary mechanical stratigraphy discussed in Section 4.1. The basal contact of this Formation with the Tombador Formation is unconformable (Dominguez, 1993), whereas the upper contact is tectonic in the Serra de Martim Afonso, which constitutes direct evidence of Brasiliano compressional deformation (Brito Neves, 1967; Pedreira, 1994). Regional geochronological data (Souza, 2025) place the final stages of deformation between 640 and 580 Ma, coinciding with the main collisional event of the Araçuaí–Western Congo Orogen (Alkmim et al., 2006; 2007).

3.3. Structural and Lithostructural Controls

Brasiliano deformation structures constitute a relevant factor in determining the present-day morphology of the municipality of Morro do Chapéu. Bedding planes, as primary depositional structures, also act as lithological controls on relief because they drive mechanical anisotropy even after folding (Fossen, 2010). Brasiliano deformation imparted NNW–SSE-oriented folds to the Mesoproterozoic sedimentary package and produced N–S-oriented thrust faults with duplex geometry, which represent the main controls on the current morphostructural compartmentalization (Uhlein et al., 1995; Alkmim et al., 2006; 2007; Heilbron et al., 2017).

The municipality lies in the transition zone between a more intensely deformed western domain, characterized by tighter-wavelength folds, and an eastern domain of lower deformational intensity (folds with larger wavelength/greater arc) (Pedreira, 1994; Alkmim et al., 2006). The drainage network unequivocally reflects this structural control: main channels follow the NNW–SSE fold hinges, while transverse tributaries exploit ENE–WSW to E–W discontinuities corresponding to conjugate joints of the folding system. It is on this structural framework that the formation mechanisms of the shelters analyzed in the following section develop (Figure 6).

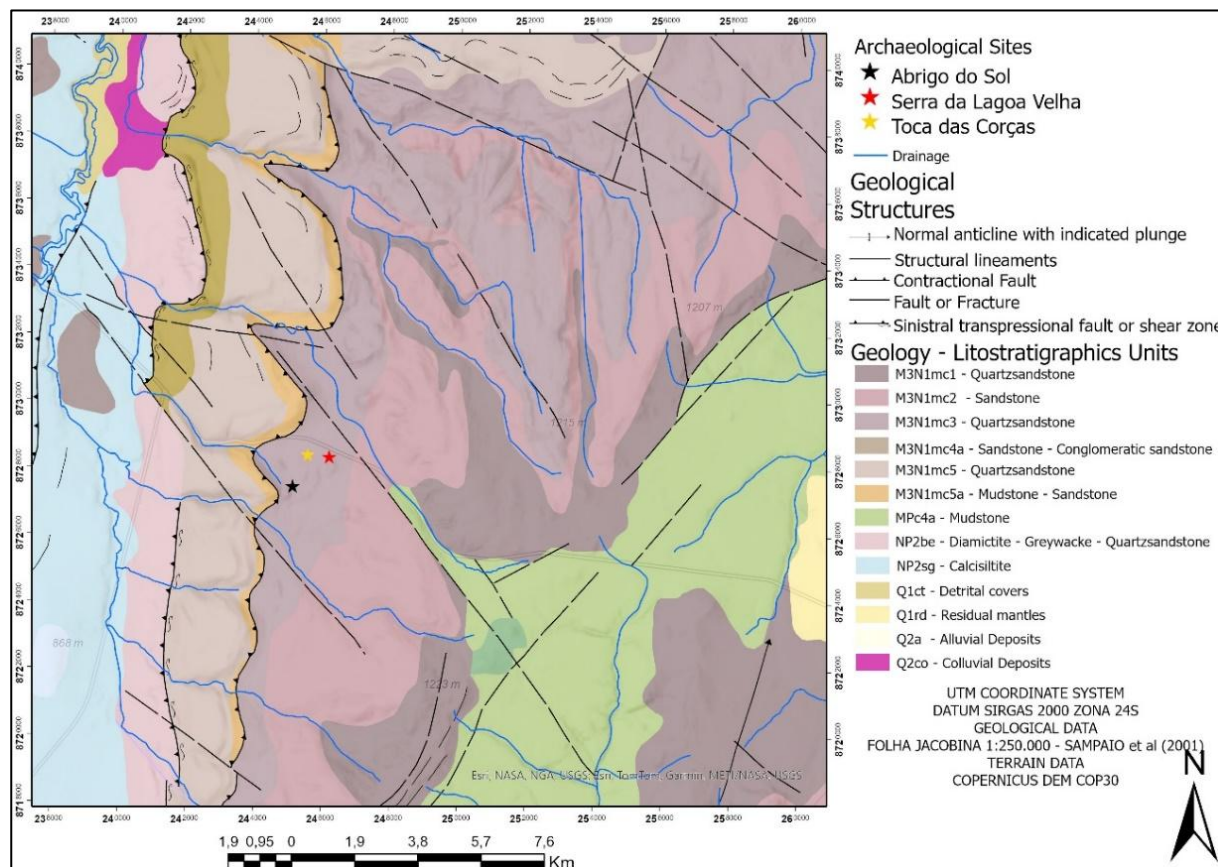


Figure 6. Lithological and structural map of the western edge of the Morro do Chapéu Plateau, Bahia. Source: Araújo et al., 2026. Adapted from Sampaio et al. (2001).

4. Methodology

The investigation of the morphology of the rock shelters of the Lagoa da Velha Archaeological Complex was conducted through a multiscale approach, integrating field surveys, remote sensing, aerial photogrammetry, and structural analysis. The methodological strategy was organized into three complementary stages: regional geological-structural characterization, geomorphological survey at outcrop scale, and mechanical modeling of formation mechanisms.

The regional characterization was based on the compilation and interpretation of cartographic and remote-sensing data. Digital Elevation Models (DEMs) derived from Copernicus DEM COP30 were used to extract morphometric parameters, delineate the drainage network, and identify structural lineaments. The cartographic base was complemented by the Jacobina Sheet 1:250,000 (Sampaio et al., 2001), from which lithostratigraphic units, Brasiliano structures (anticlines, contractional faults, and sinistral transpressional shear zones), and associated lineaments were extracted. Based on this information, integrated morphostructural and lithological-structural maps were produced.

The field survey included systematic measurement of attitudes of fracture planes, joints, and bedding surfaces at the three investigated sites: Abrigo do Sol, Serra da Lagoa da Velha, and Toca das Corças, all belonging to the Lagoa da Velha Archaeological Complex. Structural data were plotted in rose diagrams to identify preferential

discontinuity families. Macroscopic features associated with shelter instability were also recorded, such as detached blocks, active subvertical and subhorizontal fractures, and roof-collapse morphologies (slab fall).

The aerial photogrammetric survey was carried out using an Unmanned Aerial Vehicle (UAV), which enabled the acquisition of high-resolution oblique and vertical aerial images. These images were used to map the surface fracture field and identify grid-pattern and staircase-pattern fractures, complemented by the fracture-orientation data obtained from rose diagrams.

Mechanical modeling was based on the cantilever beam theory, following the models of Wu et al. (2018) for instability of unsupported rock cantilevers. The stability analysis considered the decomposition of gravitational load into normal and shear components on bedding planes, according to the structural dip measured in the field, with reference to the criteria of Hoek & Bray (1981) and Goodman & Bray (1976). Fracture-propagation mechanisms were analyzed according to Linear Elastic Fracture Mechanics (LEFM), considering Mode I and Mode II nucleation and subcritical propagation by stress corrosion cracking (SCC), following the models of Atkinson (1987) and Anderson (2005). The geostructural and geomechanical dataset was integrated into the UTM Coordinate Reference System, SIRGAS 2000 Datum, Zone 24S.

The use of artificial intelligence in the research occurred during the stage of constructing the research problem, by proposing the cantilever beam model, and in the results and discussion to reinforce the empirical data collected in the field and, from this, generate models based on the information collected in the field and processed in the laboratory. In this sense, ChatGPT and Gemini prompts were used for image creation to reinforce the data collected both in field and laboratory. For each generated image, reference bases from the literature were used to construct the figures included in this research. However, each image followed strict correction criteria to avoid interpretative errors inconsistent with the premises of the study — that is, the data collected and used to support the creation of the figures were grounded in the literature cited in the article.

In the results and discussion stage, the images generated through AI were based on data previously collected in the field and processed in the laboratory; thus, the images are products of the discussion developed in these sections, following rigorous procedures in their creation.

5. Results

5.1 Formation Mechanisms of the Rock-Shelter Morphology of the Lagoa da Velha Archaeological Complex.

The formation of the rock shelters of the Lagoa da Velha Complex cannot be explained as the isolated result of weathering and surface-erosion processes. Weathering and erosion act as executing agents, processes that, as demonstrated by Viles (2013), operate synergistically and nonlinearly on the rock substrate; however, the resulting geomorphological architecture is determined, in first order, by the binary mechanical stratigraphy of the Morro do Chapéu Formation (lithostructural control), a depositional factor and therefore temporally prior to folding; in second order, by Brasileiro deformation, which produced a system of large-wavelength folds (morphostructural control); and, in third order, by the fracture field inherited from regional deformation and stress release (internal geometric control). This hierarchy is developed in a sequence of three scale orders.

The large-wavelength folds establish the fundamental geometry of the inclined flanks, define the orientation of bedding dip, and organize the drainage network adapted to inherited structures. This organization reverberates in the relief, where a folded morphology with anticlines and synclines can be observed, adjusted to the structural controls of the area. This condition governs the orientation of the shelters, which face according to the dip angle of the strata. In this way, there is an order of scales in the control of landforms: folding produces a large-wavelength folded morphostructure, slopes that dip according to the structural angle, and rock shelters in the metasediments that are morphologically controlled by the folded structure (Figure 7).

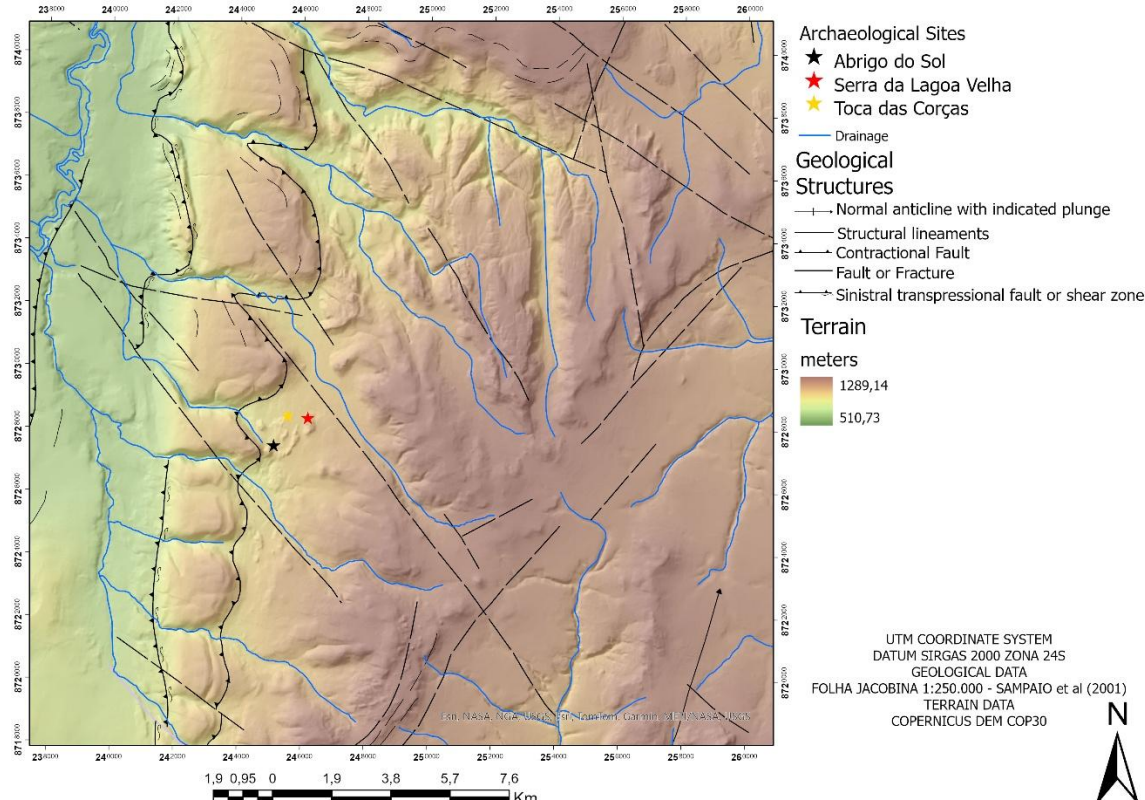


Figure 7. Hypsometric map of the Morro do Chapéu Plateau, showing the geological structures that control the morphostructures, Bahia, Brazil. Source: Araújo et al., 2026.

In sedimentary sequences with alternating competent and incompetent layers, flexural-slip folding is the most plausible accommodation mechanism, given the low metamorphic grade and the preservation of original sedimentary structures in the Morro do Chapéu Formation, conditions that favor low-friction interfaces between strata. In this mechanism, Ramsay (1967) showed that differential slip between layers is zero at the fold hinge and increases progressively toward the inflection points of the flanks in multilayer sequences with competent beds separated by low-friction interfaces (Ramsay, 1967; Tanner, 1989; Twiss & Moores, 2007).

Shelter morphology is controlled by mechanical stratigraphy, which acts upon the structural fabric inherited from folding. As Fossen (2010) demonstrated, in folded sedimentary sequences fracture fields generated by folding preferentially propagate in the upper crustal levels where confinement conditions are reduced. Associated with these fields are unloading (stress-relief) joints that, in exhumed sequences, propagate in a shallow domain whose minimum effective stress (σ_3) is tensile and horizontal — a regime described by Hancock and Engelder (1989) for subhorizontal platform sequences and applicable to the Morro do Chapéu Formation with the caveat that, in folded sequences, the unloading stress field superimposes on the residual bending stresses inherited from folding, thereby modifying both the orientation and the density of the resulting joints (Fossen, 2010). Etchevarne (2007), characterizing the sandstone outcrops of the complex, describes a mushroom-shaped morphology with pronounced basal undercuts, a direct expression of differential weathering sustained by the cantilever-beam mechanism.

5.2. Mechanical Stratigraphy of the layers

The concept of mechanical stratigraphy refers to the vertical and lateral variation of elastic and strength properties of rocks within stratified sedimentary sequences (Narr & Suppe, 1991; Fischer et al., 1995). At the scale directly relevant to shelters, mechanical stratigraphy controls fracture nucleation and spacing, the geometry of discontinuity planes, and the partitioning of deformation between competent and incompetent horizons (Narr & Suppe, 1991; Fischer et al., 1995; Bai & Pollard, 2000; Ferrill et al., 2017). In the Morro do Chapéu Formation, this variation is characterized by an alternation between packages of quartzose sandstones with intense silica cementation and levels of siltstones and pelites with significantly lower strength, configuring a binary mechanical stratigraphy (Figure 8).

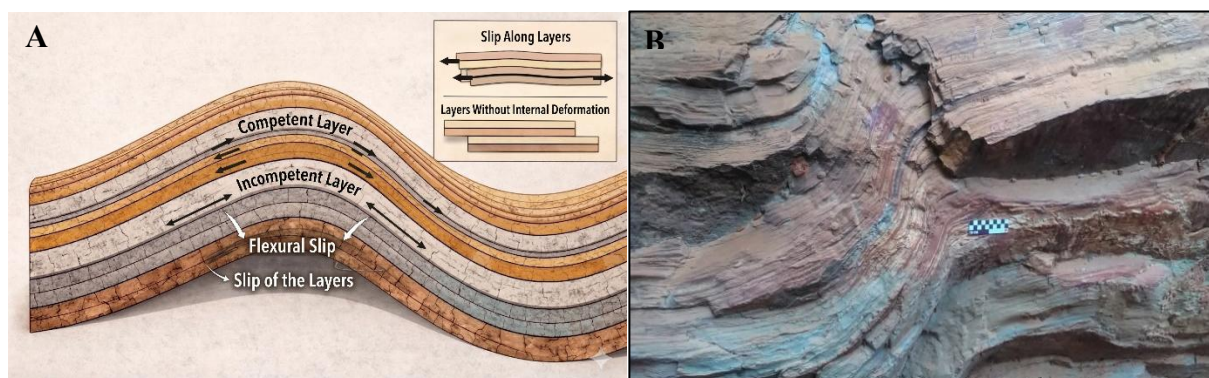


Figure 8. Flexural slip mechanism: (a) schematic geomechanical model; (b) field record in the Morro do Chapéu Formation. Source: Araújo et al., 2026.

Diagenetic silicification, identified by Pedreira (1994) as the dominant cementation process in the formation's sandstones, plays a central role in this mechanical stratigraphy. Quartz overgrowths, optically continuous with detrital grains, fill primary intergranular porosity and create a continuous, stiffer framework.

The resulting mechanical behavior is governed by Linear Elastic Fracture Mechanics (LEFM), in which fracture propagation occurs catastrophically once the critical fracture toughness is reached, without a prior detectable plastic-deformation stage (Atkinson, 1987; Wu et al., 2018). This failure pattern is analogous to that described by Marchiori (1997), Pollard & Fletcher (2005) and Wang et al. (2025) in high-competence lithologies. Full applicability of LEFM rests on the Small-Scale Yielding (SSY) assumption, according to which the process zone or plastic-deformation zone at the crack tip is negligible relative to the total crack length (Irwin, 1957; Anderson, 2005).

In the intensely silicified sandstones of the Morro do Chapéu Formation, the high stiffness conferred by secondary silica cementation (Battilani et al., 1996) minimizes the development of nonlinear microcracking, approximating the material to an ideal elastic-brittle behavior. This characteristic allows rupture to be reliably described by the critical stress-intensity factor K_{Ic} , as observed in toughness studies of analogous high-competence rocks (Atkinson, 1987; Whittaker et al., 1992). Complementarily, the SSY assumption may be locally violated under high-humidity conditions, where stress-corrosion cracking (SCC) promotes subcritical propagation governed by the chemical activity of interstitial water.

These two mechanisms operate on distinct timescales and along different trajectories: the catastrophic collapse governed by LEFM is an abrupt event corresponding to the crossing of an intrinsic threshold by progressive accumulation of bending moment until discrete failure; SCC is a subcritical propagation trajectory controlled by chemical kinetics and the thermodynamic activity of pore water, constituting a kinetic-chemical threshold rather than a purely mechanical one. SCC progressively reduces the rock's effective toughness until the LEFM collapse threshold becomes attainable. This behavior is exemplified in rock shelters where detached blocks at the outcrop base are associated with the incipient projection of a cantilevered roof that already displays a set of subvertical and subhorizontal fractures, indicative of ongoing subcritical propagation (Figure 9).

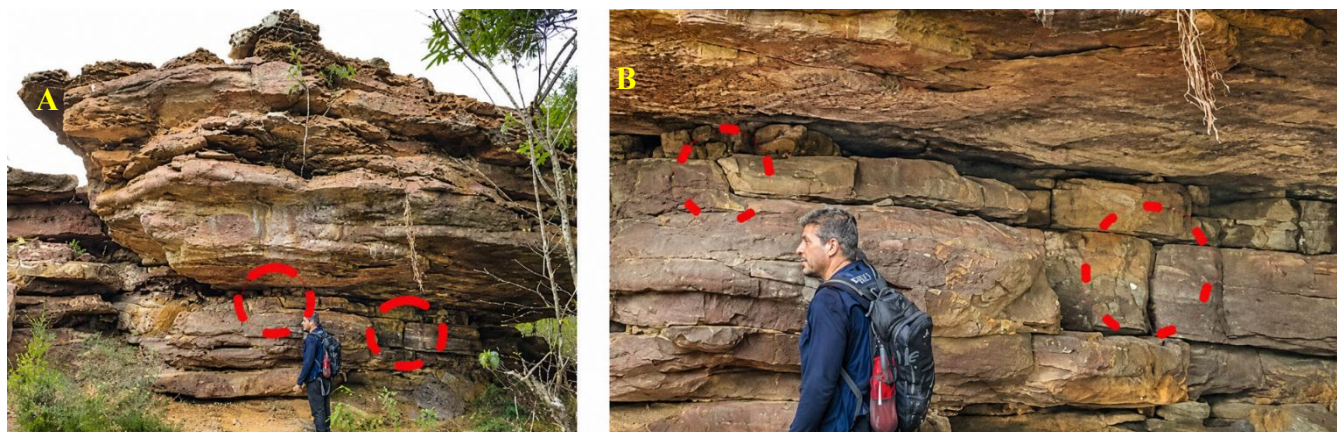


Figure 9. Structural features at the Lagoa da Velha Archaeological Complex. Source: Araújo et al, 2026.

The two mechanisms are therefore sequentially complementary: stress-corrosion cracking (SCC) conditions the threshold and Linear Elastic Fracture Mechanics (LEFM) execute it. This elastic-brittle behavior has a direct morphological implication: the silicified sandstone can sustain meter-scale overhangs without apparent deformation, acting as structural beams favorable to shelter formation, while simultaneously developing joints with spacing proportional to the thickness of the competent packages (Narr & Suppe, 1991; Fischer et al., 1995; Bai & Pollard, 2000).

5.3 Fracture framework and Geometric Control of the Shelters

The internal geometry of each shelter is influenced by the stress field acting on a substrate previously weakened by fracturing. In sedimentary sequences with alternating competent and incompetent layers subjected to buckling folding, the **flexural-slip** mechanism is the principal mode of deformation accommodation on the fold flanks (Ramsay, 1967; Tanner, 1989; Twiss & Moores, 2007) (Figure 10).



Figure 10. Morphological and structural aspects of the Lagoa da Velha Archaeological Complex. (a) Level view showing the outcrops in the context of a perennial lagoon. (b) Aerial image acquired by UAV, highlighting the spatial distribution of the outcrops and the lagoon associated with the complex. (c) Detail of a rock surface with well-developed subvertical and subhorizontal fracture systems at metric scale, illustrating the fracture pattern that controls block individualization and the geometry of the shelters. Source: Araújo et al., 2026.

The mesoscopic discontinuities that result preferentially form two families: the first, longitudinal to the fold axis (NNW–SSE), generated by tensile stresses parallel to the axis during folding (Stearns & Friedman, 1972; Price & Cosgrove, 1990; Fossen, 2010); the second, transverse to the axis, originated by extension perpendicular to the axis on the fold flanks during folding (Price & Cosgrove, 1990; Fossen, 2010). The spacing of the transverse joints follows the stratigraphic confinement relationship documented by Gross (1993) for cross-joints in subhorizontal sequences, which is controlled by the product of competent-layer thickness and the ratio between remote tensile stress and the rock's tensile strength. These two families are identified in sectors of the archaeological complex, which gathers the fractures, confirming the preferential NNW–SSE orientation of the longitudinal family and the subordinate orientation of the transverse family (Figure 11).

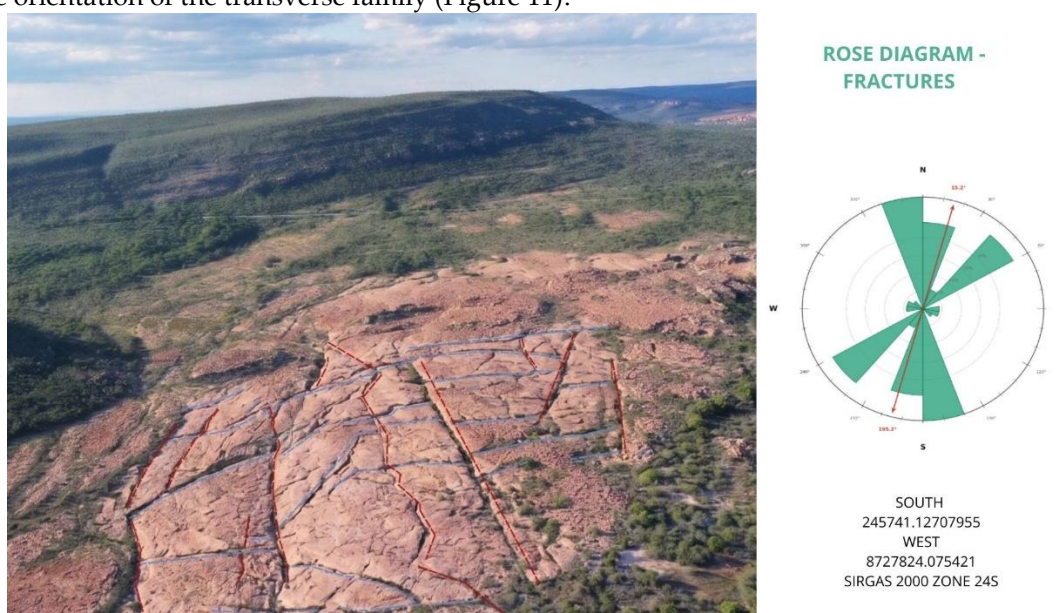


Figure 11. Fracture field mapped by UAV on the rock surface of the archaeological complex. Emphasis on the orientation of the inventoried fractures, showing the dominant NNW–SSE family (~N33°) and a subordinate transverse family, consistent with buckling and flexural-slip fracturing. Source: Araújo et al., 2026.

The mechanism of fracture termination and step-over at stiffness-contrast interfaces is grounded in the models developed by Cooke & Underwood (2001), who showed, counterintuitively, that interface opening is the mechanism responsible for fracture termination and lateral deflection, whereas sliding favors direct propagation across the interface. This application must be considered with the caveat that the Cooke & Underwood (2001) model was developed for subhorizontal configurations under specific stress fields; in folded sequences, the residual bending stresses from Brasiliano folding superimpose on the exhumation stress field and can modify the relationship between the interface deformation mode and propagation behavior. Application to the Morro do Chapéu Formation is therefore analogous but not direct and requires additional validation through numerical modeling focused on the geometry of folded flanks.

The superposition of the two fracture families produces grid and staircase patterns, resulting from the deflection and step-over mechanisms proposed by Helgeson & Aydin (1991) and Cooke & Underwood (2001). The grid pattern, characterized by two orthogonal sets of vertical joints arranged over the bedding surface, is supported by the stress-transition models of Bai & Pollard (2000) and Bai et al. (2002) (Figure 12).

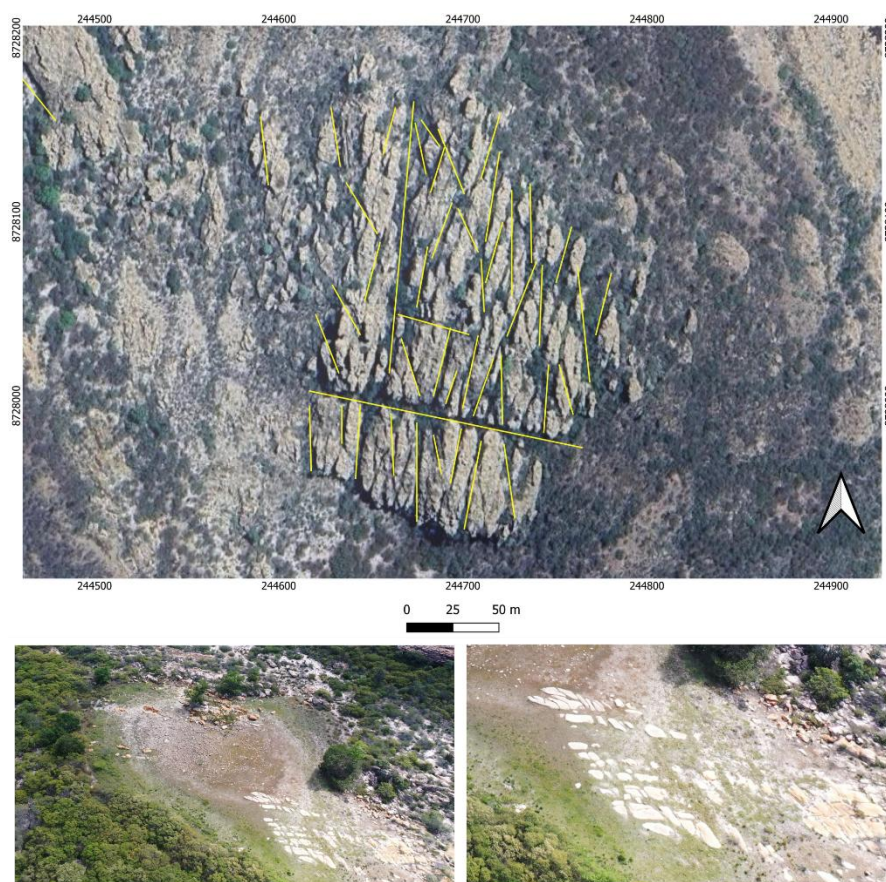


Figura 12. Grid pattern resulting from the superposition of orthogonal fracture families at the Lagoa da Velha Archaeological Complex. Aerial images acquired by UAV (upper) showing the distribution of fractures in an orthogonal arrangement; schematic sequence (lower) illustrating the stages of nucleation of pressure-relief joints in the less competent strata according to the model of Bai and Pollard (2000) and Bai et al. (2002). Source: Araújo et al., 2026.

5.4 The Cantilever Beam: Dipping Geometry and Collapse Dynamics

The convergence of the controls described above culminates in the central mechanism of shelter formation (Figure 13). This mechanism integrates structural geology, mechanical stratigraphy, and geomorphology into a model that explains not only the existence of the shelters but also their specific geometry and the patterns of stability and collapse observed in the field (Wu et al., 2018; Young & Young, 1992; Young et al., 2009; Gleadow et al., 2025).

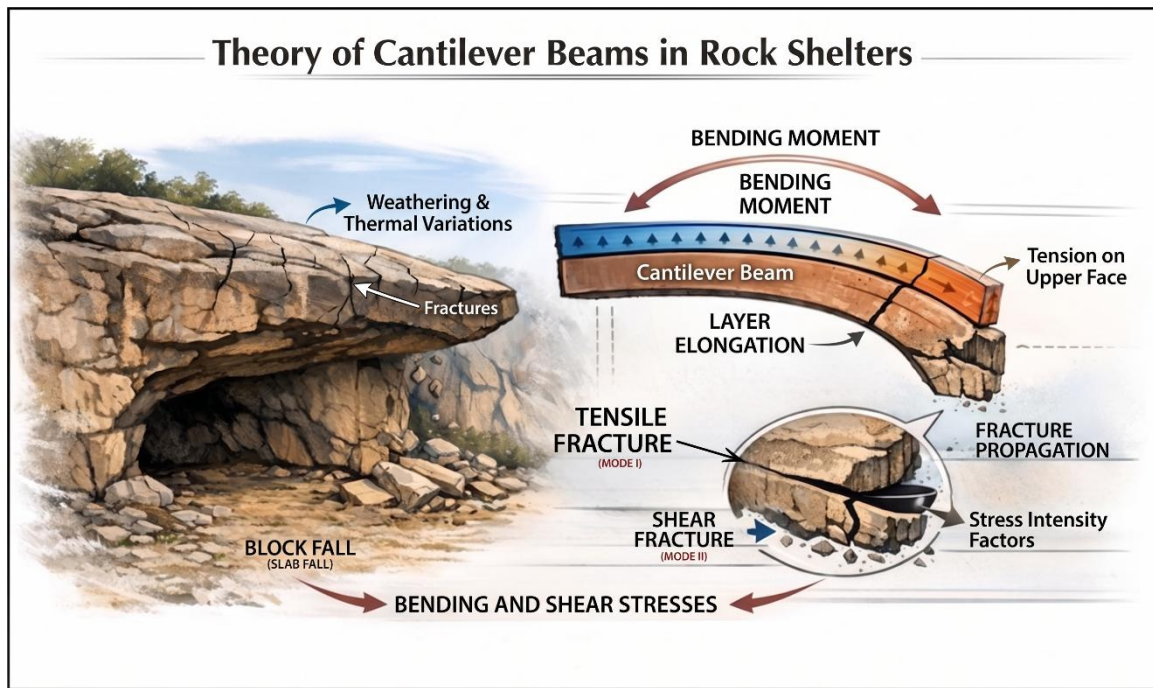


Figure 13. Conceptual model of a cantilever beam applied to the genesis of rock shelters in sedimentary sequences. Stress components acting on the cantilever beam: bending moment, tension on the upper face, and layer extension — and the fracture propagation cycle by tensile failure (Mode I) and by shear (Mode II), with the respective stress intensity factors that govern progressive collapse by slab fall. Source: Araújo et al., 2026.

The model integrates: (I) the shelter's morphological context with indication of fractures and block fall (slab fall); (II) the force diagram on the cantilever beam, showing bending moment, tensile stress on the upper face, and layer extension, grounded in Euler–Bernoulli beam theory; and (III) the fracture-propagation cycle by tensile mode (Mode I) and shear mode (Mode II), with the stress-intensity factors that govern progression to collapse. Weathering and thermal variations act as agents of progressive weakening of the system.

Shelter stability is conditioned by the orientation of bedding planes, according to rock-mechanics models of Hoek & Bray (1981) and Goodman & Bray (1976). In roofs composed of inclined layers (angle δ), the gravitational load W is partitioned into bending moments, which induce flexure in the block, and tangential forces, which promote shear along bedding interfaces. Because stiffness and bending moment govern the deformation of these strata, increasing structural dip amplifies destabilizing stresses. In practice, this mechanical behavior limits the maximum span a cantilevered roof can reach before collapse, thereby imposing a strict geometric constraint on free spans. (Figure 14).

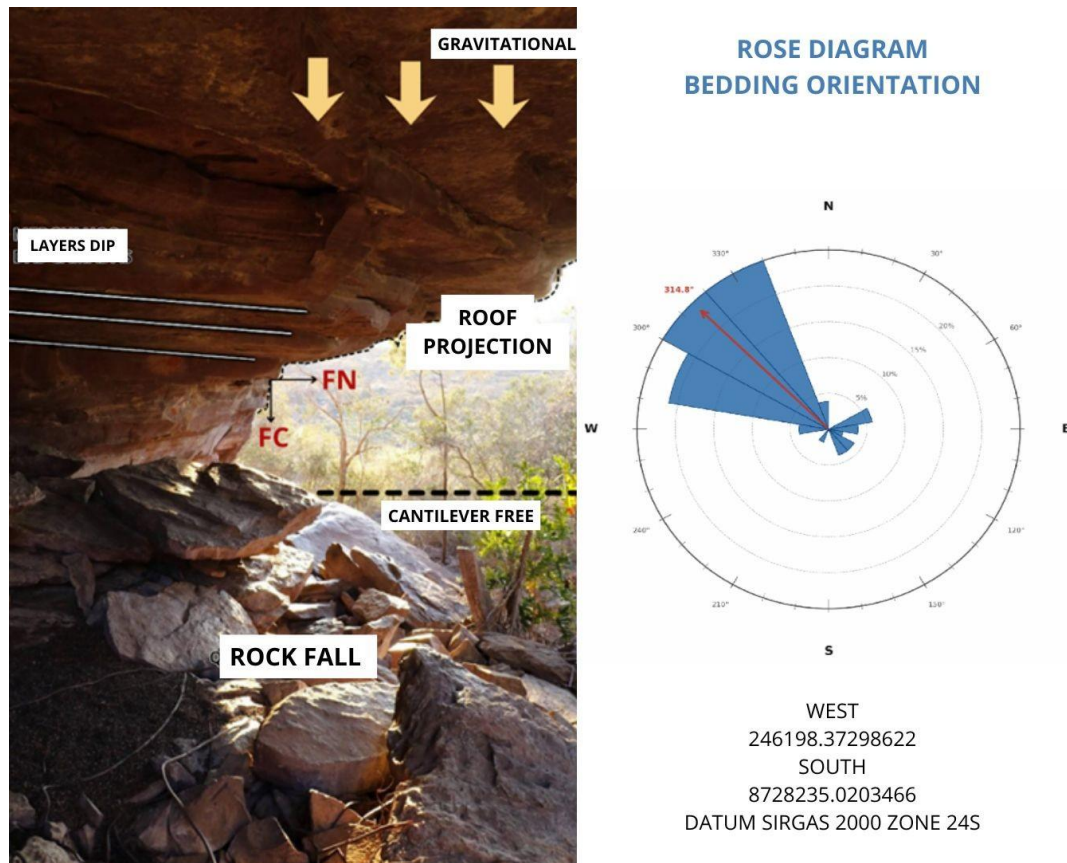


Figure 14. Structural conditioning of roof stability in a rock shelter at the Lagoa da Velha Archaeological Complex. Source: Araújo et al., 2026.

The distribution of shelters within the Lagoa da Velha Complex reveals a systematic orientation of the openings relative to the fold axial plane, a consequence of Brasiliano deformation that controls the morphostructure, directs fracture patterns, and enhances shelter collapse. Although each roof collapse constitutes a discrete failure, the cumulative effect of successive events is stabilizing: each block fall reduces the cantilever length, redistributes the bending moment, and establishes a new, lower-span meta-stable equilibrium.

5.5 Synthesis of the Morphostructural Model

The analysis of the morphology of the shelters in the Lagoa da Velha Complex follows a hierarchy of controls and processes that operate at distinct spatial and temporal scales. The choice of analytical scale directly conditions the methodological strategies and technical procedures adopted in the geomorphological investigation (Kohler, 2002). From this premise, three controlling mechanisms are observed (Figure 15).

The first-order control is exerted by the mechanical stratigraphy of the Morro do Chapéu Formation, which defines the specific stratigraphic levels where shelters develop. The vertical stepping observed in the strata is the geomorphological expression of this lithological heterogeneity.

The second-order control defines the regional morphostructure, composed of large-wavelength folds. At this scale, the model explains the spatial distribution of shelters in the municipality of Morro do Chapéu and the consistency of their preferred orientations.

The third-order control is defined by the fracture system developed by the stress field through geological time, which determines the rate of weathering between lithological beds. These fracture systems generally occur in characteristic patterns: a grid pattern (longitudinal and transverse to the fold axis) and a staircase pattern that develops at bedding contacts.

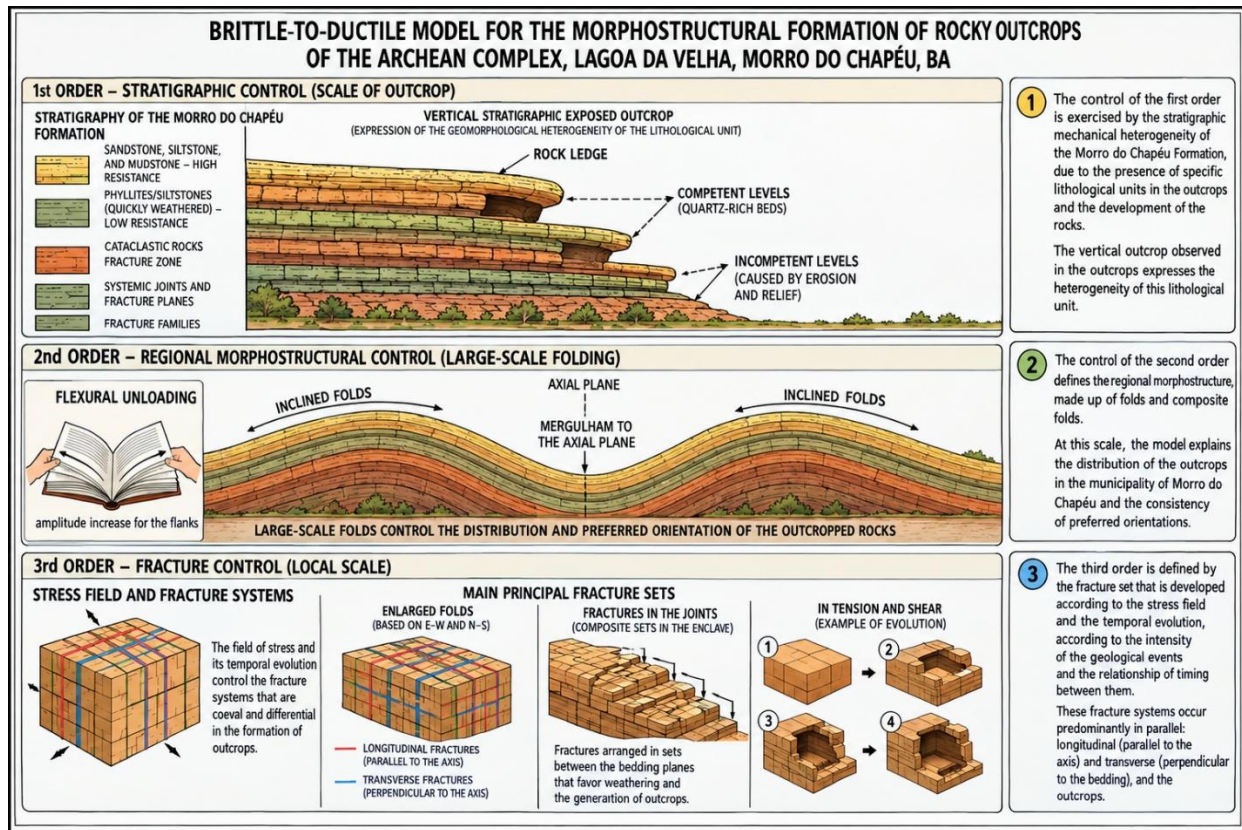


Figure 15 – Morphostructural model of rock Shelter formation at the Lagoa da Velha Archaeological Complex, Morro do Chapéu.

Source: Araújo et al, 2026.

The model organizes the controls into three hierarchical orders: (first order) the mechanical stratigraphy of the Morro do Chapéu Formation, with vertical stepping of competent and incompetent strata; (second order) regional morphostructural control by large-wavelength folding, which governs the spatial distribution and preferred orientations of the shelters; (third order) fracture systems in grid, staircase and step patterns, conditioned by the inheritance of the geological stress field, unloading joints, differential erosion processes and wall retreat.

It is concluded that a multiscale approach is indispensable for landscape studies. In the Lagoa da Velha Archaeological Complex, the analysis demonstrates that shelter morphology results from a hierarchy of processes, integrating regional morphostructural mechanisms with local fracturing and evidencing the superposition of processes in the sculpting of relief. This organization of geological and geomorphological controls suggests that multidimensional modeling of the landscape arises from the interaction between tectonic events, lithostratigraphic specificities and surface processes

6. Discussion

6.1. The Morphostructure as a Temporal Palimpsest

The morphostructure of the shelters in the Lagoa da Velha Archaeological Complex constitutes a strict temporal palimpsest. In these sites the physical space reveals the superposition and interaction of geological inheritances operating at radically different timescales. The lithology is Mesoproterozoic (~1.4–1.1 Ga); the tectonic fabric derives from processes associated with the Brasiliano orogeny (~640–480 Ma); and the present landform is Cenozoic, conditioned by denudational mechanisms. Outcrop-scale documentation — through field photographs, fracture measurements and bedding-plane mapping — is necessary to directly evidence the structures that record each stage of this palimpsest (Figure 16).

These features, in turn, result from the contemporary conjunction of surface processes and the inherited structural framework. This temporal hierarchy is consistent with Phillips's historical geomorphology perspective (1992), which shows how nonlinear systems generate trajectories sensitive to initial conditions, making present

forms contingent expressions of distinct geological inheritances. Complementarily, Phillips (2003) details the sources of this nonlinearity (thresholds, hysteresis, competitive feedback, self-organization), reinforcing the premise of historical contingency rather than replacing it



Figure 16. Pictorial record of the Lagoa da Velha Archaeological Complex, Morro do Chapéu, Bahia, illustrating the site's temporal palimpsest. (a) Panoramic view of the geomorphological setting, showing the distribution of Morro do Chapéu Formation outcrops across the landscape. (b) Detail of the outcrop face, with subhorizontal stratification and detached blocks at the base, indicating active collapse processes. (c) Interior of a rock shelter with a projecting roof and red-pigment rock art preserved on the bedrock surface, with a group of researchers for scale, evidencing the superposition of geological, structural, and cultural inheritances that characterize the site's temporal palimpsest. Source: Araújo et al., 2026.

The use of the cantilever-beam model is fundamental for geometric and mechanical analysis, enabling quantitative description of forms, stability modelling, and technically precise prediction of failure mechanisms. However, applying this model also exposes the limits between mechanistic morphological analysis and the intrinsic complexity of the feature's genesis. The shortcomings of this process-based approach demand a holistic integration across spatial and temporal scales, combined with geochronological and geochemical methods and with direct monitoring of active processes.

6.2. Landscape Sensitivity and Dynamics of the Rock Shelters

The application of the landscape-sensitivity concept, as used by Brunsden and Thornes (1979) in the study area, establishes that morphological stability is ensured by the mechanical resilience of the silicified sandstone. This lithostructural property of the Morro do Chapéu Formation controls the morphology's capacity to respond to external perturbations and defines its resistance in terms of event recurrence intervals. The shelters that have persisted despite external disturbances demonstrate systemic resilience: their survival indicates that destabilizing forces have not exceeded irreversible collapse thresholds, or that partial failures produced balance at shorter spans. Schumm (1979) frames these as intrinsic thresholds driven by the system's internal evolution, independent of external climatic perturbations, implying that extrinsic sensitivity to climatic variables (Brunsden and Thornes, 1979; Brunsden, 2001) is insufficient to anticipate collapses driven by internal dynamics.

The longevity of the shelter morphology in the Lagoa da Velha Archaeological Complex should not be read as an absence of process activity but rather as the outcome of the rock's mechanical robustness, which modulates

the landscape response to environmental variations. The predominance of intrinsic thresholds suggests that the evolution of these forms follows a trajectory of self-organization, in which roof enlargement progressively adjusts to the load-bearing capacity of the rock support. Thus, the observed stability is a verifiable manifestation of a meta-stable equilibrium, where morphological persistence attests that the system's energetic input has not yet overcome the inherited structural resistance. Consequently, predictive models based solely on climatic oscillations are limited; a deeper analysis prioritizing geomechanical behavior and the system's internal history is required to explain shelter genesis.

6.3. Complexity as an Analytical Foundation

The cantilever-beam model refers to a system composed of two components: the projected element and its support base. The morphology of rock shelters is more complex, because it involves the behavior of a heterogeneous lithological succession subjected to stress fields resulting from multiple deformation records, in a climatic environment that varies across temporal scales, over a substrate whose mechanical properties change from centimetric to metric proportions. The nonlinearity of geomorphological systems (Phillips, 1992; 2003) implies the absence of a predictable evolutionary trajectory for each shelter: units in apparently identical conditions can respond differently to the same perturbation, which highlights sensitivity to initial conditions. Catastrophic collapses correspond to intrinsic thresholds, the outcome of the system's internal evolution without any change in external controls; by contrast, degradation by stress-corrosion cracking follows a continuous fatigue trajectory that does not constitute a threshold in the strict sense of abrupt collapse but is a conditioning process that progressively reduces the rock's effective toughness and thus increases susceptibility to catastrophic failure.

Therefore, the genesis of the shelters in the Lagoa da Velha Complex cannot be reduced to a mechanical cantilever model; it must be understood as a dynamic system of coupled thresholds. The transition between continuous wear by stress-corrosion cracking and catastrophic rupture exemplifies how processes of different magnitudes and temporalities feedback on one another, transforming apparent stability into a meta-stable equilibrium. From this perspective, the geomorphological complexity inherent to the rock substrate, the structural inheritance and contemporary processes impose intrinsic uncertainty on landscape modelling, in which the resulting transcends a mere expression of the rock's structural memory. It follows that geomorphological analysis of these shelters requires overcoming mechanical determinism and recognizing nonlinearity as the rule rather than the exception in their morphologies. To assess the current stress field and the temporal evolution of processes, future investigations should employ numerical modelling (finite elements), cosmogenic-nuclide or luminescence dating, and direct monitoring of roof displacements.

7. Conclusion

The study proposes a geomechanical approach to the morphology of the shelters in the Lagoa da Velha Archaeological Complex, simulating the support of rock roofs by a cantilever-beam model and correlating structural stability with the nonlinearity of morphological processes, subordinated to a space-time hierarchy. From the analysis developed, the following conclusions are drawn:

Morphostructure as a temporal palimpsest. The current configuration of the shelters does not arise from an isolated event but from the superposition of events through time, in which the synergic dynamism of processes was fundamental to feature formation via inputs of energy and matter that are not random but derive from the landscape's own evolutionary dynamics. This historical contingency shows that the final form results from processes operating at distinct temporal scales, with the present relief preserving memories of inherited tectonic stresses integrated with contemporary surface dynamics. Reconstructing the temporal scale involved requires techniques such as cosmogenic-nuclide dating (^{10}Be), low-temperature thermochronology and detailed geomorphometric surveys, to be incorporated in subsequent research phases.

Although the cantilever model is effective for geometric quantification and for predicting imminent collapses, its explanatory capability for genesis is limited. The physical determinism of the beam must be integrated into a systemic approach because mechanical stratification and physical-chemical processes—such as stress-corrosion cracking—dynamically alter resistance properties that are treated as static in purely mechanistic models. Shelter genesis is a complex, nonlinear phenomenon in which multiple variables and the principle of equifinality demonstrate that distinct evolutionary trajectories can converge to similar morphologies.

Multiscale hierarchy of controls. Multiscale analysis and process hierarchy establishes that morphological evolution is complex, governed by multiple mechanisms operating across scales with oscillating energy inputs that produce unequal responses. At the regional level, morphostructure defines the geological framework; at the local level, mechanical stratification—characterized by alternating competent and incompetent layers—dictates predisposition to basal retreat; at the feature and short-term scale, the fracture system associated with weathering acts as the trigger that overcomes resistance thresholds.

Meta-stable equilibrium and nonlinear accumulation of stress. Meta-stable equilibrium and nonlinearity influence the longevity of shelter morphology, characterizing a system that accumulates stress nonlinearly until intrinsic thresholds are reached. Surpassing these thresholds results in episodic readjustments that establish new equilibrium states. The persistence of these forms does not indicate stagnation of contemporary surface dynamics but rather resilience derived from the mechanical strength conveyed by silicification of the Morro do Chapéu Formation sandstones, which modulate landscape sensitivity to environmental fluctuations.

The genesis and evolution of the Lagoa da Velha shelters emerge from the coupling between the accuracy of mechanical laws and the uncertainty of nonlinear dynamics. Understanding these features requires moving beyond purely descriptive views and recognizing them as dynamic systems whose stability is a temporary manifestation of inherited structural resistance within the complex trajectory of morphological evolution.

Data Availability Statement: The datasets that underpin this study, including field maps, sampling locations and raw measurement files, are available from the authors upon reasonable request. Researchers seeking access should contact the corresponding author to arrange data sharing; requests will be considered in accordance with ethical and legal constraints and with provisions to ensure reproducibility and proper attribution.

Declaration of Use of Artificial Intelligence (AI) Data Analysis and Methodology: During the image-processing phase of this study, the authors used the ChatGPT and Gemini tools to assist in generating models from field and office data collected by the researchers. The image models are based on field data (fracture measurements and bedding dip angles) and, in the office phase, on the digitization of fractures in aerial photogrammetric images acquired in the field. The results were produced by the authors from their field and Laboratory research. AI was used only to enhance the images and the models conceived by the study authors. The scripts employed are available upon request by contacting the authors directly.

Conflict of Interest Declaration: The authors declare that there is no conflict of interest in conducting this research, and that there are no financial, institutional, or personal relationships that could have influenced the results or interpretations presented in the study.

Funding Statement: The research received no external funding.

Acknowledgements: The authors thank the Geoarchaeology Laboratory at UFPE for providing the computers necessary for data processing, and the Federal University of Pernambuco for providing transportation for the visit to the study area to collect the field data that made this research possible.

References

1. ALKMIM, F. F.; MARSHAK, S.; PEDROSA-SOARES, A. C.; PERES, G. G.; CRUZ, S. C. P.; WHITTINGTON, A. Kinematic evolution of the Araçuaí-West Congo orogen in Brazil and Africa: Nutcracker tectonics during the Neoproterozoic assembly of Gondwana. *Precambrian Research*, v. 149, n. 1-2, p. 43-64, 2006.
2. ALKMIM, F. F.; PEDROSA-SOARES, A. C.; NOCE, C. M.; CRUZ, S. C. P. Sobre a evolução tectônica do Orógeno Araçuaí-Congo Ocidental. *Geonomos*, v. 15, n. 1, p. 25-43, 2007.
3. Anderson, T. L., *Fracture mechanics: fundamentals and applications*. CRC Press. 2005.
4. ATKINSON, B. K. (Ed.). *Fracture Mechanics of Rock*. London: Academic Press, 1987. 534 p.
5. BAI, T.; POLLARD, D. D. Fracture spacing in layered rocks: a new explanation based on the stress transition. *Journal of Structural Geology*, v. 22, n. 1, p. 43-57, 2000.
6. Bai, T., Maerten, L., Gross, M. R., & Aydin, A. Orthogonal cross joints: do they imply a regional stress rotation?. *Journal of Structural Geology*, 24(1), 77-88. 2002.
7. BARBOSA, J. S. F.; SABATÉ, P. Archaean and Paleoproterozoic crust of the São Francisco Craton, Bahia, Brazil: geodynamic features. *Precambrian Research*, v. 133, p. 1-27, 2004.
8. Barbosa, J. S. F., Mascarenhas, J. F., Correa-Gomes, L. C., Dominguez, J. M. L., & Souza, J. S. *Geologia da Bahia Pesquisa e Atualização*, vol. 1. 2012.

9. BARBOSA, J. S. F.; BARBOSA, R. G. The Paleoproterozoic eastern Bahia orogenic domain. In: HEILBRON, M.; CORDANI, U. G.; ALKMIM, F. F. (Ed.). *São Francisco Craton, Eastern Brazil: Tectonic Genealogy of a Miniature Continent*. Cham: Springer International Publishing, 2016. p. 57-69.
10. BATTILANI, G. A.; GOMES, N. S.; GUERRA, W. J. Evolução diagenética dos arenitos da Formação Morro do Chapéu, Grupo Chapada Diamantina, na região de Morro do Chapéu, Bahia. *Geonomos*, v. 4, n. 2, p. 81-89, 1996.
11. Bertalanffy, L. V. (1969). *General system theory*, New York (George Braziller) 1969.
12. BRADY, B. H. G.; BROWN, E. T. *Rock Mechanics for Underground Mining*. London: George Allen & Unwin, 1985. 527 p.
13. BRITO NEVES, B. B. Estudos geológicos no nordeste da Chapada Diamantina. *Boletim da Sociedade Brasileira de Geologia*, v. 16, n. 1, p. 5-21, 1967.
14. BRUNSDEN, D. A critical assessment of the sensitivity concept in geomorphology. *Catena*, v. 42, p. 99-123, 2001.
15. BRUNSDEN, D.; THORNES, J. B. Landscape sensitivity and change. *Transactions of the Institute of British Geographers*, n.s., v. 4, n. 4, p. 463-484, 1979.
16. CHORLEY, R. J. *Geomorphology and General Systems Theory*. U.S. Geological Survey Professional Paper, 500-B, 1962.
17. CHORLEY, R. J.; KENNEDY, B. A. *Physical Geography: A Systems Approach*. London: Prentice-Hall International, 1971. 370 p.
18. COOKE, M. L.; UNDERWOOD, C. A. Fracture termination and step-over at bedding interfaces due to frictional slip and interface opening. *Journal of Structural Geology*, v. 23, p. 223-238, 2001.
19. CPRM — Serviço Geológico do Brasil. *Geologia e recursos minerais do estado da Bahia*. Salvador: CPRM, 2012.
20. DOMÍNGUEZ, J. M. L. As coberturas do Cráton do São Francisco: uma abordagem do ponto de vista da análise de bacias. In: DOMINGUEZ, J. M. L.; MISI, A. (Ed.). *O Cráton do São Francisco*. Salvador: SBG/SGM/CNPq, 1993. p. 137-159.
21. DIAS, A. N.; MARTINS-FERREIRA, M. A. C.; PEREIRA, V. Q.; SALES, A. S. W.; CHEMALE JR., F. Insights into the Phanerozoic evolution of the São Francisco Craton based on detrital zircon thermochronology and U-Pb-Hf geochronology. *Geological Society of America Bulletin*, v. 136, n. 11-12, p. 5109-5122, 2024.
22. ETCHEVARNE, C. *O patrimônio arqueológico rupestre da Bahia: sítios registrados, diagnósticos de conservação e perspectivas de gestão*. Salvador: IPAC-BA, 2007.
23. FERRILL, D. A.; MORRIS, A. P.; MCGINNIS, R. N.; SMART, K. J.; WIGGINTON, S. S.; HILL, N. J. Mechanical stratigraphy and normal faulting. *Journal of Structural Geology*, v. 94, p. 275-302, 2017.
24. FISCHER, M. P.; GROSS, M. R.; ENGELDER, T.; GREENFIELD, R. J. Factors controlling joint spacing in interbedded sedimentary rocks. In: AMEEN, M. S. (Ed.). *Fractography*. London: Geological Society, 1995. p. 215-233.
25. FOSSEN, H. *Structural Geology*. Cambridge: Cambridge University Press, 2010. 463 p.
26. GLEADOW, A.; GREEN, H.; FINCH, D.; BOONE, S.; FINK, D.; FÜLÖP, R. H.; CODILEAN, A.; UNGHANGO, A. The origin, evolution and life cycle of rock art shelters in the Kimberley Basin of NW Australia. *Earth Surface Processes and Landforms*, v. 50, n. 9, e70124, 2025.
27. GOODMAN, R. E.; BRAY, J. W. Toppling of rock slopes. In: *Proc. Specialty Conf. on Rock Engineering for Foundations and Slopes*. ASCE, Boulder, CO, v. 2, p. 201-234, 1976.
28. GROSS, M. R. The origin and spacing of cross joints. *Journal of Structural Geology*, v. 15, p. 737-751, 1993.
29. GUADAGNIN, F.; CHEMALE JR., F.; MAGALHÃES, A. J. C.; SANTANA, A.; DUSSIN, I.; TAKEHARA, L. Age constraints on crystal-tuff from the Espinhaço Supergroup. *Gondwana Research*, v. 27, n. 1, p. 363-376, 2015.
30. HANCOCK, P. L.; ENGELDER, T. Neotectonic joints. *Geological Society of America Bulletin*, v. 101, n. 10, p. 1197-1208, 1989.
31. HEILBRON, M.; CORDANI, U. G.; ALKMIM, F. F. (Ed.). *São Francisco Craton, Eastern Brazil*. Cham: Springer, 2017.
32. HELGESON, D. E.; AYDIN, A. Characteristics of joint propagation. *Journal of Structural Geology*, v. 13, p. 897-911, 1991.
33. Irwin G. R. Analysis of stresses and strains near the end of a crack traversing a plate. *J Appl Mech* 24:361-364. 1957.
34. HOEK, E.; BRAY, J. D. *Rock Slope Engineering*. CRC Press, 1981.
35. KOHLER, H. C. A escala na análise geomorfológica. *Revista Brasileira de Geomorfologia*, v. 3, n. 1, 2002. <https://doi.org/10.20502/rbg.v3i1.12>

36. MARCHIORI, D. G. A mecânica da fratura elástica linear e o modelo coesivo na previsão do fraturamento de rochas. 1997. Tese de Doutorado. Universidade de São Paulo.
37. NARR, W.; SUPPE, J. Joint spacing in sedimentary rocks. *Journal of Structural Geology*, v. 13, p. 1037-1048, 1991.
38. PEDREIRA, A. J. *O Supergrupo Espinhaço na Chapada Diamantina centro-oriental, Bahia*. Tese (Doutorado) — Universidade de São Paulo, São Paulo, 1994.
39. PHILLIPS, J. D. Nonlinear dynamical systems in geomorphology. *Geomorphology*, v. 5, p. 219-229, 1992.
40. PHILLIPS, J. D. Sources of nonlinearity. *Progress in Physical Geography*, v. 27, n. 1, p. 1-23, 2003.
41. POLLARD, D. D.; FLETCHER, R. C. Fundamentals of structural geology. Cambridge University Press, 2005.
42. PRICE, N. J.; COSGROVE, J. W. *Analysis of Geological Structures*. Cambridge: Cambridge University Press, 1990.
43. RAMSAY, J. G. *Folding and Fracturing of Rocks*. New York: McGraw-Hill, 1967.
44. SAMPAIO, A. R., ROCHA, A. J. D., SANTOS, R. A. D., & GUIMARÃES, J. T. *Projeto Jacobina, Folha SC. 24-YC*. CPRM. 2001.
45. SCHUMM, S. A. Geomorphic thresholds. *Transactions of the Institute of British Geographers*, v. 4, n. 4, p. 485-515, 1979.
46. SCHUMM, S. A. *To Interpret the Earth*. Cambridge: Cambridge University Press, 1991.
47. SGB-CPRM; CBPM. Mapa Tectônico-Geocronológico do Estado da Bahia: implicações metalogenéticas. Escala 1:1.000.000. Salvador: CBPM; SGB-CPRM, 2020.
48. Souza, G. P. D. Evolução tectônica Toniana da margem sudoeste do Paleocontinente São Francisco: geoquímica e geocronologia U-Pb de rochas metassedimentares da nappe de passos e magmatismo félsico contemporâneo, Orógeno Brasília meridional. 2025.
49. SRIVASTAVA, N. K.; ROCHA, A. J. D. Fazenda Cristal, BA. *Sítios Geológicos e Paleontológicos do Brasil*, p. 87-93, 2002.
50. STEARNS, D. W.; FRIEDMAN, M. Reservoirs in fractured rock. In: KING, R. E. (Ed.). *Stratigraphic Oil and Gas Fields*. Tulsa: AAPG, 1972. p. 82-106.
51. TANNER, P. W. G. The flexural-slip mechanism. *Journal of Structural Geology*, v. 11, p. 635-655, 1989.
52. TEIXEIRA, W.; FIGUEIREDO, M. C. H. Early Proterozoic crustal evolution. *Precambrian Research*, v. 53, p. 1-22, 1991.
53. TEIXEIRA, J. B. G.; DA SILVA, M. D. G.; MISI, A.; CRUZ, S. C. P.; DA SILVA SÁ, J. H. Geotectonic setting. *Journal of South American Earth Sciences*, v. 30, n. 2, p. 71-83, 2010.
54. TWISS, R. J.; MOORES, E. M. *Structural Geology*. 2. ed. New York: W. H. Freeman, 2007.
55. UHLEIN, A.; TROMPETTE, R.; EGYDIO-SILVA, M. Rifteamentos superpostos. *Geonomos*, 1995.
56. VILES, H. A. Synergistic weathering processes. In: SHRODER, J. F. (Ed.). *Treatise on Geomorphology*. San Diego: Academic Press, 2013. p. 12-32.
57. Wang, T., Ye, W., Liu, L., Liu, X., & Sun, X. . Pioneering insights into High-Temperature sandstone fracture Mechanics: Integrating damage evolution modeling with experimental validation. *Engineering Fracture Mechanics*, 111599. 2025.
58. Whittaker, B. N., Singh, R. N., & Sun, G. Rock fracture mechanics. Principles, design and applications. 1992.
59. WOLMAN, M. G.; MILLER, J. P. Magnitude and frequency. *Journal of Geology*, v. 68, n. 1, p. 54-74, 1960.
60. WU, L. Z.; SHAO, G. Q.; HUANG, R. Q.; HE, Q. Overhanging rock modeling. *Rock Mechanics and Rock Engineering*, v. 51, n. 12, p. 3585-3597, 2018. <https://doi.org/10.1007/s00603-018-1543-9>
61. YOUNG, R. W.; WRAY, R. A. L.; YOUNG, A. R. M. *Sandstone Landforms*. Cambridge: Cambridge University Press, 2009.
62. YOUNG, R. W.; YOUNG, A. R. M. *Sandstone Landforms*. Berlin: Springer-Verlag, 1992.



This work is licensed under the Creative Commons License Attribution 4.0 Internacional (<http://creativecommons.org/licenses/by/4.0/>) – CC BY. This license allows for others to distribute, remix, adapt and create from your work, even for commercial purposes, as long as they give you due credit for the original creation.