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Application of a Ground-Penetrating Radar in the Characterization of the Archaeological Environment of Site GO-JA-02, Serranópolis-GO: A Non-Invasive Approach for Archaeological Excavation Planning

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Abstract: This study used a ground-penetrating radar (GPR) to characterize the archaeological environment of site GO-Ja-02 in Serranópolis, Goiás, Brazil. In the Serranópolis region, there are records of numerous human burials in archaeological sites located in predominantly sandy soils. Thus, this study proposed the application of a ground-penetrating radar to locate buried archaeological structures. Using a 400 MHz shielded antenna, the 2D data revealed distinct reflection patterns associated with subsurface elements such as rock blocks, roots, and rock surfaces, which were correlated with the anomalies observed in the depth slices of the generated pseudo-3D block. A ranking methodology was developed based on the archaeological context of the area and was used to indicate priority excavation areas. The results provided an understanding of the site's archaeological environment, allowing for prior knowledge of areas to be excavated. The non-invasive GPR approach enabled a detailed investigation without disturbing the site, aiding in decision-making for the archaeological team. Furthermore, this study establishes a methodological foundation for future investigations, demonstrating the effectiveness of integrating advanced technologies into archaeological research.

Keywords: 3D archaeological mapping; burials in shelters and caves; archaeology of Serranópolis

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1. Introduction

The Serranópolis Archaeological Complex is recognized as one of the most significant sets of archaeological sites in Brazil. With dates going back approximately 12,000 years Before Present (BP), this complex provides crucial information about pre-colonial occupation dynamics in the Brazilian Central Plateau [1]. Among the various sites that make up this complex, GO-Ja-02 stands out as a location of particular archaeological interest, notably for the richness of its findings, including cultural and skeletal remains.

The preservation of archaeological sites in Serranópolis faces significant limitations due to both natural and human factors that threaten the integrity and survival of these valuable historical records. Erosion, microbial growth, and climatic variations are just some of the natural elements contributing to the deterioration of these ancient cultural manifestations [2]. At the same time, agricultural expansion, urbanization, and unregulated tourism impose additional risks, often accelerating the degradation of these sites [3].

In this context, research activities not only provide knowledge about the first societies that inhabited the region but also play an important role in promoting the protection of cultural heritage. The importance of urgent conservation actions has been emphasized in recent studies, which point to the need for effective protective measures to preserve this irreplaceable cultural heritage [4].

The investigation of archaeological sites such as GO-Ja-02 faces significant challenges: the large extent and stratigraphic complexity of the site make it impractical to conduct comprehensive excavations across the entire area. The site presents a complex stratigraphy, with multiple overlapping occupation layers, which complicates the precise identification and delimitation of areas of archaeological interest. The presence of funerary structures, particularly sensitive from an archaeological and heritage perspective, requires a non-invasive approach for their preliminary location, avoiding accidental disturbances during excavations. Additionally, the heterogeneous spatial distribution of archaeological artifacts necessitates a method capable of systematically mapping the entire area of interest. In this context, the use of geotechnologies, such as ground-penetrating radars (GPRs), has proven fundamental, offering the possibility of generating detailed subsurface images without the need for extensive excavations, thus facilitating the study and preservation of archaeological sites [5].

The main objective of this study is the geophysical characterization of the archaeological environment of site GO-Ja-02 through the analysis of the different reflection patterns obtained by the GPR method. The process involves identifying and analyzing various GPR reflection patterns in the data acquired from an area of the site, aiming to develop a comprehensive understanding for the general characterization of the archaeological environment. This characterization focuses on prioritizing areas for future excavations, based on the pseudo-3D GPR mapping of the distribution of elements and structures in the subsurface, as well as the depth of the rocky top and the thickness of the sediment layer.

2. Serranópolis Archaeological Complex

Located in southwestern Goiás, the Serranópolis Archaeological Complex is recognized as one of the most significant sets of archaeological sites in Brazil. This complex is notable for the diversity and richness of its archaeological sites, including rock shelters with petroglyphs and findings dated up to approximately 12,000 years Before Present (BP).

The rock shelters, formed from Botucatu sandstone, are a distinctive feature of the archaeological sites in Serranópolis. The Botucatu sandstone, formed during the Jurassic-Cretaceous period (between 145 and 200 million years ago), represents one of the most extensive geological units in the Paraná Basin [6]. This geological formation presents variable thickness, reaching over 400 m in some areas, although thicknesses between 60 and 200 m are more common [7,8]. It consists of fine- to medium-grained aeolian sandstone, formed in a depositional environment characteristic of a paleodesertic setting with extensive dune fields. One of the most striking features of this formation is the presence of large-scale cross-stratification, which evidences its formation process in a desert environment [9].

According to Schmitz et al. [1], these shelters have large openings, shallow depth, and good lighting, with inclined ceilings due to the cross-bedding of Botucatu sandstone. Rock shelters provide protection from elements such as wind, rain, and sun or a combination thereof; they are important archaeological sites because they form in various ways and in different types of rocks and landscapes. The same properties of rock shelters that provide protection to their human and animal inhabitants also contribute to the protection and preservation of archaeological deposits left within them [10].

The archaeological sites in Serranópolis provide crucial evidence of the ways of life of ancient communities that inhabited the region. Analysis of the artworks and artifacts found allows researchers to reconstruct aspects of daily life, subsistence strategies, and interactions of these peoples with the natural environment. The archaeological space of Serranópolis has some unique characteristics, including the fact that this environment was systematically occupied, hosting at least 550 human generations, initially comprising about 450 generations of hunter-gatherers followed by agricultural communities, who arrived from the north, east, and south, establishing their villages there [11].

Based on the proximity of their spatial distributions, these sites were organized into six "nuclei", initially termed as such and later referred to as "groups" in subsequent publications. However, the terminology of "nuclei" remains prevalent in the specialized literature. A structuring of archaeological sites documents the existence of 30 sites organized into six nuclei from A to F, including the newly mapped Macaco Site in nucleus F [12,13], as shown in Figure 1.

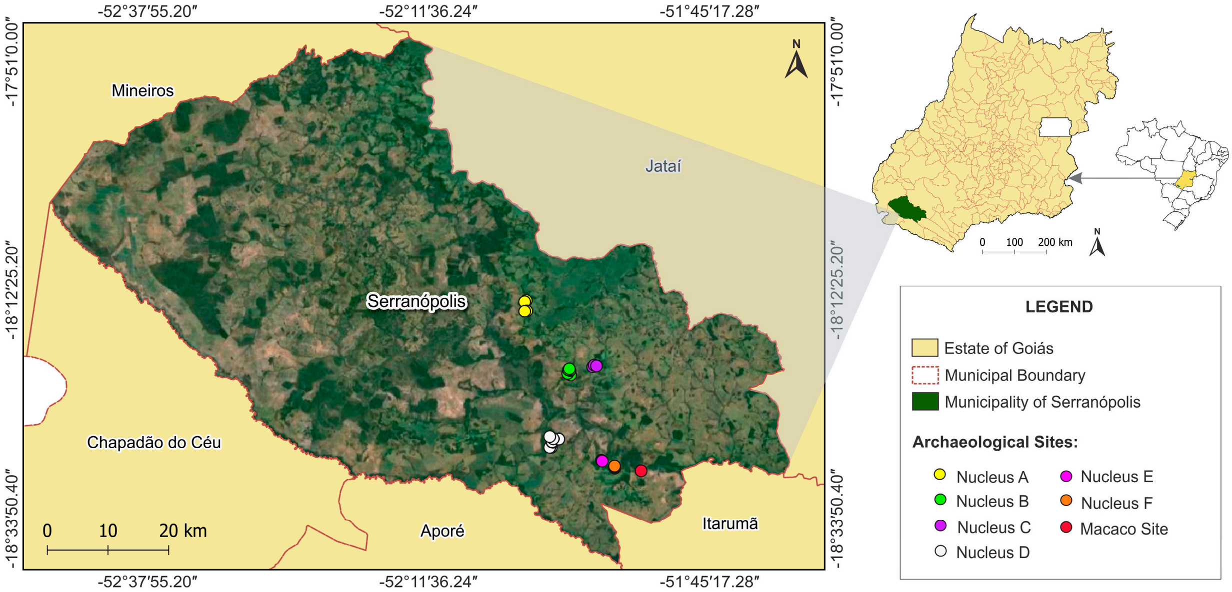


Figure 1. Map of the Serranópolis region, state of Goiás, with coordinates in decimal degrees. The map highlights the location of the sites by archaeological nuclei identified as Nuclei (A–F) as well as the newly mapped Macaco Site, marked in different colors.

2.1. Archaeological Site GO-Ja-02

The archaeological site GO-Ja-02—the focus of this study—is located in Nucleus A, on the left bank of the Rio Verde. It is characterized by a natural rock shelter, formed from Botucatu sandstone, interbedded with basalt flows from the Serra Geral Formation.

The site is divided into two main areas, referred to as Compartment A and Compartment B (Figure 2). Compartment A has an opening of 43 m and a height of 13 m, with a ceiling high enough to allow sunlight to reach its deepest interior. Compartment B is marked by a depth of 29 m, an entrance of 23 m, and a high ceiling. The constant presence of water dripping contributes to the formation of a small permanent pool [1].

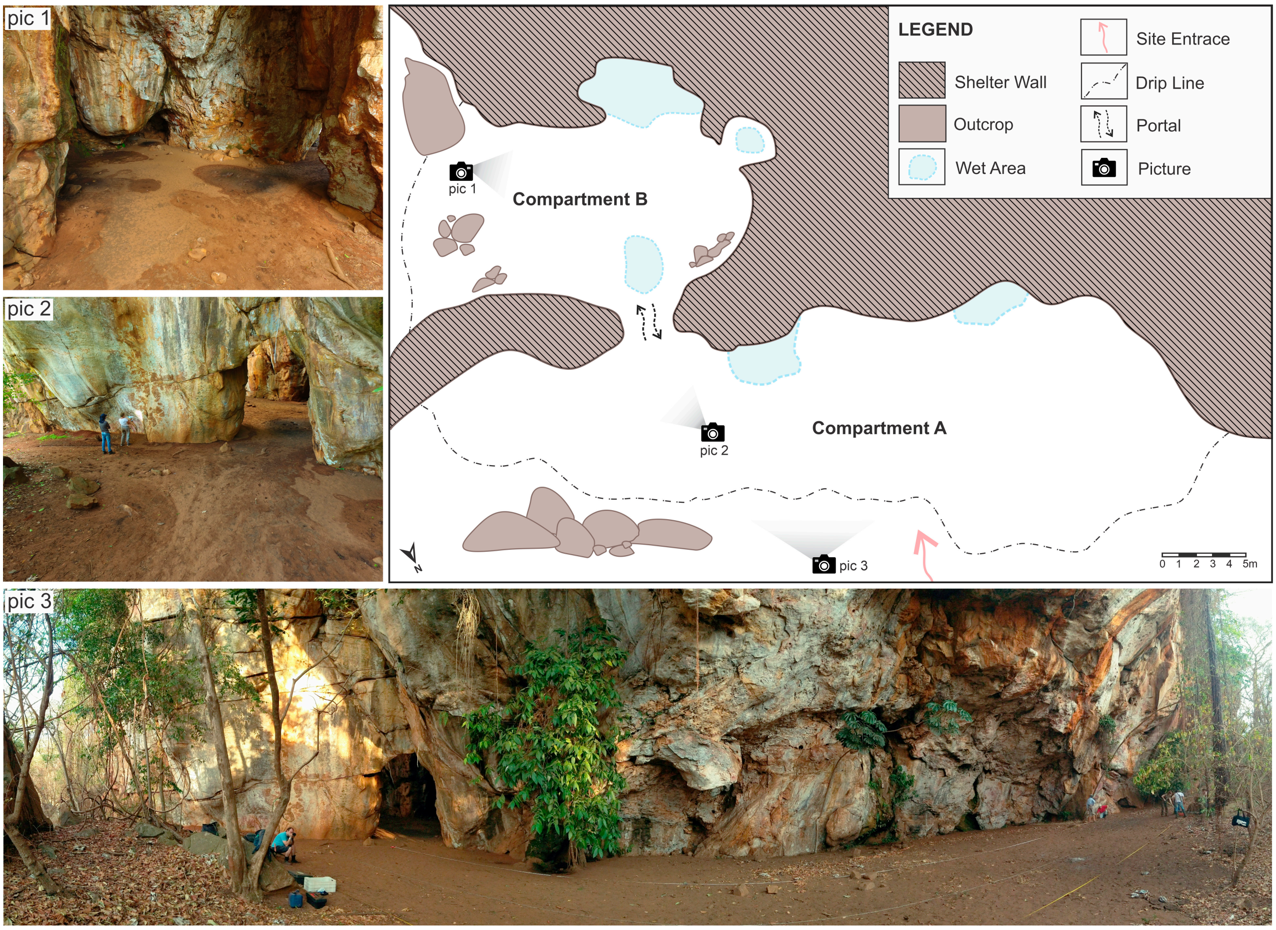


Figure 2. Sketch of the archaeological site GO-Ja-02, modified from Schmitz et al. [1] and photographs of the area.

2.2. Origin and Evolution of Research

Research in the Serranópolis region began in the 1970s through the Goiás Archaeological Program (PAG), via the Paranaíba Project. The PAG was initially planned to last seven years, from 1973 to 1979. However, the Program extended beyond its planned duration and became a reference for any archaeological study, not only in Goiás but also for Central Brazil areas [14]. During these years, a series of expeditions revealed important archaeological findings; the analysis of cultural remains found allows researchers to reconstruct aspects of daily life, subsistence strategies, and interactions of these ancient communities with the natural environment.

In 2017, the project "Excavation of archaeological site GO-Ja-02, in Serranópolis, Goiás", conducted by the Goiás Institute of Prehistory and Anthropology (IGPA) of the Pontifical Catholic University of Goiás (PUC Goiás), marked the renewal of archaeological research in the Serranópolis region. With special focus on excavation activities, the main objective of the project was to begin excavations at site GO-Ja-02 aiming to expand scientific understanding of human occupation in the Brazilian Central Plateau since the early Holocene, and potentially until the late Pleistocene. This possibility is based on the dating conducted by Schmitz et al. [1], suggesting that the deeper layers of the shelter had not been fully explored.

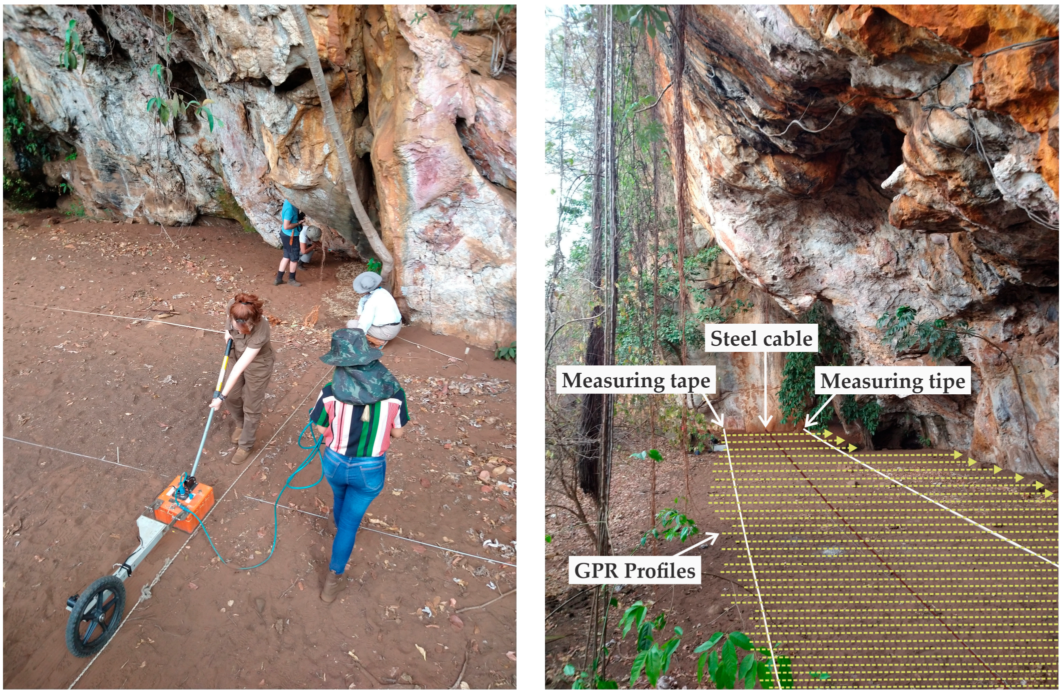
Current research has yielded significant milestones, highlighting two major discoveries: in June 2022, a funerary structure containing 10 human skulls, with a relative dating of three to four thousand years, was found at a depth of 63 cm [15], and in May 2023, researchers discovered human fossil remains dating back nearly 12,000 years at a depth of 1.70 m, making it one of the oldest human records in the Central–West region of Brazil [16].

Since 2020, studies in the region have been marked by a technological revolution in their research methodologies. Remote sensing and photogrammetry techniques were applied for a detailed mapping of site GO-Ja-02 and its surroundings, while the implementation of geophysical methods, notably a GPR, marked a new phase in investigations, allowing for the visualization of subsurface structures without direct intervention.

3. Materials and Methods

3.1. GPR Data Acquisition

The initial geophysical survey campaign was conducted in September 2021, prior to any excavation activities. For data acquisition, a 400 MHz GPR antenna was used to perform pseudo-3D surveys in Compartment A, recording parallel 2D profiles in common offset mode (Figure 3a). The GPR data were acquired with 1024 samples per trace for temporal sampling and a spatial sampling of 60 traces per meter along the survey lines.



(**a**) (**b**)

Figure 3. (**a**) Photograph of GPR data acquisition with 400 MHz antenna in Area A1, Compartment A; (**b**) Scheme illustrating the referencing of Area A1 acquisition.

The generated pseudo-3D GPR data were obtained through algorithms of equidistant 2D profiles stored sequentially, though not necessarily of equal length. For this purpose, the area delimitation in Compartment A was established to maximize linearity and space coverage.

To ensure the accuracy of pseudo-3D models, parallel 2D profiles must share common initial coordinates [17]. However, due to area irregularities, this can be difficult to achieve under real conditions. A solution can be found by implementing a georeferencing system based on a reflection common to all profiles [18,19].

The coordinate of this reflection in each profile, that is, its occurrence at "x" meters, is linearly adjusted between parallel profiles to ensure correlation between them. To generate this common reflection point across all profiles, a steel cable was placed on the surface between two measuring tapes (Figure 3b). This methodology ensures acquisition accuracy through the adjustment of 2D profile positioning, performed during pre-processing, standardizing the steel-cable reflection positions visible in the radargrams.

Data acquisition consisted of 290 parallel GPR profiles, acquired with 10 cm spacing, covering an area of approximately 250 m², designated as Area A1 (Figure 4).

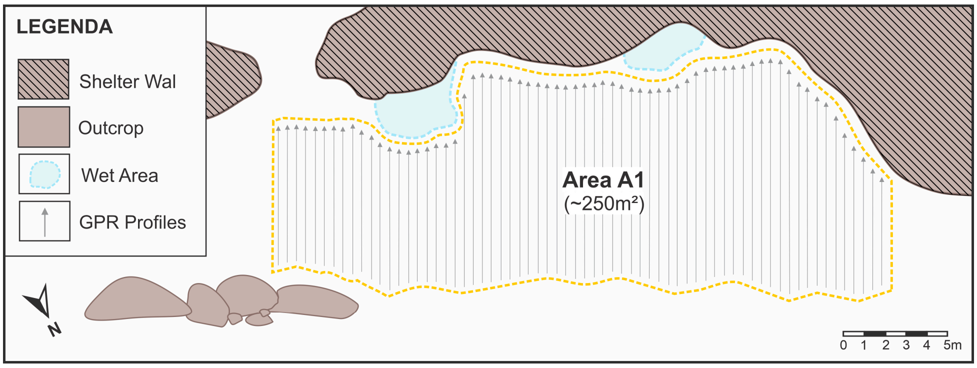


Figure 4. Sketch with GPR acquisition line projections of Area A1, Compartment A.

3.2. Data Processing

The 2D GPR data processing was performed using ReflexW 8.5 software, following a sequence of steps to improve data quality and interpretability (Figure 5). The routine began with zero-time correction, which adjusts the start of the GPR signal time record to zero at ground contact. The Dewow filter was applied to remove unwanted low-frequency components, improving signal clarity, followed by background removal to eliminate systematic noise and enhance reflections of interest.

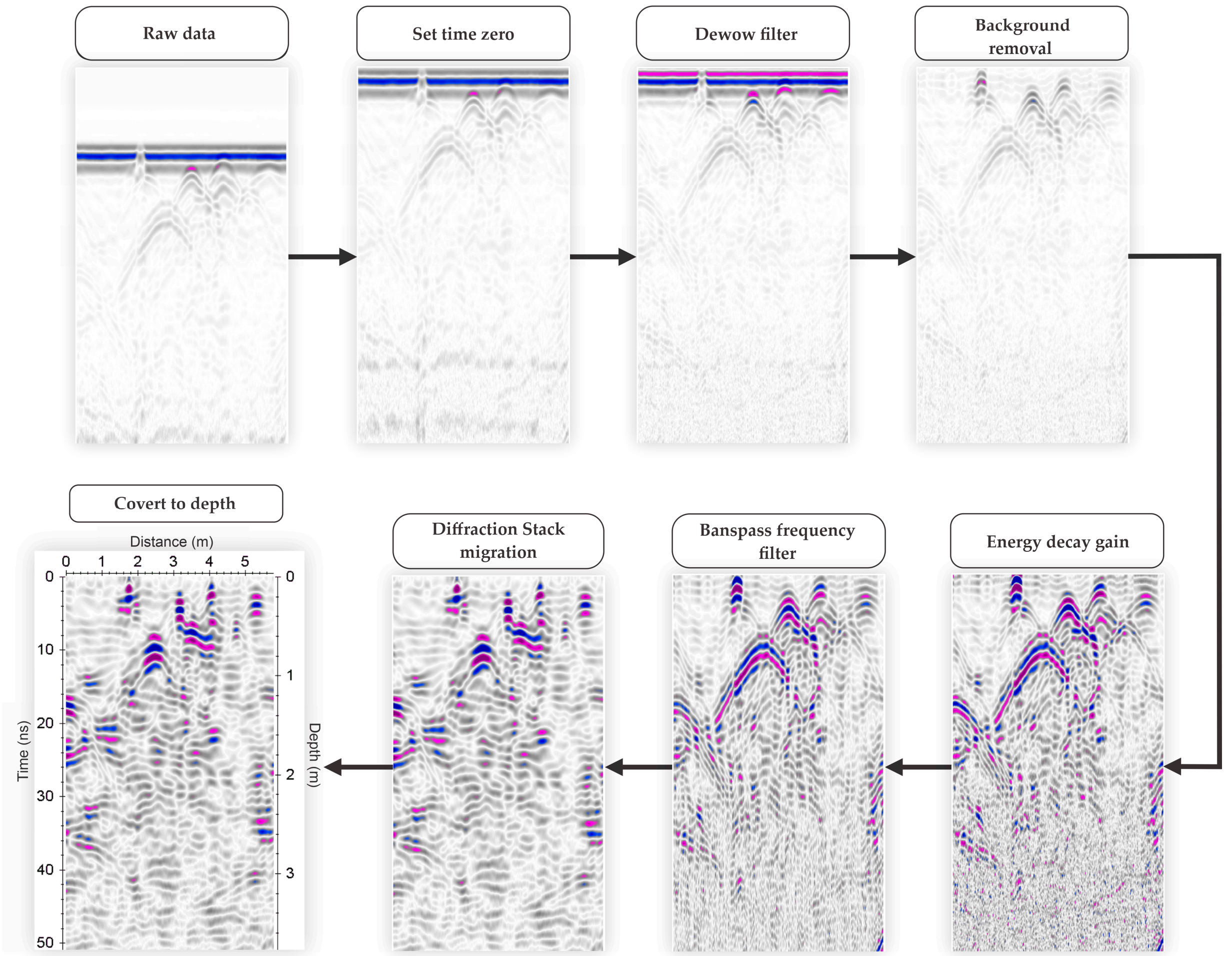
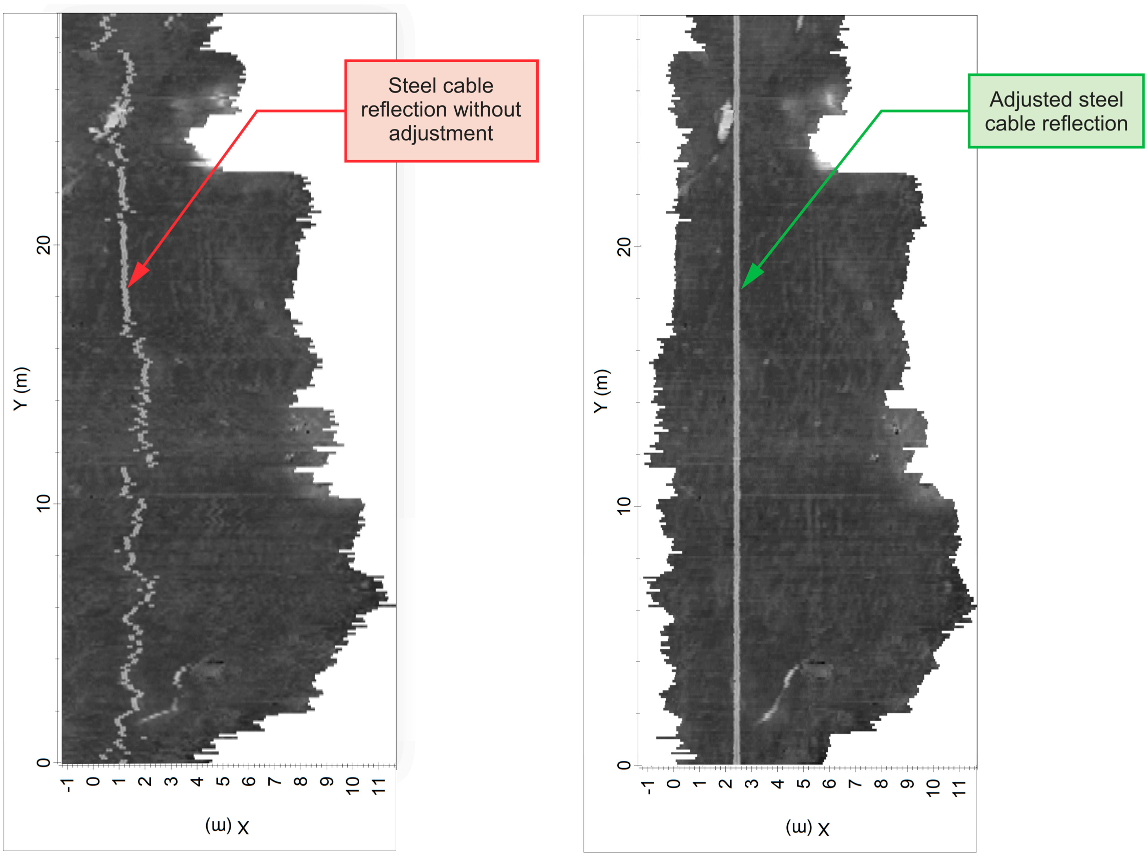


Figure 5. Flowchart of GPR data processing.

To compensate for natural signal attenuation with depth, an energy decay gain was applied, allowing for the better visualization of deeper structures. A bandpass filter was then used to remove high- and low-frequency noise, maintaining only the frequency range of interest. Diffraction stack migration was applied to collapse diffraction hyperbolas and improve the spatial resolution of structures. Finally, time-to-depth conversion was performed using the hyperbola width analysis method detected in the radargram.

A pseudo-3D model can be constructed by sequentially storing different 2D lines within a single file. The 2D lines can be either processed or raw data; in the latter case, processing is performed for the 3D data file. For pseudo-3D block generation, 2D profiles must present fixed increments such as the number of traces, points per trace, time, and identical initial coordinate. As previously mentioned, the reflection caused by the steel cable used to generate a known coordinate in all profiles was adjusted when it was impossible for them to have the same initial coordinate, as demonstrated in Figure 6 below.



(a) (b)

Figure 6. Depth slice of the generated pseudo-3D, showing without the steel-cable reflection adjustment (**a**) and after correction (**b**).

4. Results

4.1. Reflection Patterns

According to Mitchum [20], the interpretation of GPR radargrams primarily relies on the differentiation of reflection patterns present in the data.

A series of reflection traces collected along a section, originating from flat interfaces with distinct electrical impedances, will generate a set of reflected pulses aligned at the same recording time along the radargram, which is simply called planar reflection. These types of reflections are typically generated from a subsurface boundary, such as a stratigraphic horizon or other physical discontinuity, like the water table, a soil horizon, or any other horizontal structure of interest [5].

Furthermore, according to Conyers [5], point-source reflections, also known as diffractions, can occur, which are generated from features or objects with dimensions equal to or smaller than the radiated frequency content. Examples of buried materials that generate point-source reflections include rock blocks and roots (perpendicular profiles). A large number or density of hyperbolas in a reflection profile can complicate interpretation because many closely spaced hyperbolic reflections have interfering axes and produce very complex profiles (caustic effect) [21].

These considerations were the starting point for analyzing the results, where it was necessary to classify the reflective responses seeking a deeper understanding of the subsurface characteristics present in these areas. This task occurred through the integrated analysis of reflection patterns (RPs) from 2D sections with depth slices in pseudo-3D blocks, which were characterized by reflection amplitude, geometry, and anomaly positioning.

The GPR data analysis revealed four distinct reflection patterns (RP-1 to RP-4), each associated with different subsurface characteristics. Pattern RP-1 is related to rock blocks, while RP-2 corresponds to roots. RP-3 was identified as the rock top, and RP-4 is associated with carbonate sediment.

In 2D radargrams, rock blocks (RP-1) and roots (RP-2) present similar reflective characteristics, characterized by chaotic hyperbolic reflection patterns due to their irregular distribution and size variation, with amplitudes varying between low, medium, and high (Figures 7c and 8c). In the pseudo-3D block depth slices, rock blocks appear as point anomalies, while roots manifest as elongated and continuous anomalies, with variations in sinuosity, narrowing, and amplitude (Figures 7b and 8b). Thus, the distinction between anomalies is more effective in the 2D profile.

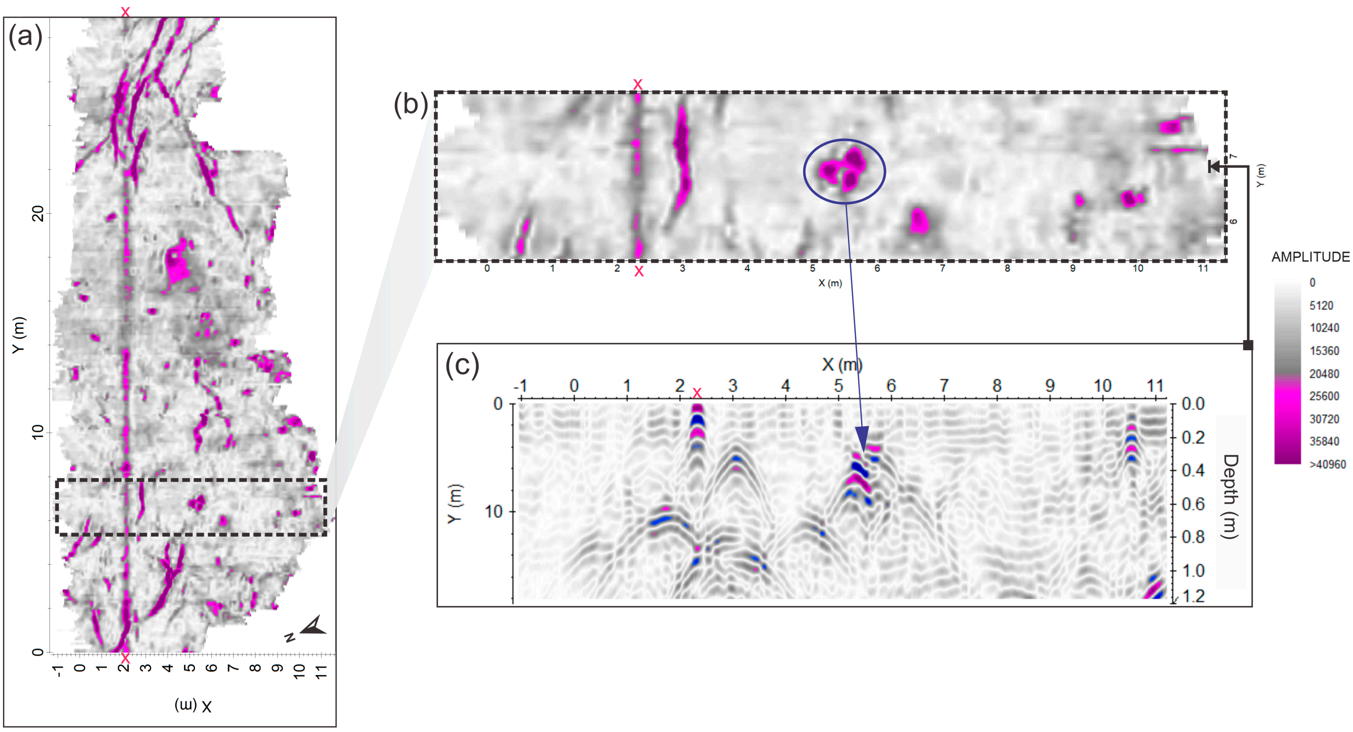


Figure 7. (**a**) Depth slice (40 cm) of the pseudo-3D block; (**b**) Detail of the pseudo-3D block depth slice showing anomalies from a set of rock blocks; (**c**) 2D profile (position 6.80 m) with the respective rock block reflection (RP-1). The x symbol (red) represents the steel-cable anomaly used in section georeferencing.

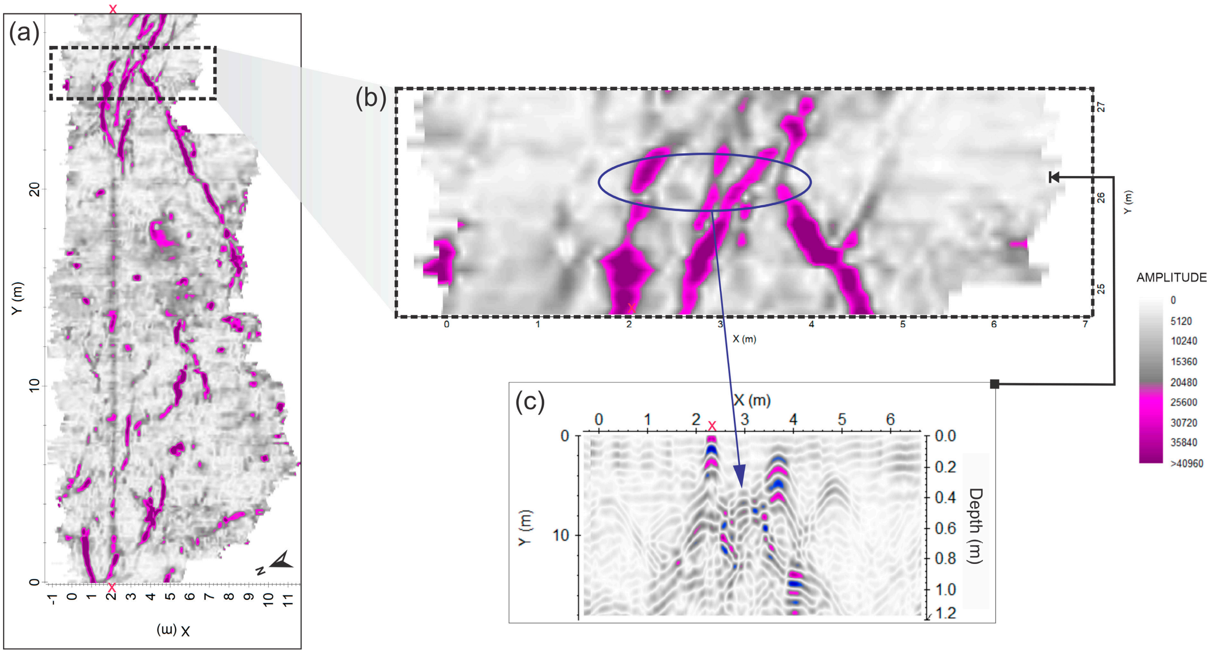


Figure 8. (**a**) Depth slice (50 cm) of the pseudo-3D block; (**b**) Detail of the pseudo-3D block depth slice showing anomalies from a set of roots; (**c**) 2D profile (position 26.2 m) with the respective reflection from a set of roots (RP-2). The x symbol (red) represents the steel-cable anomaly used in section georeferencing.

The reflection pattern RP-3, interpreted as representative of the rock top, is characterized by chaotic or continuous hyperbolic reflections of high amplitude in 2D profiles (Figure 9c). In the pseudo-3D block, it appears as a "cluster" of juxtaposed point anomalies with high amplitude (Figure 9b).

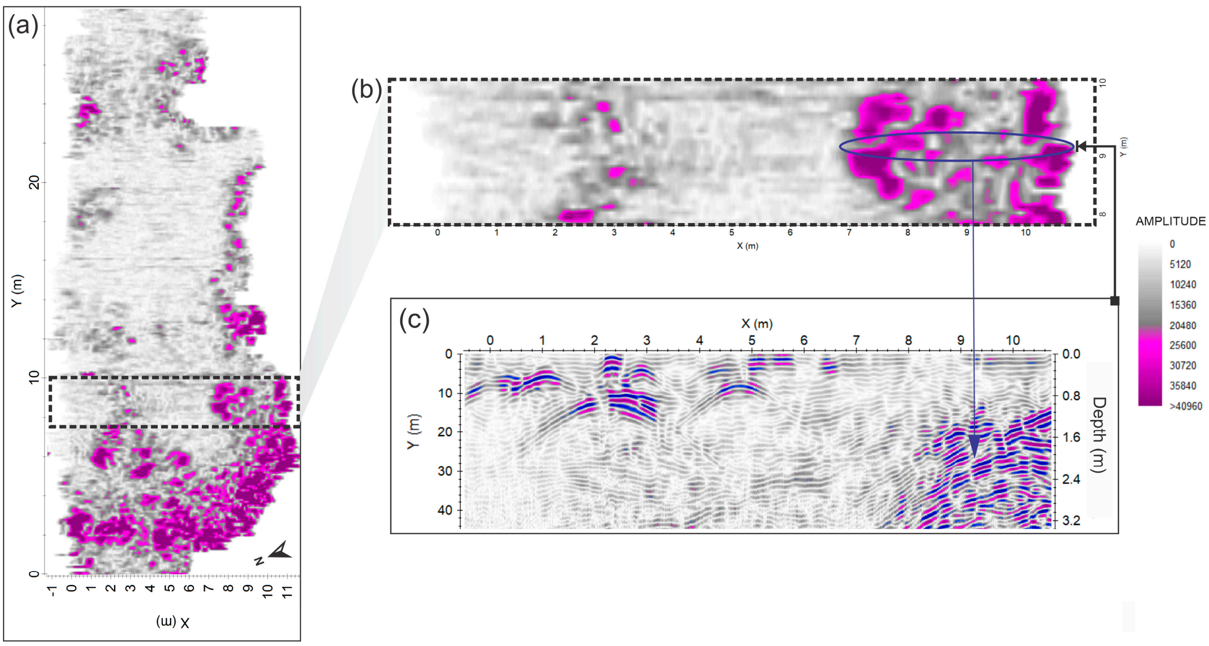


Figure 9. (**a**) Depth slice (2 m) of the pseudo-3D block; (**b**) Detail of the depth slice showing the rock top anomaly; (**c**) 2D profile at y = 9.2 m with the respective subsurface rock top reflection (RP-3).

The carbonate sediment (RP-4) identified in Area A1 of the GO-Ja-02 site in Serranópolis is a significant element for understanding the local archaeological context. This sediment is characterized by the presence of calcium carbonate, hearth ashes, and fine-textured carbonate lenses composed of calcitic limestone. Ongoing studies discuss the possibility that this layer's formation is associated with human activities in the past.

In the GPR results, this sediment manifests as a medium-to high-amplitude reflection pattern, with flat, continuous, horizontal, or slightly inclined reflectors in 2D GPR results (Figure 10c). In the pseudo-3D block depth slice, a medium-to-high-amplitude anomalous region is observed that is continuous, with geometry that delineates a broad area (Figure 10b).

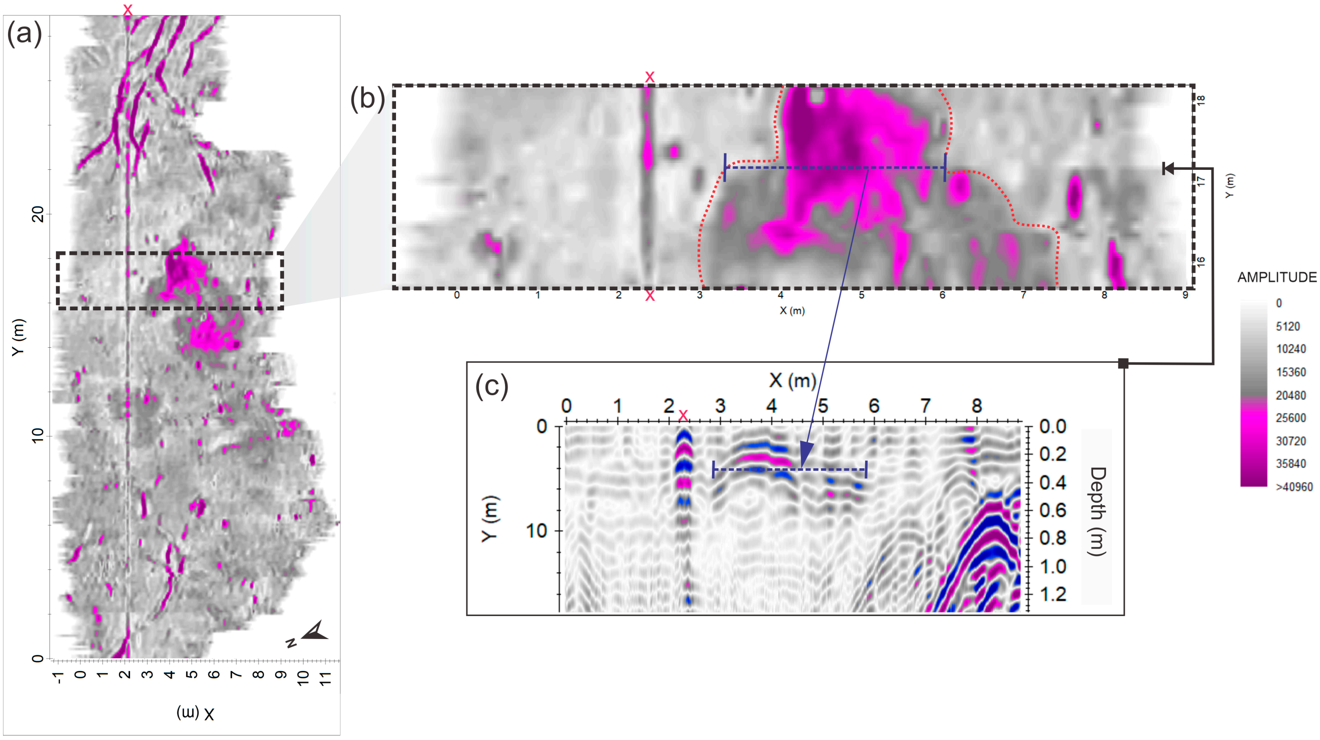


Figure 10. (**a**) Depth slice (30 cm) of the pseudo-3D block; (**b**) Detail of the depth slice showing anomalous areas related to carbonate material presence; (**c**) 2D profile at y = 17.0 m with reflection possibly related to carbonate material occurrence (RP-4) in an area delimited by red dashed line. The x symbol (red) represents the steel-cable anomaly used in section georeferencing.

4.2. Ranking Methodology for Excavation Area Prioritization

To suggest excavation locations, a ranking methodology was developed that considered various factors, each with an assigned weight. The weight assignment to each factor was based on the studied area's context, considering both positive and negative (Table 1) factors of their occurrences. The objective was to determine the highest-priority areas (P1, P2, P3, etc.) based on the weighted sum of these factors.

Each grid unit was evaluated on a scale of 0 to 10 for each factor. The score for each unit was calculated using the equation below.

$$\text{Score} = (5a + 4b + 3c - 3d - 2e) \quad (1)$$

where a, b, c, d, and e are the evaluations assigned to each criterion, respectively.

This equation allows positive factors (presence of carbonate sediment, sediment package thickness, and blocks with archaeological potential) to increase the area's score, while negative factors (presence of roots and blocks without archaeological potential) decrease it. The relative weighting of factors reflects their perceived importance for archaeological potential and excavation feasibility.

From this analysis, priority areas were then delimited and classified based on the average scores of units contained in each grid. This approach allows for a comprehensive evaluation of each potential excavation area, considering both factors that increase archaeological potential and those that may hinder excavations or decrease the likelihood of finding well-preserved remains.

Table 1. Positive and negative factors for archaeological potential, with their respective weights and justifications, organized into two headers: positive factors and negative factors.

Positive Factors	Weight	Justification
Presence of carbonate sediment	+5	These deposits are strong evidence of human activity. Therefore, the identification of carbonate sediment can provide valuable information about occupation dynamics and space use by ancient inhabitant groups, as well as greater potential for archaeological findings.
Sediment package thickness	+4	Sediment package thickness is directly related to rock top depth, as a thick sediment package means the underlying rock is located at a greater depth, consequently allowing deeper excavation. Deep excavations are essential for adding knowledge about the site's stratigraphy.
Presence of rock blocks with archaeological potential	+3	The presence of rock blocks can be of great interest, considering that previous studies by Schmitz et al. [1] found that many burials were frequently related to the occurrence of rock blocks in their proximity, indicating the possibility of some relationship with the type of funerary practice exercised. Thus, although the presence of rock blocks may represent a challenge, it may also signal the proximity of valuable archaeological discoveries, justifying the additional effort needed for excavation.
Negative Factors	**Weight**	**Justification**
Presence of roots	−3	The presence of high root density in areas of archaeological interest is generally seen as a negative factor, as it can cause many interferences during the excavation process. Besides making excavation more laborious, roots can damage delicate artifacts, compromising the integrity of archaeological findings.
Presence of rock blocks without archaeological potential	−2	Areas with a large quantity of rock blocks, especially when these blocks are larger than 60 cm, can be extremely challenging to excavate. This can make excavation more laborious and time-consuming, increasing logistical and operational challenges.

4.3. Ranking Methodology for Excavation Area Prioritization

After characterizing the reflection patterns and consequently developing knowledge about the nature of the main anomalous responses, interpretation proceeded regarding anomaly mapping. The generated depth slices were plotted in relation to the grid demarcation of the excavation area initiated by researchers from the Pontifical Catholic University of Goiás (PUC Goiás) up to the date of writing. This ongoing excavation is marked in the figures by pink and blue markings, with pink marking referring to excavation Area 1 and blue referring to excavation Area 2 (from the Serranópolis Project collection).

From the integrated analysis of anomalies, it was possible to verify that the presence of small-extent rock blocks and roots at shallower depths (up to 1 m) is intense (Figure 11). At greater depths (>1m), the emergence of the rocky top was observed, as well as large-extent rock blocks, revealing significant variations in sediment layer thickness throughout the studied area (Figure 12). The delimitation of carbonate sediment provided an important perception of possible regions of greater activity intensity (Figure 13). Variations in anomaly amplitude associated with all these elements can be attributed to various factors, including material heterogeneity, water content, structure orientation and geometry, and soil depth [5].

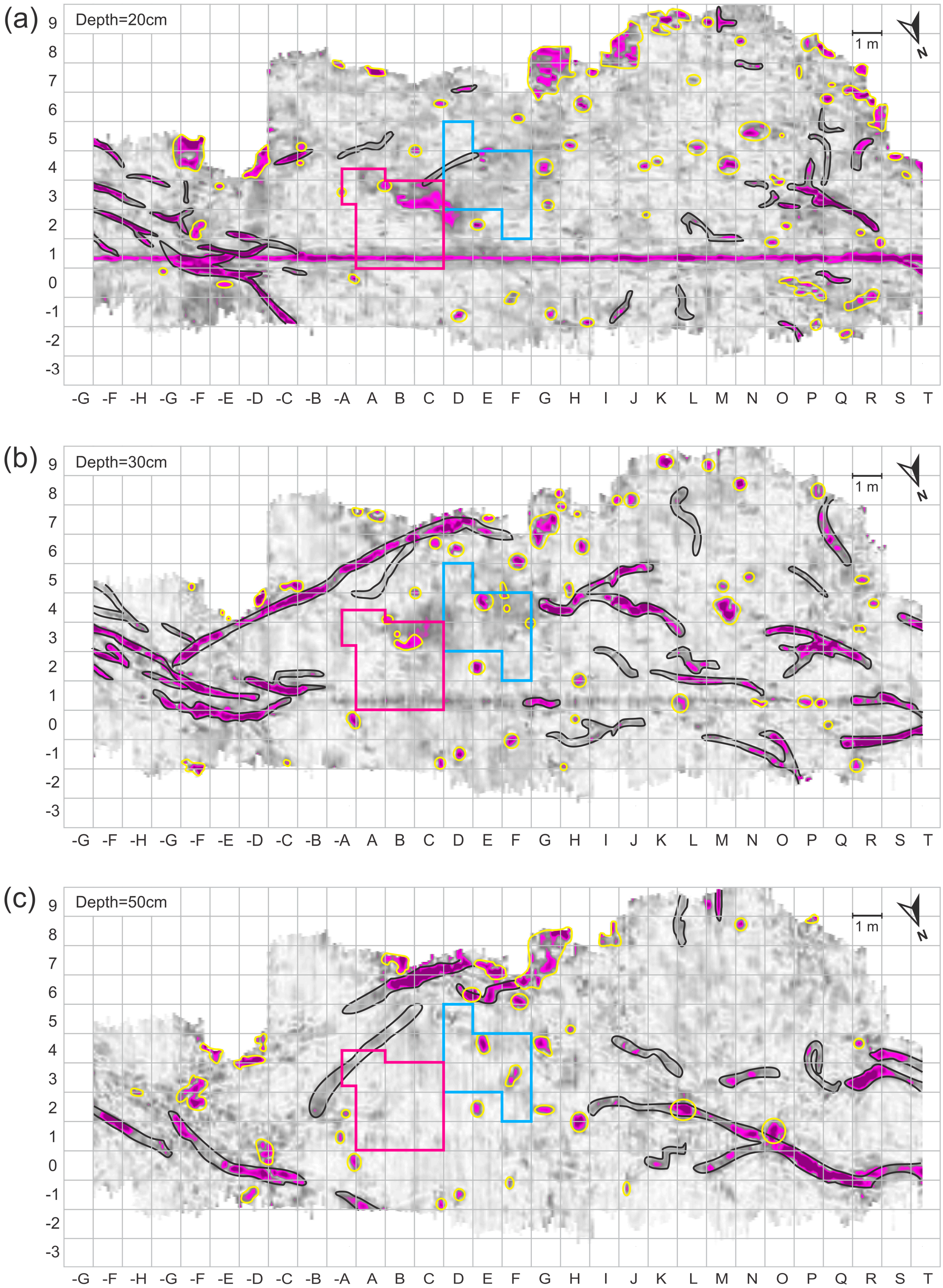


Figure 11. Surface depth slices of the pseudo-3D block, showing the mapping of anomalies related to rock blocks (yellow line) and roots (black line). The pink demarcation refers to Excavation Area 1, and the blue demarcation to Excavation Area 2, both areas of ongoing excavations.

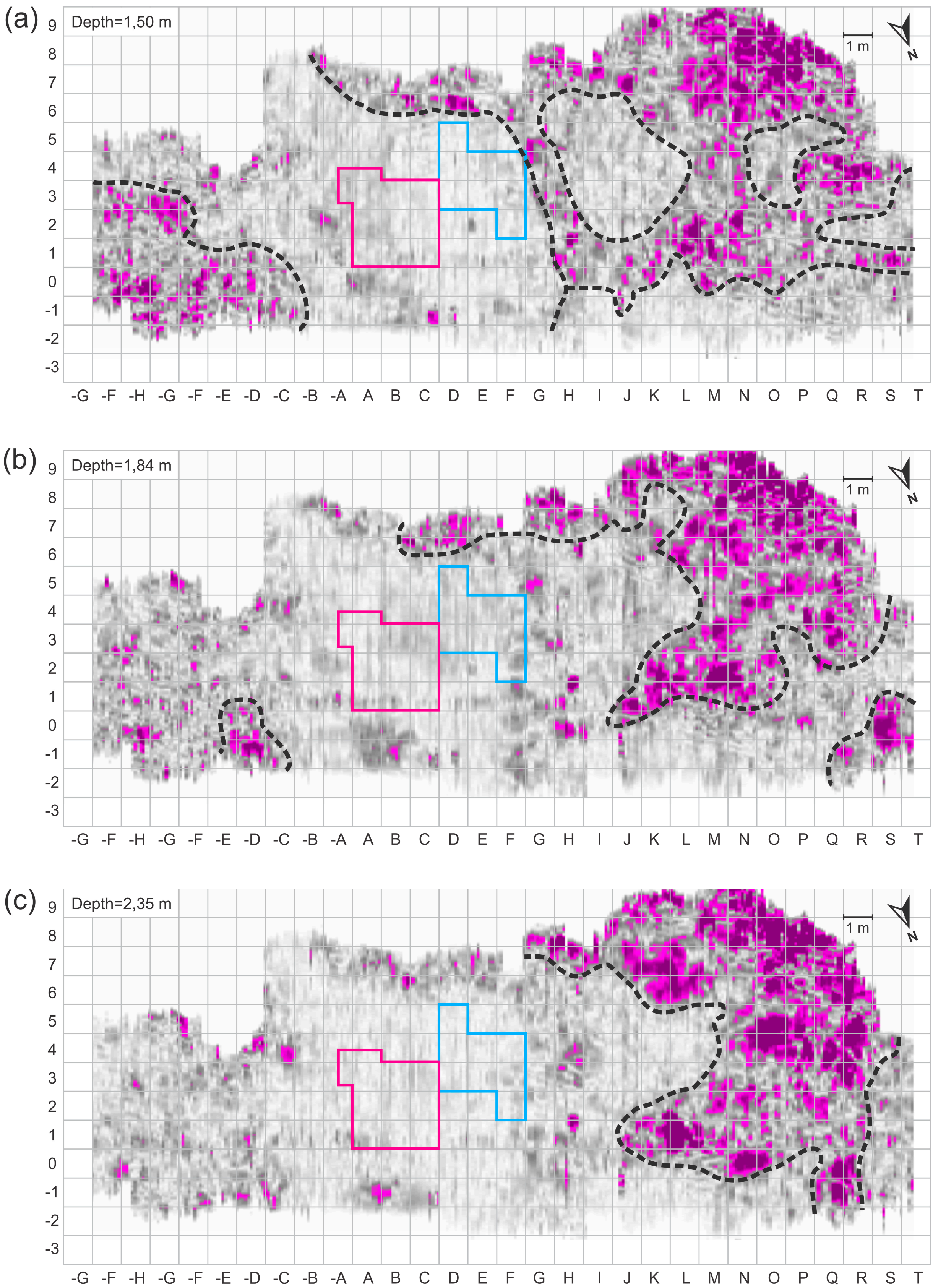


Figure 12. Deeper depth slices of the pseudo-3D block, with grouped mapping of areas with higher concentrations of high-amplitude anomalies (black dashed line), mainly related to rock blocks and/or rocky tops. Excavation Area 1, and the blue demarcation to Excavation Area 2, both areas of ongoing excavations.

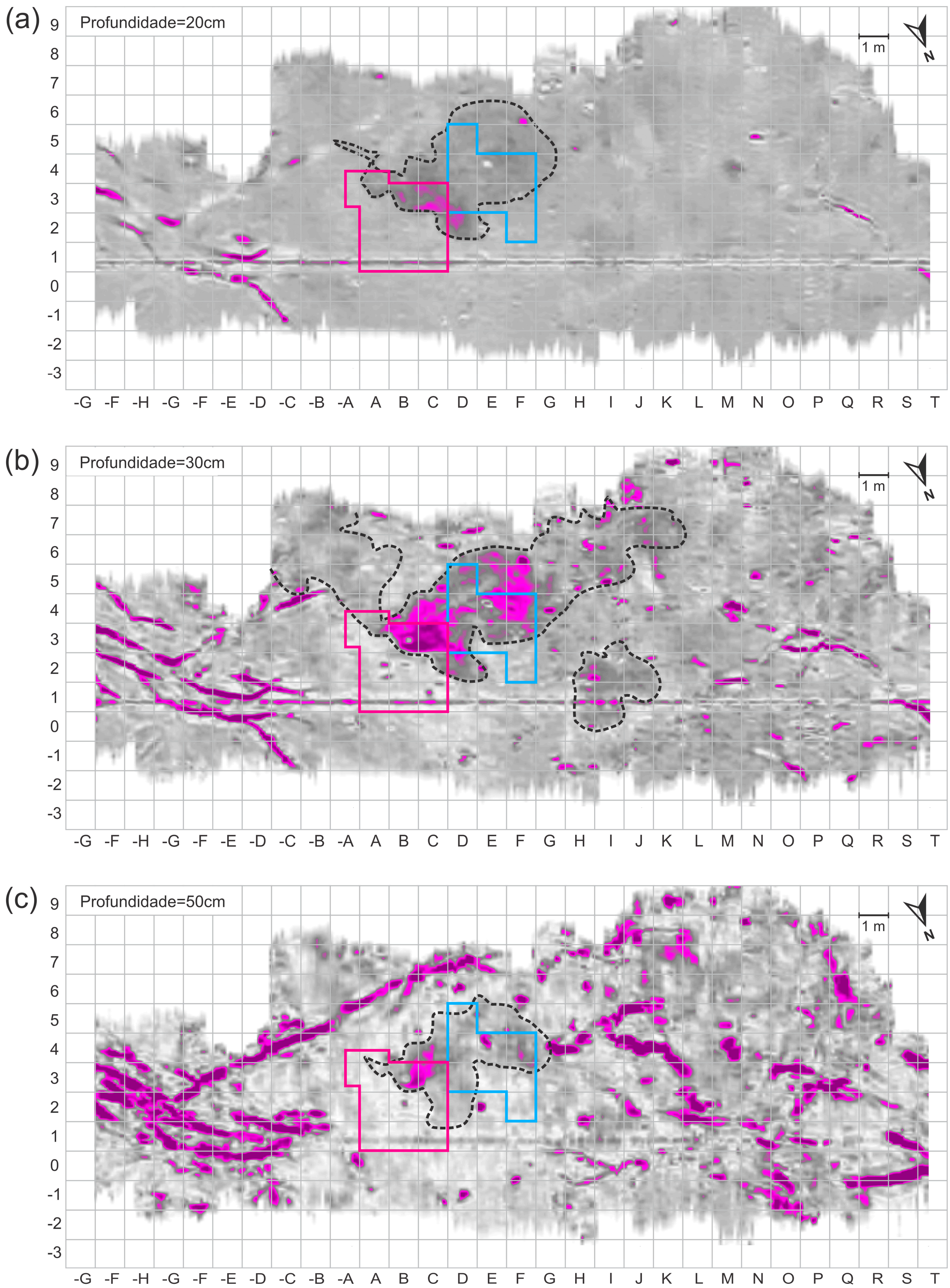


Figure 13. Depth slices of the pseudo-3D block, showing the mapping of anomalies possibly related to carbonate sediment occurrence (black dashed line). Excavation Area 1, and the blue demarcation to Excavation Area 2, both areas of ongoing excavations.

4.4. Ranking Methodology for Excavation Area Prioritization

Based on the developed ranking methodology, priority areas for excavation were identified in area A1 of site GO-Ja-02 from the weighted sum of factors considered for each grid.

After calculations, a consolidation stage was carried out. In this phase, adjacent or nearby priority areas were grouped to form broader zones of interest. For example, contiguous areas or those closely related in their score values were combined into a single expanded priority zone. The consolidation took into account the spatial continuity of identified geophysical characteristics, allowing for a more integrated approach to site investigation. This grouping process aims to provide a more comprehensive and simplified view of each region's potential (Figure 14).

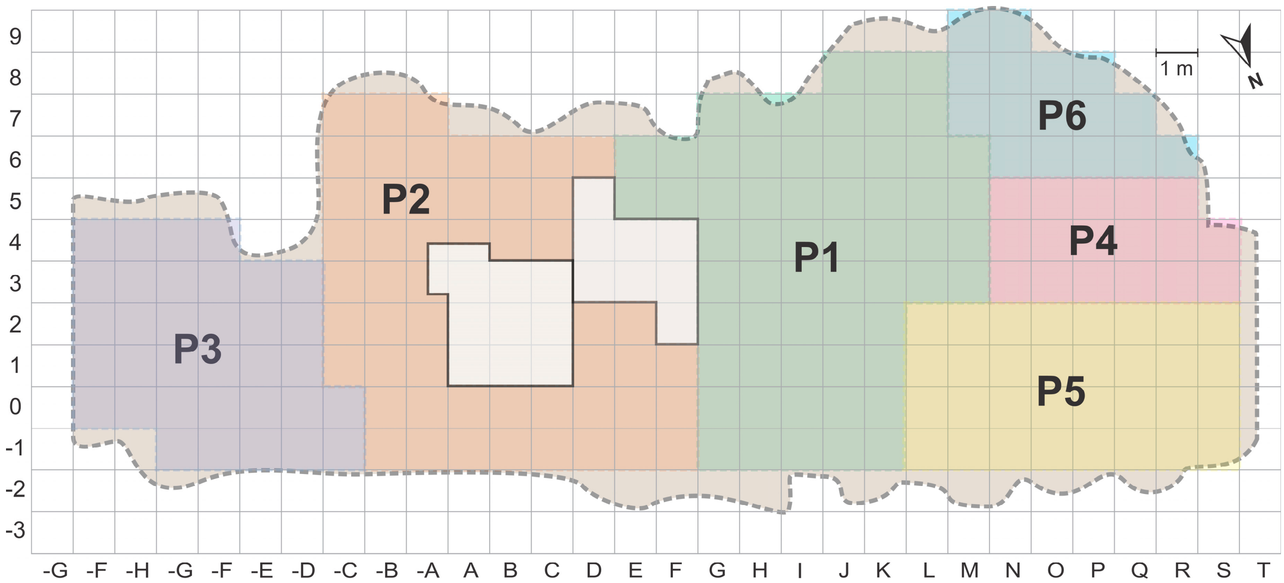
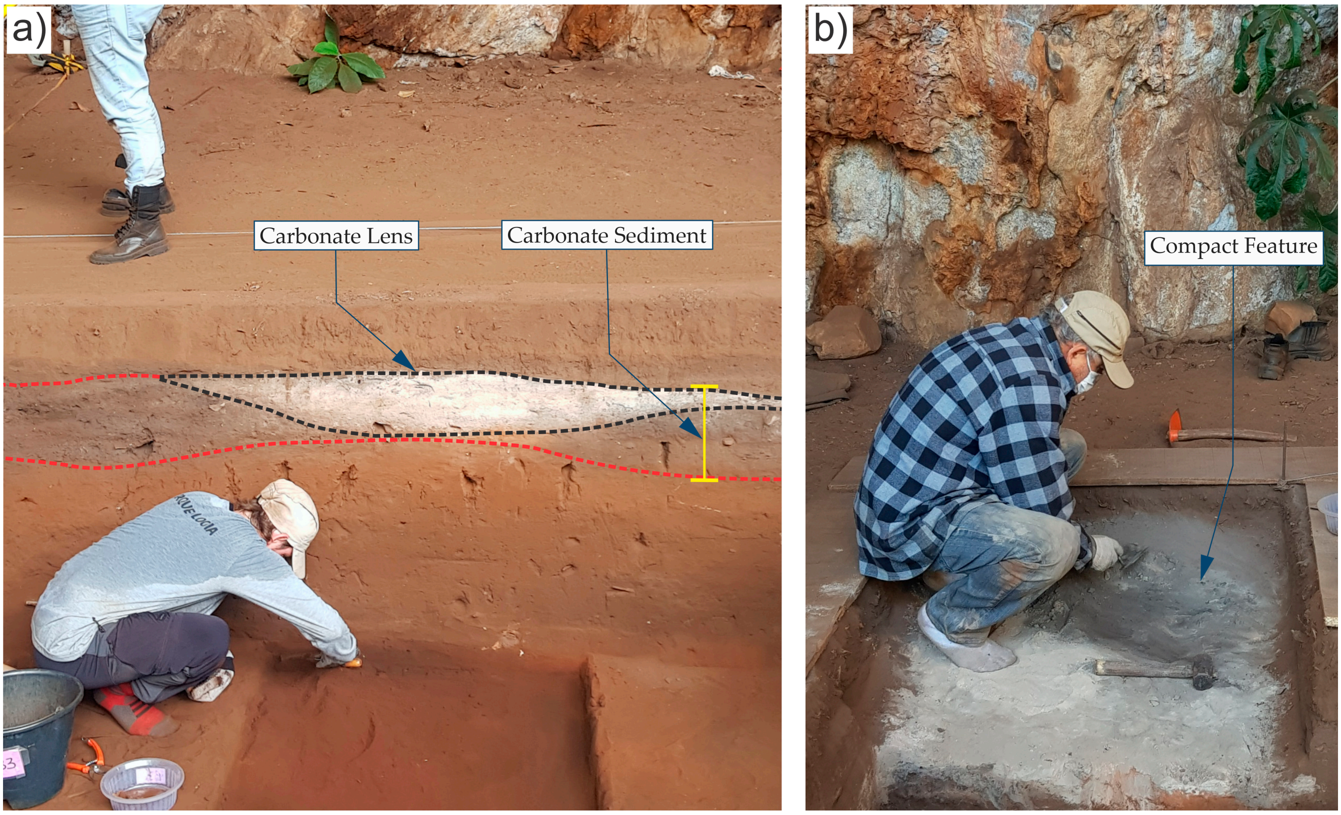


Figure 14. Sketch highlighting six priority excavation regions (P1–P6), identified through the grouping of the weighted sum of factors considered for each grid.

5. Discussion

The effectiveness of our GPR-based methodology was validated through excavations that revealed two distinct carbonate-related features at the predicted locations (Figure 15). The first corresponds to the carbonate sediment layer identified at 20 cm depth (Figure 15a), while the second represents a compact feature formed by the interaction between the carbonate layer and hearth ashes (Figure 15b). Both features were found at depths consistent with the GPR anomalies, confirming the reliability of our prioritization approach in identifying archaeologically significant areas.



(**a**) (**b**)

Figure 15. Field photographs showing two different contexts of the carbonate layer: (**a**) Profile in the excavation area, approximately 60 cm deep, highlighting the carbonate sediment package with the presence of a carbonate layer lens at 20 cm depth. (**b**) Excavation in an area where the "compact feature" was found at 20 cm depth, generated from the contact between the carbonate layer and hearth ashes.

6. Conclusions

This study demonstrated the effectiveness and potential of the GPR method in characterizing the archaeo-environment of the GO-Ja-02 archaeological site in Serranópolis, Goiás. The implementation of this non-invasive geophysical technique enabled detailed subsurface analysis, providing valuable information about the site's archaeo-environment prior to excavation stages.

The main results and contributions of this study encompass various aspects, both in geophysical and archaeological investigation. GPR data analysis revealed distinct reflection patterns associated with different subsurface elements, such as rock blocks, roots, bedrock surface, and the existence of particular carbonate sediment. Through the three-dimensional analysis of GPR data, it was possible to discriminate anomaly identity and obtain a detailed spatial visualization of subsurface element distribution.

Furthermore, a significant contribution of this study was the development of a ranking methodology to prioritize archaeological excavation areas. Its objectivity, based on quantifiable criteria, reduces subjectivity in selecting areas for excavation, while its flexibility allows for adjustments according to each site's particularities. The efficiency in optimizing excavation resources, directing them to areas of greater potential, is complemented by the methodology's reproducibility, which can be applied in new studies.

It is important to emphasize that, although this methodology provides a basis for prioritizing excavation areas, it should be used in conjunction with archaeologists' expert knowledge and the particularities of each archaeological site. The a posteriori delimitation of priority areas allows for an adaptive approach, where judgment can refine and adjust areas suggested by quantitative analysis.

Another important aspect is that, although this study focused on characterizing the archaeo-environment through analysis of GPR reflection patterns mainly associated with geological elements, there is a possibility that some reflections may be related to archaeological artifacts. The detection of individual artifacts by GPR depends on various factors, including artifact size, composition, antenna frequency used, and primarily the existence of dielectric contrast between the artifact and surrounding soil.

The 400 MHz antenna used in this study offers a good balance between resolution and penetration depth for archaeo-environment characterization objectives. However, this frequency may not be ideal for detecting smaller artifacts. Additionally, the complexity of the subsurface environment, with the intense presence of rock blocks and roots, tends to complicate the identification of specific artifact reflections.

The limitations encountered, such as difficulty in distinguishing certain structures due to similarity in dielectric properties, highlight the importance of a multidisciplinary approach in GPR data interpretation. The combination of geophysical, geological, and archaeological knowledge proved essential for the comprehensive and accurate interpretation of results.

Future studies specifically focused on artifact detection could benefit from using higher-frequency antennas (such as 900 MHz) to improve resolution, combined with advanced processing techniques and correlation with excavation data. Finally, this study emphasizes the importance of integrating advanced technologies, such as GPR, in preserving and studying archaeological heritage. Employing GPRs, as a non-invasive approach, not only allows for detailed investigation without disturbing the site but also contributes to fostering the conservation of these important historical records for future generations.

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