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Abstract: This paper describes the inspection for cavity detection in an urban area in Torrente (Valencia, Spain). A shallow cavity was found during excavation works for a sewerage project. Digging activities were stopped immediately and a GPR survey was required to reorganize the sewerage planning. The 3D GPR-mapping pinpointed cavities mostly on one side of the street. As a result, the sewerage system layout was moved to the side of the street where poor cavity evidences were detected. GPR technique is helpful for minimizing costs, time, work safety risks and inconveniences to neighborhood during civil engineering works, especially in urbanized areas.

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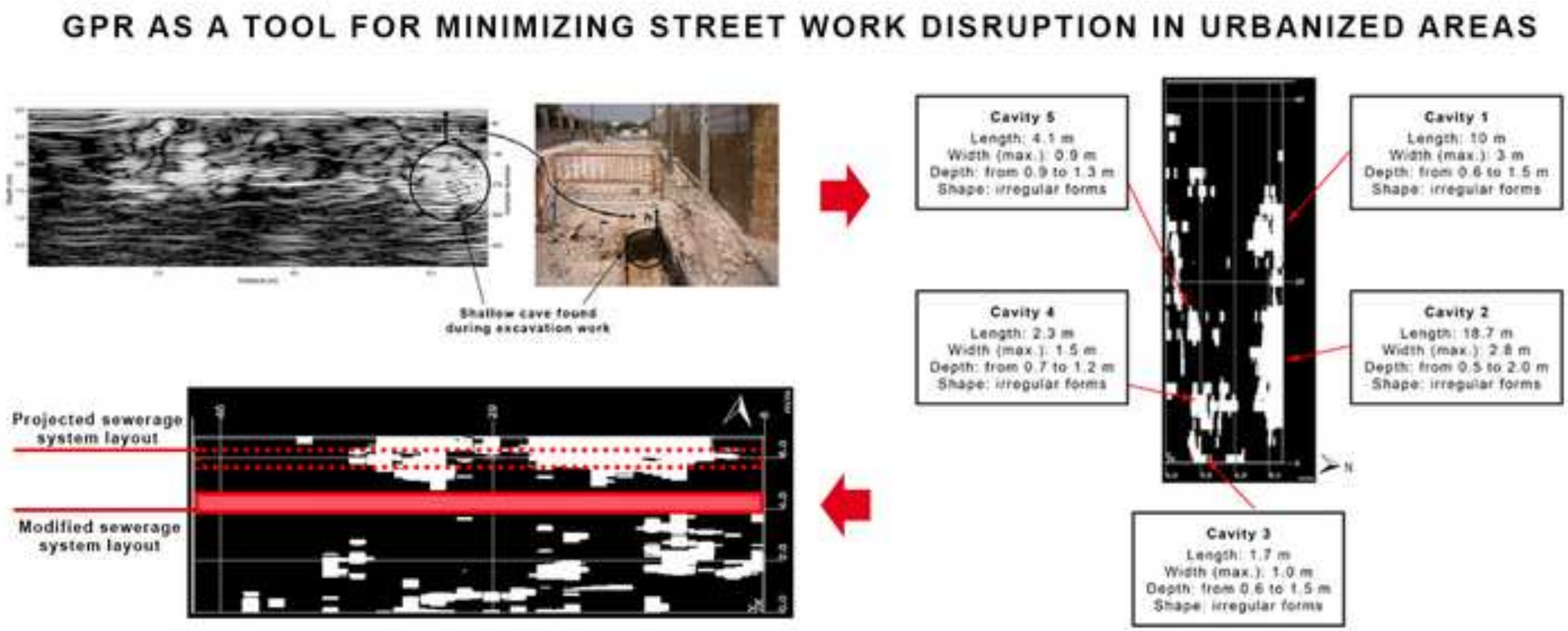
Highlights

- 3D GPR data has been used for cavity detection in urbanized areas.
- 3D representations of GPR data facilitate interpretation in civil engineering.
- GPR survey reduces work safety risks in urbanized karst hazardous areas.
- Civil engineering projects including GPR are cost-effective and time-reducing.

Graphical Abstract



Minimizing street work disruption by mapping cavities derived from 3D GPR-data: a new sewerage project in Torrente (Valencia, Spain)

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Abstract

This paper describes the inspection for cavity detection in an urban area in Torrente (Valencia, Spain). A shallow cavity was found during excavation works for a sewerage project. Digging activities were stopped immediately and a GPR survey was required to reorganize the sewerage planning. The 3D GPR-mapping pinpointed cavities mostly on one side of the street. As a result, the sewerage system layout was moved to the side of the street where poor cavity evidences were detected. GPR technique is helpful for minimizing costs, time, work safety risks and inconveniences to neighborhood during civil engineering works, especially in urbanized areas.

Keywords

street work disruption; ground-penetrating radar; GPR; cavity; cave hazards; 3D mapping; sewerage project

1. Introduction

Civil engineering works requires accurate techniques for cavity detection in urbanized areas. Non-destructive techniques (NDT) offer multiple possibilities for the documentation and interpretation of underground anomalies and structures. Geophysics is successfully employed for non-invasive explorations in all fields of civil engineering. It provides non-destructive effective solutions and offers significant information.

The most employed geophysical methods for mapping the subsurface space are: (a) the electrical and electromagnetic resistivity methods, (b) the seismic methods and (c) the gravimetric methods [1]. Each geophysical technique has its pros and cons. Microgravity is one of the most reliable techniques for the detection and outline of subterranean anomalies [2-4]. However, data acquisition and result analysis involve long processing time. The electrical resistivity [5] and the magnetic methods can offer excellent results [6,7], but they provide less information, because of their low resolution in the three-dimensional (3D) images. The seismic methods have been used to locate subterranean structures [8,9]. Nevertheless, this technique shows some limitations in the peripheral sectors, where the angular coverage limitation derives in poor results. The ground-penetrating radar (GPR) method is often a more effective means in the study of underground structures than other geophysical methods. Currently, it is the dominant technology for location surveys. This technique is a useful mapping tool due to its suitability for high-resolution subsurface imaging and 3D data representation. It allows attaining reliable results, ensures complete coverage of the site and, therefore, increases the survey effectiveness and reduces costs [10].

This technique has been widely applied for mapping the underworld [11], focusing on utility location [12-14], road maintenance [15-17] and inspection of natural or man-made underground structures [18-21]. There have also been published studies on imaging of collapsed underground systems in natural and urban areas [22,23]. Air-filled cavities reflect the electromagnetic wave with maximum relative amplitudes at the top of the cavity on a GPR section. So, this method is usually employed for non-destructive detection of cavities in karst areas with special attention to those located in urbanized zones [24-29].

Civil engineering projects aim at reducing safety risks and cost risks, especially in street works. Clients request high levels of accuracy, while surveyors have interest in effectivity and high quality of the location survey to ensure client confidence. Street work disruption results in economic and management drawbacks [30]. The accuracy in pinpointing subsurface structures and defining their geometry provide additional information to design and perform maintenance and new projects by minimizing potential errors [31]. The GPR method is proposed in this study due to its high resolution subsurface imagery, fast data acquisition and suitability for detecting and mapping buried anomalies.

In order to evaluate the effectiveness of the GPR technique for cave detection in urbanized areas, a sector of a housing development was analyzed. Prior to this study, a shallow cave was found during sewerage excavation work. Given the nature of the urban project location, cave evidences and indicators were masked. The aim of this work is twofold: first, to pinpoint cave hazards in a street using 3D GPR data visualization with iterative depth and profile slice and second, to prove that GPR is a time and cost-effective method for civil engineering works and urban planning. As a result of this study 5 cavities were detected with a volume greater than 1 m^3 in irregular forms and depths, and several smaller ones were identified.

2. Site description

The study area is situated in Torrente, a town located 12 km southwest of Valencia city (Fig. 1). Valencia is located at the Spanish Mediterranean shore. Torrente is placed on Tertiary formations that border with alluvial sediments and flooding silt from the River Turia. These Tertiary formations emerge in western and southwestern areas, where they form the first limestone foothills [32,33].

Torrente population growth (more than 80,000 inhabitants last year) has caused urban development southwards from its downtown. New urbanized areas are located in mountains composed of fractured limestone with presence of karst activity. The studied zone is located in this setting, where housing estates were built. The need to expand the sewerage system in the area resulted in a civil engineering street work. Urbanized areas in karst hazardous zones suffer from infrastructure jeopardy, which usually implies economic losses. During street excavation work, a shallow cave was found. This fact resulted in digging activity stoppage. Therefore, a GPR survey was required for cavity detection in order to minimize street work disruption and reduce safety risks and cost risks.

Fig. 1

3. Materials and Methods

3.1. Field data acquisition

Data collection was required from the whole street under study. A profile grid 2x2 m was carried out on the street (Fig. 2). So, three-dimensional (3D) GPR methodologies were performed for pinpointing and defining underground karst activity. The GPR data were collected using a GSSI SIR-3000 equipment with a nominal 400 MHz centre frequency antenna within a total time window of 60 ns.

Fig. 2

3.2. Data processing

Preliminary excavation works unveiled a shallow karst cave and expose a cross-sectional image of the street (Fig. 3). The reflection from the top of this shallow karst was recorded at the end of profile P3 line. It was used as a calibration to collect the karst zone data. So the soil thickness over the cavity distance (h) could be measured. This value in addition to the two-way travel time (t) defined by GPR measurements allowed calculating the dielectric permittivity (ε) according to the following equation [34-36]:

$$\varepsilon_r = \left(\frac{c}{v}\right)^2 = \left(\frac{ct}{2h}\right)^2 \qquad (1)$$

For time scale to depth conversion, the subsurface electromagnetic wave velocity was obtained from ε [35,36]. An average velocity of 0.084 m/ns for limestone medium was obtained from the following equation:

$$v = \frac{2 \cdot h}{t} \qquad (2)$$

Fig. 3

3.3. 3D modeling

RADAN software was used for data processing. As a first stage, time zero correction, background removal and gaining function were also applied with the aim at amplifying the received signal and improving anomaly identification. Also 2D raw data were processed by applying filters such as Kirchhoff migration filter using the average velocity for diffraction removal.

A GPR-3D model of the subsurface was obtained by aligning processed 2D profiles in order to pinpoint cavity evidences beneath the street under study. Several amplitude slice maps were obtained at different levels for mapping the subsurface to the maximum depth of 1.5 m projected excavation for sewer pipe. Amplitude slice maps from the 3D model were used to identify irregularities at a constant depth. Besides, transparent visualization of the 3D GPR data set was conducted for revealing main subsurface anomalies.

The main objective was to define the location, shape and depth of the cavities detected. The results can be enriched when visualized as a volumetric rendering. This procedure allows anyone to reckon and understand how the subsurface area under study looks. Maps and 3D representations allow for the characterization of the radar data, for geometrical dimensioning of the cavities as well as for a better understanding of the electromagnetic results for clients and civil engineering employees.

4. Results

Radargram profiles showcase an overview of the site under study. Fig. 4 includes the three 2D longitudinal profiles acquired along the street. These radargrams illustrate the subsurface dissimilarities on different sections of the street. The southern profile shows scarce subsurface anomalies, while the central radargram along the street displays subtle features that may correspond with karst activity from meters 0 to 16 at a depth of 1.5 m. The northern longitudinal 2D profile indicates the strongest reflectors regarding the underground cavities. From meter 0 to meter 32 at a depth between 0.5 and 2 m, subsurface cavities are identified in Fig. 4.a).

Fig. 4

However, defining geometrical and dimensional features of caves from the GPR 2D data is time-consuming and requires an individual analysis of every radargram. 3D visualization techniques were applied to overcome this difficulty. Fig. 5.a) illustrates a set of selected depth-slices derived from the GPR 3D cube. The most representative depth-slices are identified at 0.5, 1.0, 1.5 and 2.0 meter-depth. The maximum and minimum amplitude ranges according to the amplitude-color scale characterize the cavities filled with air in the subsurface study site. Moreover, the isosurface rendering technique enabled visualizing the whole subterranean structures defined by karst activity, as shown in Fig. 5.b). The color restriction made only cavities visible and simplified cavity detection and data interpretation. Hence, it was possible to crosscheck both depth ranges and isosurface ranges and in order to determine the exact location of the subsurface karst activity and to dimension the cavities by defining their extension and depth-positioning. The 3D GPR data revealed 5 cavities with a volume greater than 1 m^3 in irregular shapes between 0.5 and 2.0 meter deep and several smaller ones.

Fig. 5

The GPR 3D data visualizations have improved the application of GPR for civil engineering prospections. In this particular case, GPR has aided in characterizing the underground karst structures for minimizing street work disruption. Despite its contribution, the interpretation of radargrams is not a simple task for non-geophysicists. In the civil engineering field, isosurface 3D modeling result in a better understanding of the outcomes derived from the GPR data. Location and general dimensions of the subsurface structures can be defined in order to characterize the detected 5 cavities in the site under study (Fig. 6).

Fig. 6

As seen in the Figures 5 and 6, the karst activity was mainly concentrated in the northern area of the street under study. This part of the street was supposed to include the sewerage layout. However, the detection of subterranean structures led to a modification of the civil engineering project. The 3D GPR data helped in the decision-making for modifying the sewerage system layout where fewer cavities with smaller dimensions were identified. So the sewerage system layout was moved to the side of the street where poor cavity evidences were detected, as shown in Fig. 7.

Fig. 7

5. Discussion and conclusions

Civil engineering projects usually focus on street work. Effectiveness, high level of accuracy and quality are terms to bear in mind when planning civil engineering surveys. However, problems usually arise during street work carrying out. This fact implies a delay in the project and an extension of the street work disruption. And hence, it can result in economic and management drawbacks.

This situation took place in the project presented in this study. The accidental discovery of cavities karst involved holdup of field work. Therefore, Geophysics experts were required to perform a survey of the underground. The aim was at identifying if it was possible to continue with the sewerage project as it was planned or if it was necessary to redirect the facility layout. The GPR results revealed the existence of cavities in the planned area for sewerage facilities, so it was necessary to modify the layout of the project. It all not only involved an extension in time but also an additional cost derived from the hiring of Geophysics experts, the equipment rental and especially from the street work disruption in an urbanized area causing unnecessary inconvenience to neighborhood.

These drawbacks can be anticipated and solved efficiently. For this purpose, geophysical prospections should be included in the preliminary studies of civil engineering projects. This way, unnecessary costs could be avoided and street work disruption could be significantly reduced in urbanized areas. Moreover, prior examination of the underground can minimize the potential for errors and increase the efficiency in field work.

We produced images of the underground in an urbanized area via a proposed method based on 3D visualization of the GPR data. This allowed us to reveal and differentiate subsurface cavities from the surrounding soil medium.

The transparent 3D imaging successfully allowed the identification of targets (cavities) in the underground, providing accurate locations and depths. The isosurface 3D modeling derived from the GPR data provided better imaging to accurately interpret the subsurface by non-geophysicists professionals that work in the civil engineering field. So these data helped them in the decision-making for modifying the sewerage system layout. The results demonstrated that the GPR method and the 3D visualization can give perfect outcomes in a delimited urbanized area.

We conclude that the GPR technique provides highly accurate results for the position and depth of cavities within civil engineering projects in urbanized areas. 3D GPR survey reduces work safety risks in urbanized karst hazardous areas. Mapping cavities within urban areas is cost-effective and time-reducing, especially regarding street work disruption.

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Figure captions

Fig. 1. Geographical location of the study site (Torrente, Valencia, Spain), where we can observe urbanized areas and plots of undeveloped land.

Fig. 2. Prospection area and GPR data acquisition in the site under study: a profile grid 2x2 m (22 transversal and 3 longitudinal profiles).

Fig. 3. The reflection from the top of the shallow karst at the end of the P3 profile line was used as a calibration to calculate an average velocity for this study. a) Radargram of the GPR profile P3: shallow cavity between meter 5.3 and meter 7.7 at 0.50 m-depth. b) Detailed image from the study site showing the cavity depth found during the excavation work for the sewerage project.

Fig. 4. a) Radargram profile P24 (northern area of the study site). b) Radargram profile P23. c) Radargram profile P25 (southern area). d) Profiles P25, P23 and P24, showing strong subsurface cavity evidences in P24 and less presence of karst activity in P25.

Fig. 5. a) Solid depth slices obtained from the 3D cube created, at 0.5, 1.0, 1.5 and 2.0 meter-depth. b) Isosurfaces showing 5 detected cavity structures with a volume greater than 1 m^3 and several smaller ones.

Fig. 6. Isosurface generated from overlay analysis considering the whole set, where the general features of the detected cavities are defined.

Fig. 7. The modified sewerage system layout according to the isosurface derived from GPR data.

Figure 1

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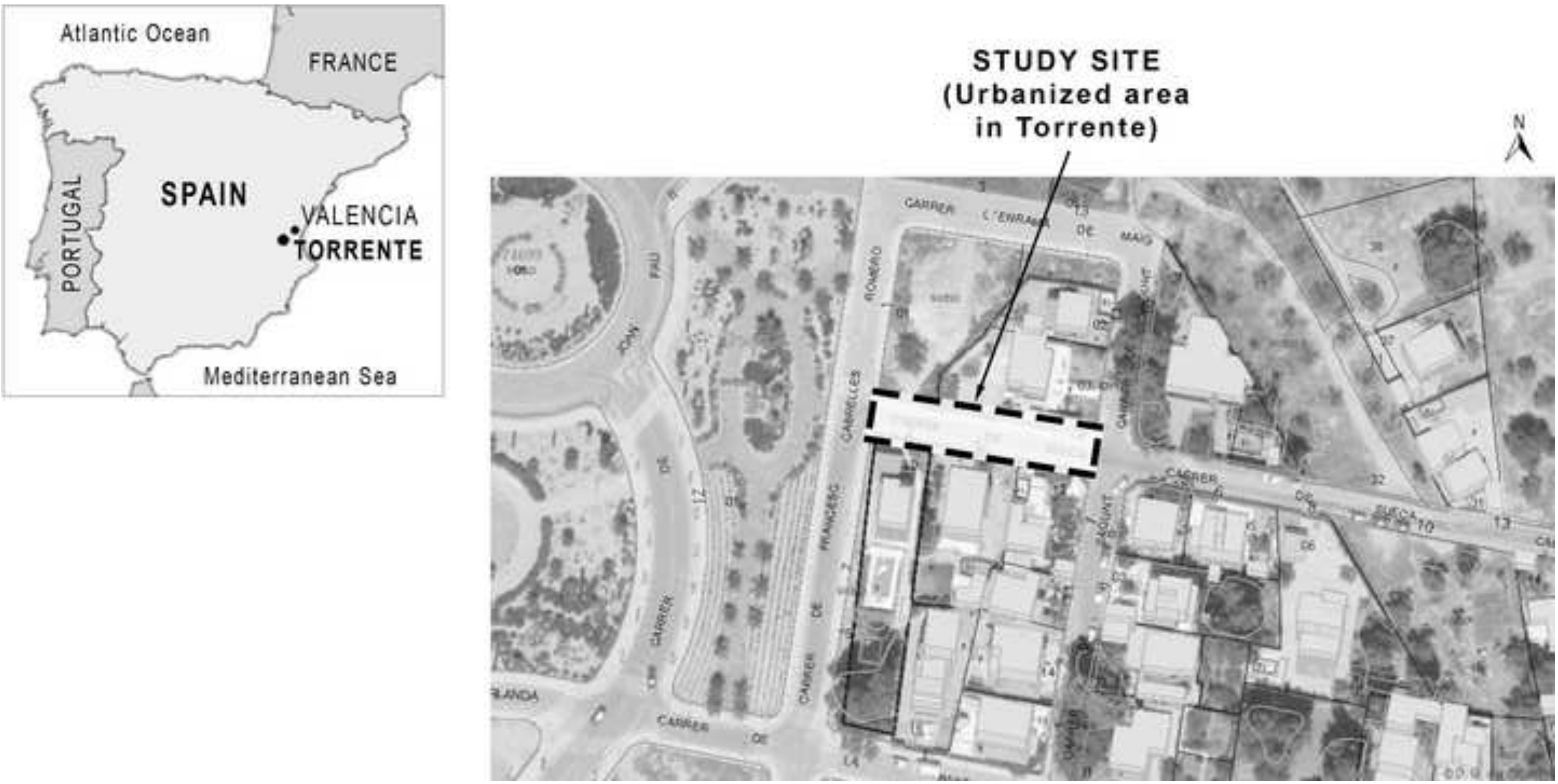

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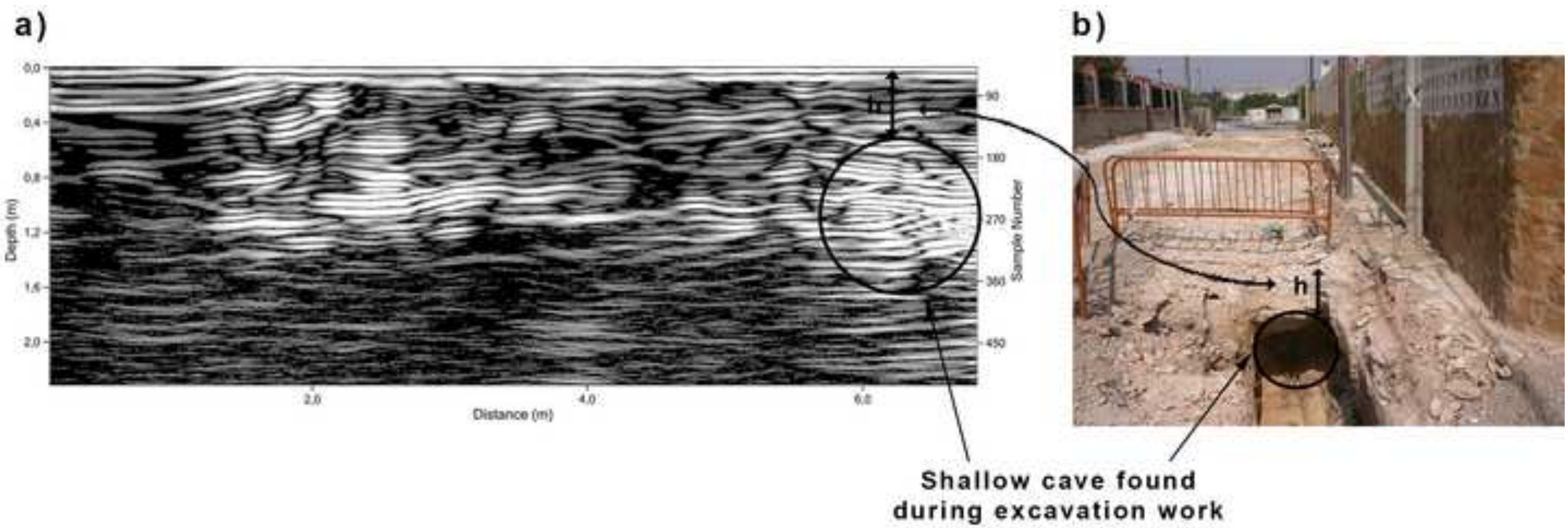

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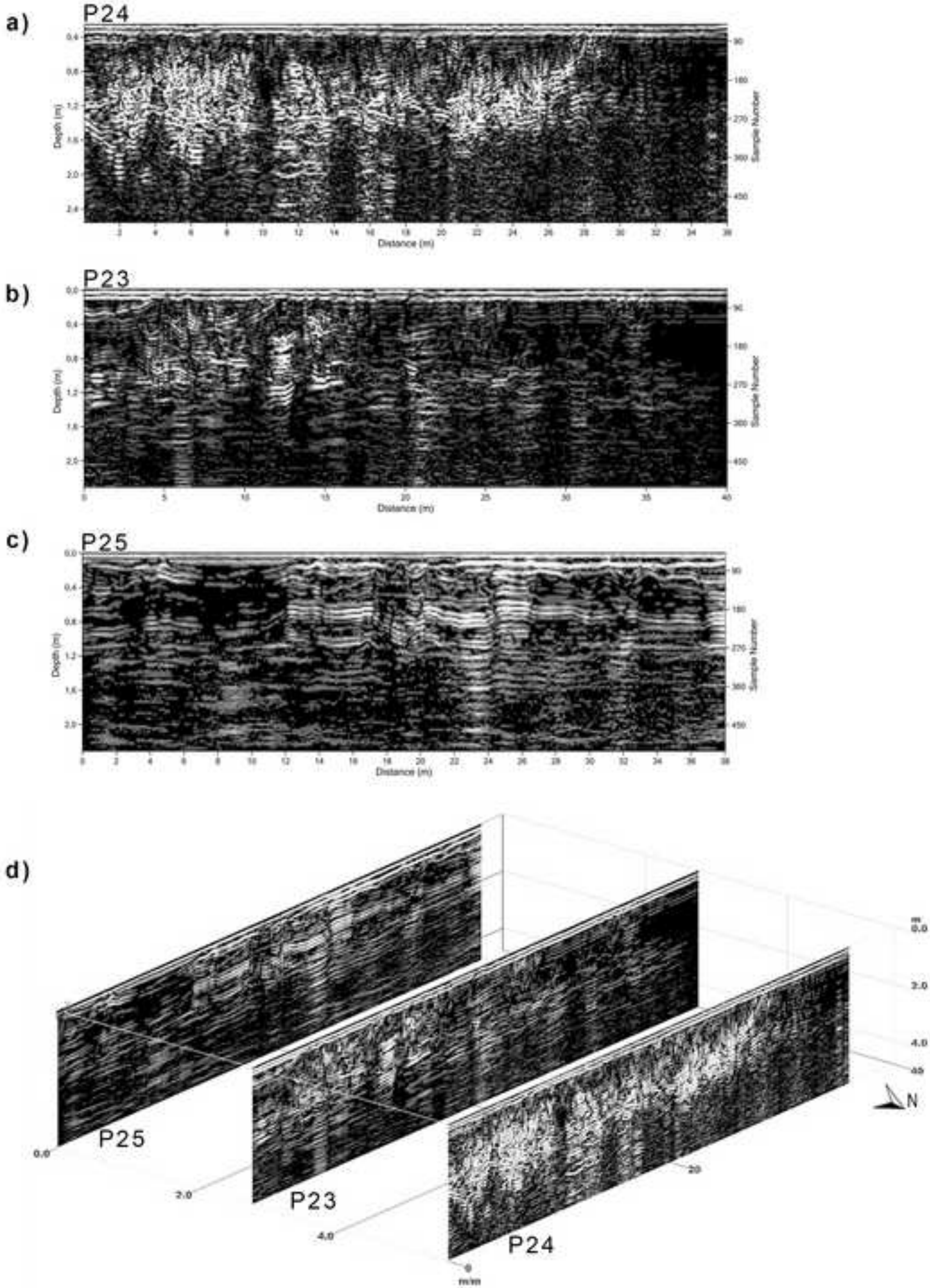

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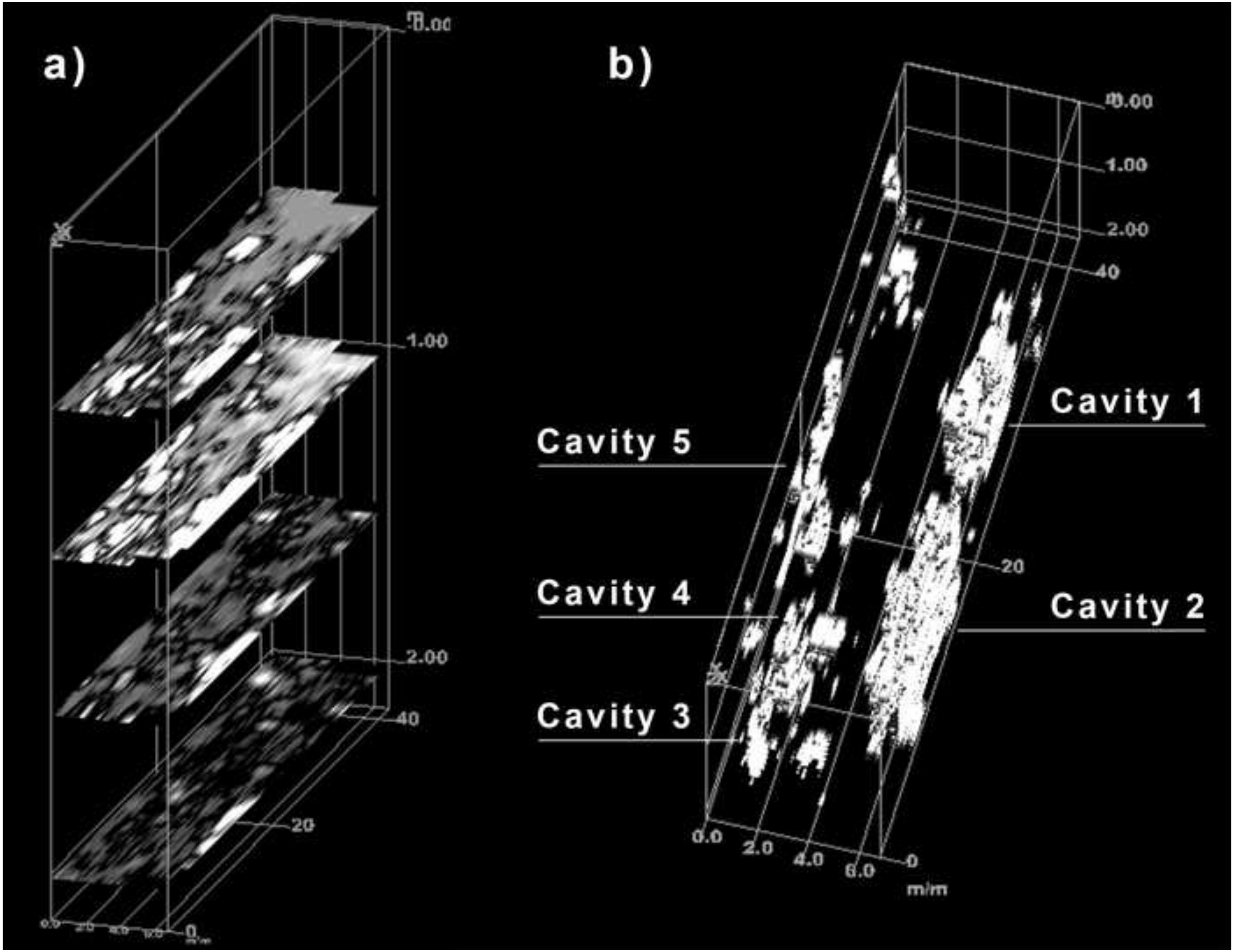

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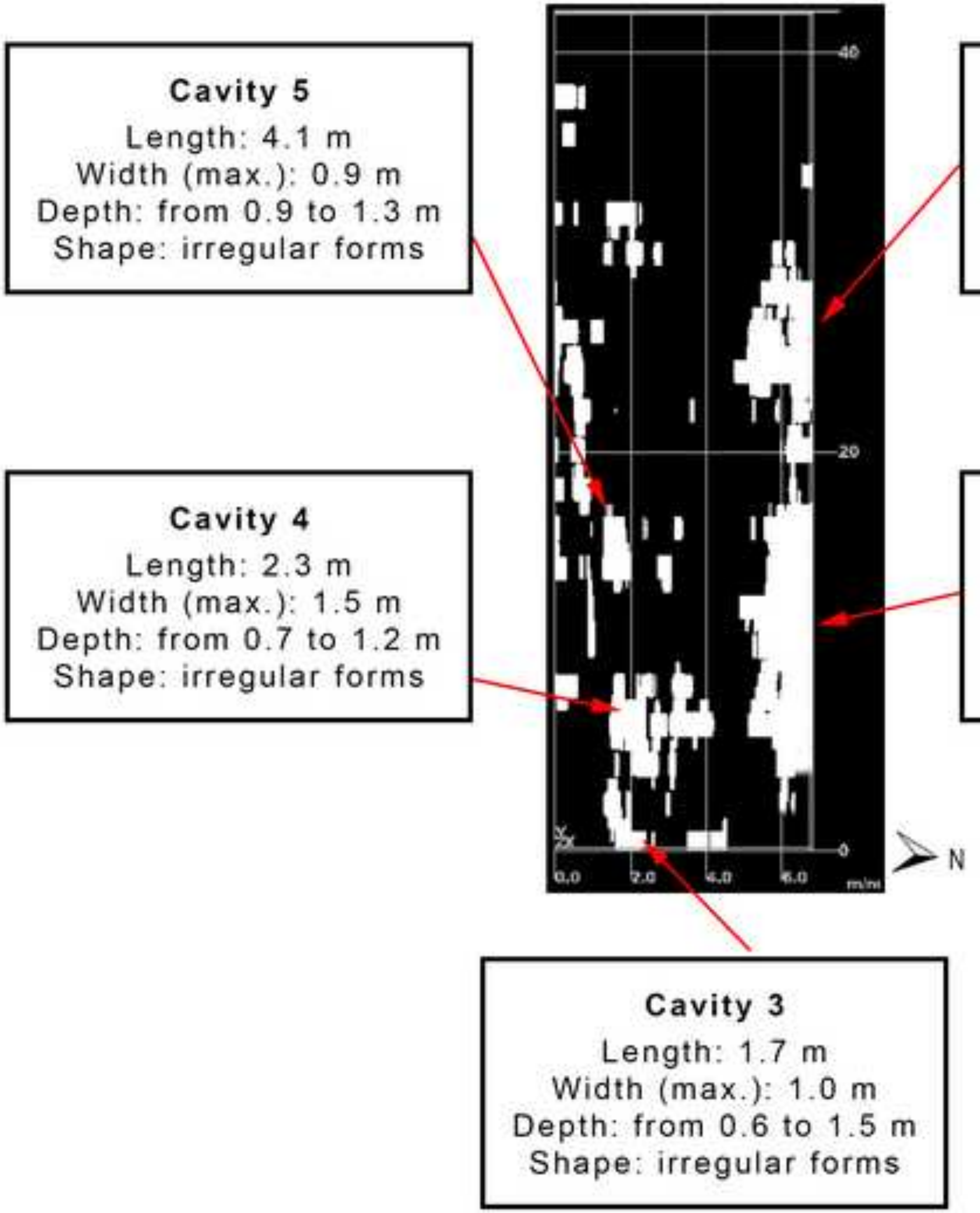

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