

Article

An Integrated and Hierarchical Geophysical Workflow for Subsurface Cavity Assessment in Legacy Mining Districts

Javier Rey ¹, Francisco José Martínez-Moreno ², Isabella Sánchez-Sosa ¹ and María del Carmen Hidalgo ^{1,*}

¹ Department of Geology and CEAITEMA, Higher Polytechnic School of Linares, University of Jaen, Technological Scientific Campus, 23700 Linares, Spain; jrey@ujaen.es (J.R.); iss00016@red.ujaen.es (I.S.-S.)

² Geodynamics, Stratigraphy and Paleontology Department, Faculty of Geological Science, Complutense University of Madrid, Ciudad Universitaria, C/José Antonio Novais n° 12, 28040 Madrid, Spain; fjmmoreno@ucm.es

* Correspondence: chidalgo@ujaen.es

Highlights

What are the main findings?

- FDEM provides high horizontal resolution to locate underground disturbance trends.
- Discontinuous anomalies delineate gallery collapses and sediment infills down to 30 m.

What are the implications of the main findings?

- Integrated geophysics effectively locates hidden abandoned mine cavities and assesses ground collapse risks.
- The multi-geophysics approach improves subsurface characterization for geohazard management.

Abstract

The presence of near-surface cavities poses a significant geohazard due to potential ground subsidence and structural collapse. To mitigate threats to urban stability, this study presents an integrated geophysical framework to locate and characterize abandoned mining galleries and exploitation voids near Linares (Jaén, Spain). The approach combines four complementary techniques: electrical resistivity tomography (ERT), ground-penetrating radar (GPR), frequency-domain electromagnetics (FDEM), and microgravity. The resulting multi-physics responses were cross-referenced with visible surface subsidence features and archival mine plans. Air-filled galleries and shafts generated highly pronounced high-resistivity anomalies. Shallow voids detected at depths of 2–5 m were undocumented in 19th-century mining maps, suggesting older historical origins, whereas deeper ERT profiles and structural disturbance trends (up to 30 m) correlated well with historical records. Within this framework, FDEM provided high-resolution lateral mapping, GPR excelled at resolving ultra-shallow structural boundaries, and ERT characterized deep gallery networks. Crucially, microgravity mitigated inversion non-uniqueness by directly confirming physical mass deficits over the anomalies. This integrated workflow overcomes individual resolution limits, offering a practical tool for land-use planning and early geohazard risk assessment in collapse-susceptible areas.

Keywords: electrical resistivity; frequency domain electromagnetic method; ground-penetrating radar; microgravimetry; voids; geohazards



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1. Introduction

The presence of cavities and galleries in the subsoil, whether of natural (karst systems) or anthropogenic origin (abandoned mining and urban infrastructure), represents a first-order geological hazard. The primary risk is land subsidence caused by void collapse or terrain deformation, leading to structural instability and economic damage [1–3]. Therefore, early identification of high-susceptibility collapse areas is critical for spatial planning and foundation design [1,3–5].

1.1. State of the Art

Geophysical prospecting has proven to be an essential methodology for locating and characterizing cavities by exploiting the contrast in physical properties between the void (filled with air or water) and the surrounding host rock. In the literature, numerous studies have reported the use of various techniques, whose success depends on the target depth and the resolution of the applied method [5–7].

Among individual techniques, electrical resistivity tomography (ERT) is a primary tool for mapping near-surface anomalies due to its high resolution and ability to distinguish between air-filled resistive voids and water- or clay-filled conductive zones [7–10]. For density-based detection, microgravimetry remains a robust technique for identifying mass deficits associated with subsurface voids, tunnels, mining galleries, and deep cavity systems [11–13]. In materials with low electromagnetic attenuation, ground-penetrating radar (GPR) also tends to yield satisfactory results and provides the highest resolution for defining the geometry and depth of very shallow cavities, typically within the first few meters of the subsoil [14]. Electromagnetic techniques in the time domain allow for rapid spatial coverage, which is advantageous for mapping vast areas [15]. Additionally, seismic methods including scattered-wave imaging have shown promise in identifying zones of mechanical weakness in complex urban environments [16].

To address the inherent limitations and interpretive ambiguities of single-technique surveys, the use of at least two different methods is necessary to reduce indeterminacy and ensure structural consistency between different physical models [17–23]. Furthermore, contemporary research emphasizes the integrated use of multiple geophysical methods to reduce uncertainty and avoid erroneous interpretations [24–28]. Recent studies applying multi-method integration incorporate spatially constrained inversion, probabilistic approaches, and deep learning-based methods [29–32].

1.2. Research Focus

This study proposes a multi-geophysical workflow to locate and characterize shallow, unmapped mining voids within the Linares metallogenic district (SE Spain; Figure 1). This historical underground mining area is characterized by vein-type mineralization hosted in granitic basements, where small, shallow cavities are often partially backfilled with granitic debris and surficial clays.

The primary objective is to integrate ERT, microgravimetry, and GPR with FDEM—the latter being an electromagnetic technique whose application remains heavily underreported in this specific context, particularly at depths exceeding 6.5 m [15]. By coupling these four complementary methods, this work establishes an optimized, cost-effective survey and decision-support framework to prioritize underground mining hazards for land-use planning and civil engineering.

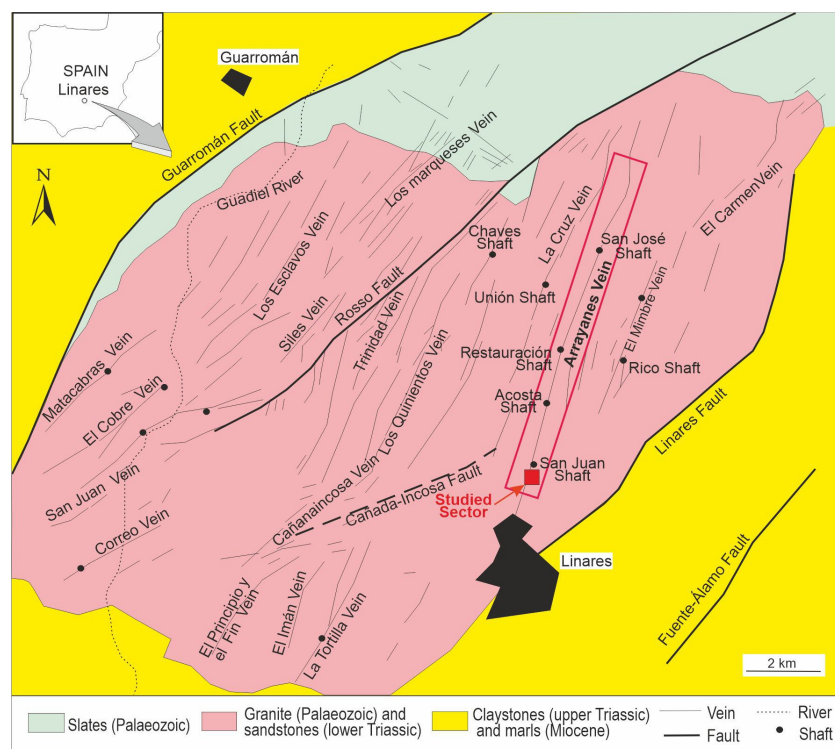


Figure 1. Geographic and geological setting of the study area. The inset highlights the boundaries of the Arrayanes mining concession. The locations of the San Juan shaft and the investigated sector are indicated.

2. Geological and Mining Context

The Linares mining district is characterized by the presence of galena (PbS) deposits, which are hosted within a Paleozoic basement as subvertical, NE–SW-trending veins. This basement is essentially composed of a granitic igneous batholith that intruded into a highly deformed Paleozoic slate (Figure 1). The entire assemblage (slates, granite and veins) is unconformably overlain by a sedimentary cover comprising Triassic sandstones and red shales, Miocene marls and marly limestones and Quaternary alluvial facies [33,34]. The mineralization was concentrated within the vein unit in areas enriched with lenticular ore bodies. Although galena was the primary mineral exploited, the paragenesis also included other minerals such as sphalerite (ZnS), pyrite (FeS₂), chalcopyrite (CuFeS₂), argentite (Ag₂S) and barite (BaSO₄), among others [33,35].

This district contains a vast network of historical concessions (totaling 1011 in 1890), whose boundaries and designations evolved over time [36]. Among these, the “Arrayanes concession” is the most emblematic due to its exceptional mineral wealth and long history. Located northeast of Linares (Figure 1), this rectangular concession features a N23°E orientation parallel to the veins, spanning a total length of over 14 km. Essentially, the focus of this work was on four aligned veins, all of which are subvertical and embedded in granite: the main vein, also known as San José, San Ignacio, Zulueta, and Ocharán.

At present, two features are most characteristic of this concession and, in general, of the entire mining district. On the one hand, the subsurface contains extensive voids from historical mining that reach depths of up to 600 m. This network is estimated to include over 780 km of galleries, approximately 60 km of main shafts, and numerous production chambers [36]. On the other hand, at the surface, there is the presence of relatively extensive sectors occupied by the ruins of old mining facilities, as well as waste dumps from historical mineral processing and metallurgical activities.

This study was conducted on the San José vein, near the Acosta shaft (Figure 1). Historical documentation shows that this shaft was already active in 1749, reaching its peak in 1867 and attaining a final depth of 497 m [36]. However, in the vicinity, there are much older works, which in some cases date back to Roman times, utilizing primitive exploitation methods that were very superficial and limited exclusively to the most enriched sectors of the vein. Because the mine was abandoned over 60 years ago and the regional district closed more than 30 years ago, historical archives for these ancient, ultra-shallow works are scarce or non-existent, leaving a significant information gap regarding shallow subsurface stability.

The only available partial documentation on mining operations in the immediate study area consists of surviving plans from 1846 and 1910 preserved in the historical mine archive, as shown in Figure 2. In the upper part (Figure 2A), the projection onto a vertical plane of these documented workings is shown, including shafts, galleries and voids generated during exploitation (mining voids in Figure 2). Similar to other sectors of the mining district, these cavities are likely partially filled with gangue or even with Triassic clays carried by water from the surface. The positions of the seven ERT profiles obtained in this study (ERT 1, ERT 1B, ERT 2, ERT 3, ERT 4, ERT 5, and ERT 6) are shown in Figure 2. The lower panel (Figure 2B) shows the plan view of levels 2 and 4 of the mine. These are sinuous galleries that bifurcate in some sections. The displacement of the projections of levels 2 and 4 suggests a downward progression of the workings towards the southeast, conditioned by the dip of the mined vein. Notably, the 1910 documentation refers to the presence of much older, undocumented mining operations on level 2, between the Mantecón shaft and the San Juan shaft (“older mining voids” in Figure 2A), for which no mine plans were preserved. Specifically, the surface traces of these unmapped cavities coincide with both the ground subsidence and the surface trace of the mineralized vein, which strongly suggests the collapse of these shallow structures (Figure 3).

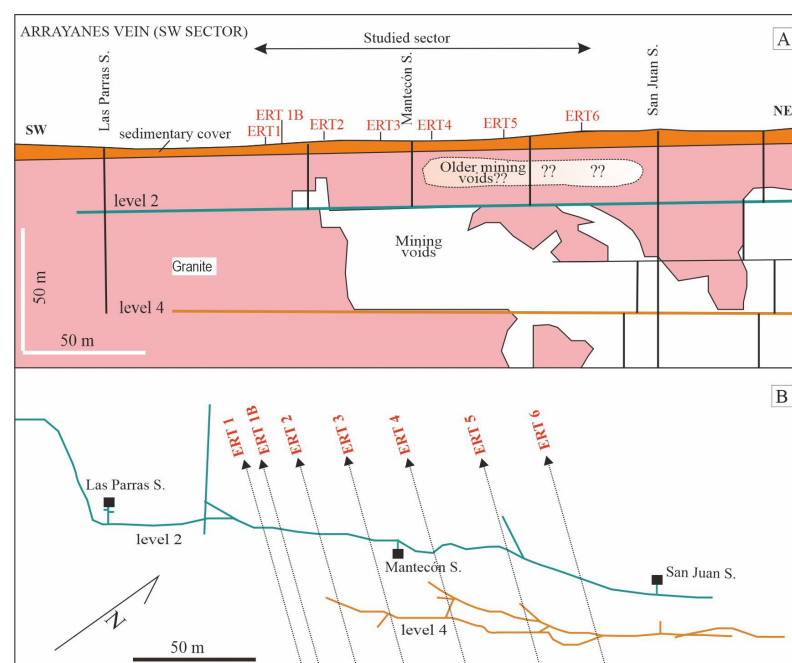


Figure 2. (A) Historical mine plan of the Arrayanes concession along the southwestern sector of the San José vein; the position of the studied sector is indicated. Alphanumeric codes ERT 1 through ERT 6 mark the location of the electrical resistivity tomography profiles presented in Figure 4. (B) Planview projection of underground galleries 2 and 4, showing the main shafts and the superimposed traces of the ERT profiles.

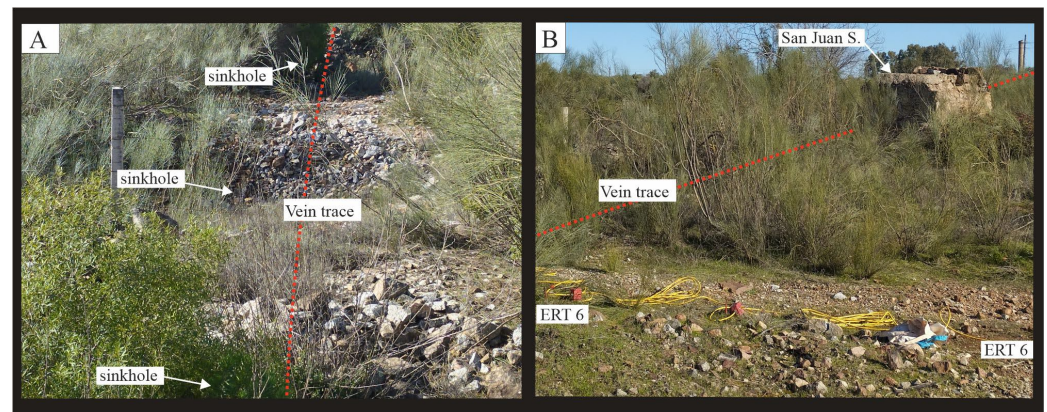


Figure 3. (A) Field photograph taken from an elevation of approximately 2 m above ground level looking southwest (SW) along the strike of the vein; surface subsidence is visible above the remains of the San Juan shaft. (B) Ground-level photograph looking northeast (NE) along the strike of the vein, showing the location of profile ERT 6, near the San Juan shaft.

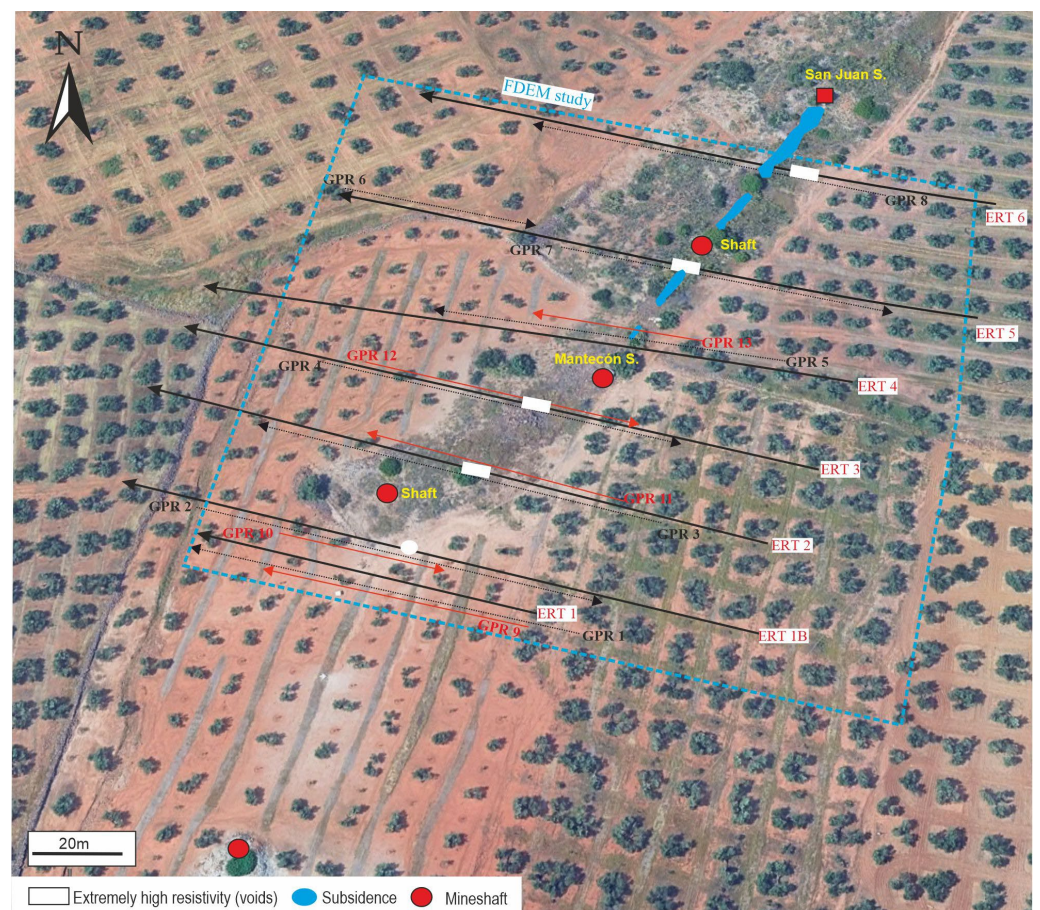


Figure 4. Aerial orthophoto map of the investigated sector showing the positions of the electrical resistivity tomography (ERT 1–ERT 6) profiles, the ground-penetrating radar (GPR) transects, and the frequency-domain electromagnetic (FDEM) survey grid. Microgravimetric profiles 2 and 3 are co-located with the trajectories of profiles ERT 2 and ERT 3, respectively.

3. Materials and Methods

The choice of the four geophysical prospecting methods (ERT, GPR, FDEM technique and gravimetry) corresponds to the need to contrast different physical properties of the subsol to obtain a robust interpretation. The combined application of these methods allows,

on the one hand, a reduction in the degree of uncertainty inherent in the interpretation of the results obtained through a single indirect technique. On the other hand, it allows the comparison of the potentialities and limitations of each of these techniques to delimit both the cavities and the host rock. For any of these techniques to be effective, it is essential that there is sufficient physical contrast (in resistivity, dielectric properties or density) between the cavity and its surroundings. In the next section, each of the methods used is introduced.

3.1. Electrical Resistivity Tomography (ERT)

The measurement of resistivity has proven to be effective for determining the location of cavities in mining areas [20,22,37,38] since the air-filled voids act as a dielectric (positive resistive anomaly). However, when they are filled with water or lutitic material, they result in a negative resistive anomaly in the granitic assemblage. ERT consists of determining the distribution of resistivity in the subsoil from a very high number of measurements taken from the ground surface. It is based on the installation of numerous electrodes along profiles, with a spacing determined by the desired resolution and investigation depth: the smaller the electrode spacing, the higher the resolution; the larger the spacing, the greater the investigation depth [39–43]. The electrodes are connected to the measuring equipment, and a specific sequential program is used to select the electrodes that should be working at different times, as well as their arrangement [42,43].

The advantages of this technique include its high vertical/lateral resolution, which allows 2D representations, and its remarkable penetration depth. However, it has an important limitation: the need to nail electrodes into the substrate to guarantee the passage of electric current and its proper propagation in highly resistive materials such as granite. The Wenner–Schlumberger device was chosen for this work, since it has good sensitivity for detecting horizontal structures (sedimentary cover) as well as vertical structures (fractures, veins or gallery walls in the granite). In addition, this device is less sensitive to noise than the Dipole–Dipole device [38,44].

The ERT equipment used was the RESECS system from Deutsche Montan Technologie (DMT, Essen, Germany). In this work, seven ERT profiles were obtained perpendicular to the trace of the vein. This trace can be followed approximately in aerial photography by the alignment of the different mining indications existing in the area and coincides, in some cases, with the presence of sinkholes (Figures 3 and 4). For the first profile (ERT 1), an electrode spacing of 1 m and a total of 80 electrodes were used, which means a total length of 79 m for the profile (maximum distance AB). A total of 1455 measurements were taken in the field, and a depth of 16.9 m was reached (Figure 5A). The remaining profiles (Profiles ERT 1B, ERT 2, ERT 3, ERT 4, ERT 5 and ERT 6) were obtained at a spacing of 1.5 m and a total of 96 electrodes (maximum distance AB of 142.5 m, Table 1). Overall, 2097 measurements were obtained per profile, and a vertical depth of 28.8 m was reached (Figure 5B). In all cases, both the on-injection time and the off-injection time were 350 ms, and the delay was 100 ms. To ensure maximum data quality and evaluate experimental noise, each measurement was acquired using a minimum of 2 and a maximum of 4 automatic stacks; readings exhibiting standard deviation errors exceeding 2% were rejected in the field. The apparent resistivity values obtained in the field were preprocessed using PROSYS II (IRIS Instruments, version 03.14). It is a useful software to download and process resistivity measurements, allowing raw data to be visualized as graphs and erroneous data points (i.e., data with standard deviations from the mean or values that produce peaks in comparison with surrounding measurements) to be isolated and removed before exporting them to the specific inversion software RES2DINV (version 4.10).

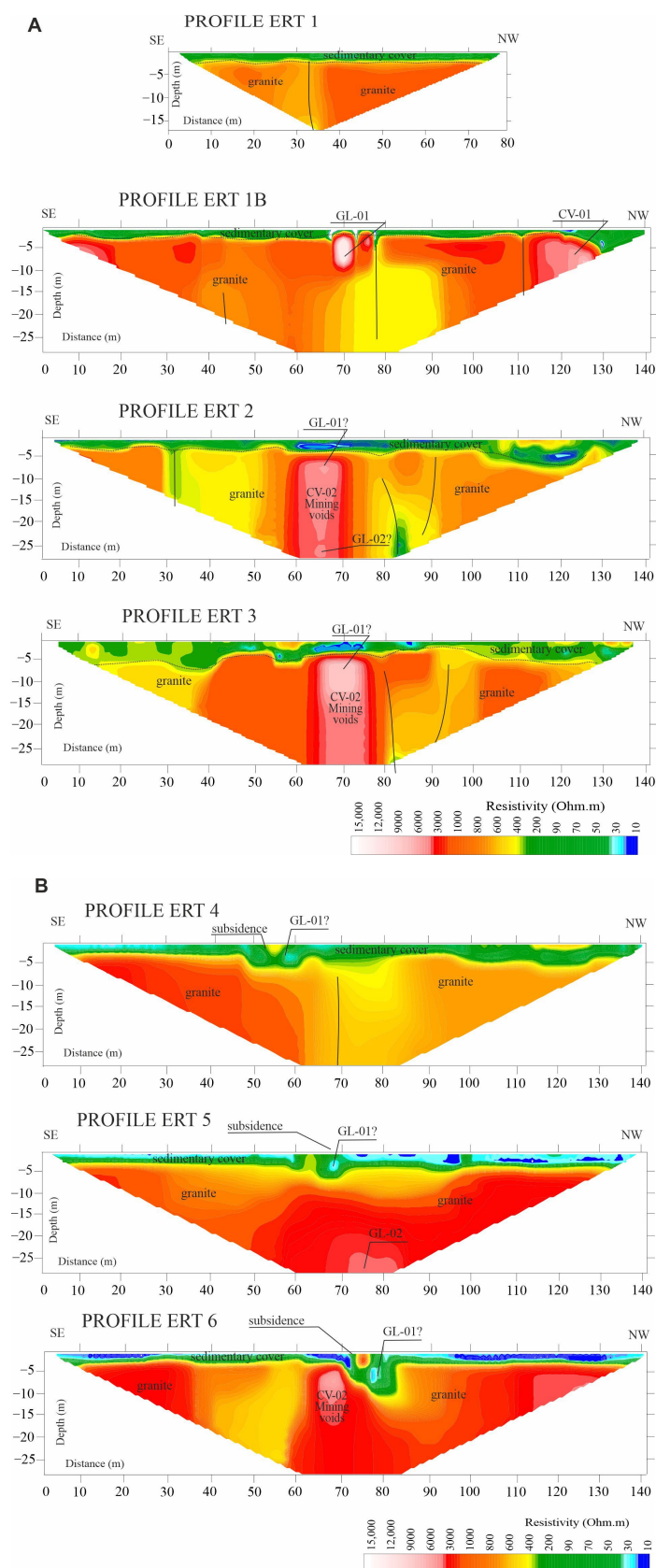


Figure 5. (A) Electrical resistivity tomography profiles (ERT 1, ERT 1B, ERT 2 and ERT 3). Positions for all profiles are detailed in Figures 2 and 4. GL-01: near-surface gallery absent from historical mine plans. GL-2: gallery (level 2 in the historical mine plans of Figure 2). CV-01: potential cavity located within the southwestern (SW) sector, exhibiting no spatial correlation with known vein trace mining

voids. CV-02: cavity directly co-located with the mineralized vein (mining voids). (B) Electrical resistivity tomography profiles (ERT 4, ERT 5 and ERT 6). Positions for all profiles are detailed in Figures 2 and 4. GL-01: near-surface gallery not included in the historical mine plans. GL-2: gallery (level 2 in the historical mine plans of Figure 2). CV-01: potential cavity located within the southwestern (SW) sector, exhibiting no spatial correlation with known vein trace mining voids. CV-02: cavity co-located with the mineralized vein (mining voids).

Table 1. Characteristics of the acquired ERT profiles.

Profile	Total Length (m)	Electrodes Space (m)	Electrodes Required	Electrode Configuration	Measurements	Iterations	RMS %	Maximum Depth (m)
ERT 1	79	1	80	Wenner-Schlumberger	1455	4	2.6	16.9
ERT1B	142.5	1.5	96	Wenner-Schlumberger	2097	4	2.8	28.8
ERT 2	142.5	1.5	96	Wenner-Schlumberger	2097	5	4	28.8
ERT 3	142.5	1.5	96	Wenner-Schlumberger	2097	7	1.59	28.8
ERT 4	142.5	1.5	96	Wenner-Schlumberger	2097	5	5.4	28.8
ERT 5	142.5	1.5	96	Wenner-Schlumberger	2097	3	9.1	28.8
ERT 6	142.5	1.5	96	Wenner-Schlumberger	2097	5	3	28.8

Forward modeling was performed using the finite-element method, configured with a 4-node option between adjacent electrodes and the finest vertical mesh refinement to ensure high numerical precision in regions with sharp structural gradients [45,46].

To balance data misfit and model roughness, and the potential field noise typical of high-resistivity cavity environments, a dual-constrained inversion strategy was deployed within the RES2DINVx64 (version 4.9.17) software [42]. Specifically, a robust inversion (L1-norm) data constraint with a cutoff factor of 0.005 was applied to minimize the impact of non-Gaussian field errors and electrode coupling artifacts [44,45]. Simultaneously, this was coupled with a smoothness-constrained (L2-norm) least-squares model constraint by enabling the preservation of smoothness-constrained model resistivity values [44,46]. This hybrid configuration strikes an optimal balance: the robust data constraint effectively mitigates data outliers, as expected across the interface between the cavity (air) and the host rock (granite), while the smoothness model constraint preserves the continuous regional geological framework (such as contacts between the granite and the sedimentary cover) and prevents the generation of localized numerical artifacts [47].

The inversion parameters were optimized to characterize the morphology and boundary ranges of the deep resistive anomalies while minimizing edge effects:

- (1) Initial and minimum damping: An initial damping factor of 0.15 was selected, with a minimum allowed damping factor of 0.02 to prevent overfitting while maintaining mathematical stability.
- (2) Near-surface and edge adjustments: A higher damping factor of 5.00 was applied specifically to the first layer to stabilize the near-surface solution. Furthermore, the damping factors were systematically increased at the model boundaries to mitigate artificial edge effects.
- (3) Geometric and depth adjustments: Damping factors were automatically adjusted to account for variations in the horizontal distance between the model blocks. To counteract the exponential decrease in resolution inherent to the DC resistivity method with depth [48], the damping factor was progressively scaled by a factor of 1.05 for each successive layer down to the maximum investigation depth of 25 m.

To systematically verify that the identified deep high-resistivity anomalies (extending down to 25 m) correspond to physical cavities rather than inversion artifacts, model sensitivity values and depth of investigation (DOI) thresholds were calculated using the model sensitivity option in RES2DINV [47,48]. This metric quantifies the degree to which a perturbation in the resistivity of a specific model block affects the calculated apparent resistivity forward response. Only anomalies located within model regions exhibiting

normalized sensitivity values well above background threshold levels were retained for structural interpretation, thereby ensuring high reliability at depth. The inversion process was limited to a maximum of seven iterations. As a limit of convergence (a condition to stop the iterative procedure), a change of 1% in the root mean square (RMS) between two consecutive iterations was selected. The program stops when the RMS adjustment error is less than this limit. In this study, the quality of the data was good for all profiles. Thus, the RMS errors of the final resistivity models for Profiles ERT 1, ERT 1B, ERT 2, ERT 3, ERT 4, ERT 5 and ERT 6 were 2.6%, 2.8%, 4.0%, 1.59%, 5.4%, 9.1% and 3.0%, respectively (4th, 4th, 5th, 7th, 5th, 3rd and 5th iterations, respectively).

Furthermore, since underground mining galleries and shafts are inherently three-dimensional features, 2D ERT inversion profiles are susceptible to 3D side-block effects (out-of-plane anomalies). To strictly minimize these distortions, two complementary strategies were implemented: (1) the acquisition profiles were oriented perpendicular (SE–NW) to the dominant structural strike (NE–SW) of the mineralized veins, and (2) the “reduce effect of side blocks” option was explicitly enabled within the RES2DINV settings [49]. This mathematical constraint applies a damping factor to the weighting of the outermost lateral model blocks, effectively suppressing off-line artifacts and ensuring that the inverted high-resistivity anomalies accurately represent the true in-plane lateral and depth positions of the subsurface voids.

The results obtained were subsequently processed with the SURFER 13 program, which offers the possibility of representing the variation in the resistivities in the profiles in a continuous and progressive way.

3.2. Ground Penetrating Radar (GPR)

GPR is based on the emission of high-frequency electromagnetic pulses through an emitting antenna that moves continuously over the ground surface. The signal propagates through the substrate and is partially reflected at contact surfaces that separate materials with different dielectric constants [50], such as the interface between the cover and the granite, fractures in the granite or the boundary between the rock and a void filled with air or water. The penetration depth and resolution depend on the electromagnetic properties of the materials traversed and the antenna used. Thus, the propagation of waves in the subsoil decreases when the conductivity of the ground increases or when the frequency of the transmitted signal increases [42,51]. For the same profile, when higher-frequency antennas are used, higher resolution and lower penetration depth are obtained, which is reversed when the frequency is decreased [43]. A detailed description of the method is reported in numerous studies [39,50–52].

GPR has the highest resolution for the detection of shallow cavities and the definition of their geometry [39]. However, the maximum depth of investigation is highly dependent on the conductivity of the material traversed such that the presence of very conductive materials (in this case, Triassic clays overlying the granite) becomes a limiting factor.

The equipment used in this study was a Pro-Ex RAMAC/GPR system manufactured by MALA GEOSCIENCE (Mala, Sweden). The GPR profiles were acquired for the same traces that were used to obtain the ERT profiles (Figure 4). In total, 13 profiles were obtained in the Y direction (perpendicular to the trace of the vein), using both the 100 MHz antenna (GPR 1, GPR 2, GPR 3, GPR 4, GPR 5, GPR 6, GPR 7 and GPR 8 in Figure 4) and the 250 MHz antenna (GPR 9, GPR 10, GPR 11, GPR 12 and GPR 13 in Figure 4).

Ground Vision was used as the data acquisition program. All the profiles had a trace spacing of 0.018 m and a “time window” equal to 308 ns (312 samples per trace) for the 100 MHz antenna and 158 ns (416 samples per trace) for the 250 MHz antenna. The signal obtained in the field was processed using the software Reflexw, version 4.9.17 [53].

The processing workflow was based on deterministic physical criteria to prevent artifacts and avoid attenuating target reflections. First, a static correction filter (“move start-timing”) was applied to adjust the time-zero position with a -12 ns shift, aligning the first wave arrival with the ground surface. To eliminate low-frequency continuous voltage drift (wow noise), a “subtract mean (dewow)” filter was applied with an 8 ns time window, corresponding to two full cycles of the 250 MHz antenna’s nominal frequency. The average electromagnetic wave velocity was determined through a rigorous analysis of representative diffraction hyperbolas using the ‘velocity adaptation’ tool, following the common-offset analysis criteria outlined in [54], yielding an effective subsurface velocity of 0.098 m/ns. While pristine, dry granite typically exhibits higher velocities (0.12–0.15 m/ns), this lower value is physically representative of the combined response of the sedimentary cover and the underlying altered granite. Subsequently, a “time cut” filter was applied at 70 ns to truncate late-time noise and remove non-informative deep reflections. To suppress direct wave coupling and continuous horizontal banding, a “background removal” filter was implemented using a 30-trace spatial window, effectively preserving localized hyperbolic geometry while eliminating regional continuous reflectors. To resolve low-frequency instrumentation noise, a “subtract DC shift” filter was applied over the entire trace length. Signal attenuation due to geometric spreading and material absorption was compensated for by applying a customized “manual gain” function along the time axis (Y-axis) to balance shallow and deep responses. This gain function was configured with a start time of 10 ns to avoid surface wave saturation, applying a progressive linear-exponential amplification factor (ranging from 1 to 15) up to 50 ns to effectively compensate for signal attenuation in the deeper layers. Finally, a spatial “running average” filter (three-trace window) was applied to enhance horizontal continuity and smooth high-frequency spatial noise.

To quantitatively evaluate the efficiency of the processing sequence, the signal-to-noise ratio (SNR) was calculated before and after filtering using the following expression [55]:

$$\text{SNR} = 20 \log_{10} (A_{\text{signal}}/A_{\text{noise}})$$

where A_{signal} represents the root-mean-square (RMS) amplitude within a time-spatial window containing the cavity’s reflection hyperbola, and A_{noise} is the RMS amplitude of an adjacent background noise zone. The processing workflow significantly enhanced hyperbola visibility, increasing the local SNR from an average of 4.3 dB in the raw data to 15.6 dB in the final profile. Typical profiles comparing the raw and processed data are presented in Figure 6, highlighting the preservation of the target hyperbola and the effective suppression of background clutter.

Subsequently, data acquisition was expanded using a 100 MHz antenna to achieve greater penetration depth, applying an analogous processing workflow with parameters adapted to the lower nominal frequency. For this dataset, the static correction (“move start-timing”) involved a -38 ns time-zero shift. To accommodate the longer wavelength, the “subtract mean (dewow)” time window was increased to 20 ns, corresponding to two full cycles of the 100 MHz signal. Due to the deeper investigation range, the “time cut” was extended to 120 ns, and the manual gain function was adjusted to progressively scale up to 90 ns to balance the stronger attenuation at greater depths. Hyperbola fitting via the “velocity adaptation” tool yielded a consistent velocity of 0.098 m/ns, confirming the homogeneity of the granitic host rock across scales. The background removal (30 traces) and spatial running average (3 traces) filters were maintained to ensure consistency in artifact suppression. This complementary processing yielded a local SNR improvement from 3.8 dB to 14.1 dB in the final profile, providing a clearer visualization of the deeper sections of the target gallery.

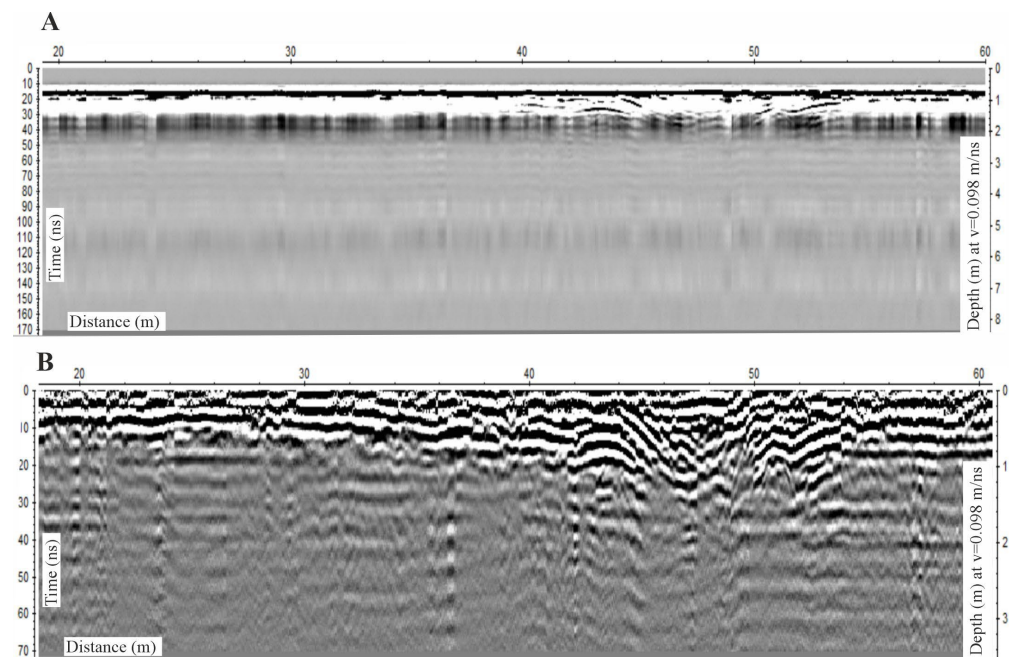


Figure 6. Ground-penetrating radar profile (GPR 12): (A) unprocessed (raw) radargram displaying original subsurface reflections; (B) corresponding radargram after application of the optimized processing sequence.

3.3. Frequency Domain Electromagnetic (FDEM) Technique

The frequency-domain electromagnetic (FDEM) or electromagnetic induction (EMI) technique is based on the physical principles of mutual electromagnetic coupling over a conductive ground [56]. The method involves circulating an alternating current of a known frequency through a transmitting coil to generate a primary magnetic field, which propagates through both the air and the subsurface. In the presence of a conducting medium, this primary field induces eddy currents that generate a secondary magnetic field (H_s). The receiving coil, positioned at a specific intercoil spacing (s), detects the total field resulting from the superposition of the primary and secondary fields [39,42]. Under low-induction-number (LIN) conditions, the quadrature component of the magnetic field ratio is approximately proportional to the apparent electrical conductivity (σ_a) of the ground. However, this measured property represents a complex spatial average of localized subsurface conductivities within the instrument's sample volume [57,58]. The 3D sensitivity distribution within this volume is highly non-uniform and exhibits both positive and negative local sensitivities depending on the coil orientation (horizontal or vertical coplanar modes), which must be critically evaluated when characterizing structural boundaries [57,58]. Furthermore, quantitative interpretation of raw EMI data requires strict calibration workflows, often utilizing co-located, robust electrical resistivity tomography (ERT) profiles to correct for instrumental drifts and shifts before inversion [59].

While EMI methods are widely recognized for their high sampling density and rapid operational speed over vast survey areas, their application to deep subsurface targets—specifically the detection of resistive mining cavities at depths approaching several tens of meters—poses substantial methodological challenges. Unlike traditional shallow characterizations, identifying deep, highly resistive voids is heavily constrained by the investigation depth and the inherent decrease in vertical resolution with depth [60].

In this work, two devices from GF Instruments (Brno, Czech Republic) were used. First, the CMD-DUO was used, which allows working with three separation lengths between the two coils (10, 20 and 40 m) and has an acquisition frequency of 0.93 kHz. When operating

in horizontal dipole mode (HDM), the approximate depths of investigation are 7.5, 15 and 30 m, respectively, in relation to each of the separations of the coils. A total of 2300, 1723 and 1986 measurement points were obtained for each of these three coil configurations. This extensive dataset provides excellent horizontal density for mapping lateral conductivity anomalies over the zone. However, because it acquires only three discrete measurement levels per station, the vertical resolution remains inherently restricted.

Second, the CMD-Explorer HVD equipment was used, with separations of 1.48 m, 2.82 m and 4.49 m between the emitting and receiving antennas and an acquisition frequency of 10 kHz, allowing simultaneous investigation at three depth ranges: 2.2 m, 4.4 m and 6.7 m. A total of 1690 conductivity measurement points corresponding to these three data acquisition bands were acquired. All data acquired were georeferenced by differential global positioning system (GPS) with centimeter-level precision. A grid of profiles parallel to those acquired with the previous techniques was designed (Figure 4), aligned perpendicularly to the trace of the vein. Measurements were performed continuously, with values taken every second. With the CMD-DUO equipment, the profiles were repeated using different separations between the coils. The same profiles were also acquired with the CMD-Explorer equipment.

The FDEM survey layout was designed to effectively cover the mineralized zone while adapting to local field constraints. A total of 14 parallel profiles were executed perpendicularly to the surface trace of the mineralized vein. To ensure systematic spatial coverage, a line spacing of 10 m was established between adjacent profiles. The data acquisition tracks were strategically placed within the existing lanes between the rows of olive trees, which provided clear lines of sight and minimized surface interference. This layout is bounded by the survey perimeter shown in Figure 4.

The apparent conductivity data collected in the field were transformed with the CMD Data Transfer program and processed jointly, applying filtering techniques and an inversion using the Occam method, implemented in the software EM4Soil version 1.4 (EMTOMO). The conductivity model was subsequently transformed to resistivity for comparison with the ERT models.

3.4. Gravimetric Prospecting

The microgravimetric method is based on the surface measurement of small variations in the vertical component of the terrestrial gravity field. Once the corresponding corrections were made (including latitude, free-air, topographic, Bouguer, temporal, and instrumental drift corrections), the resulting variations or anomalies were related to the presence of bodies with anomalous densities in the subsurface [43]. This method has been widely used in geology to identify antiform structures, salt domes, and thickness variations in sedimentary cover over the basement, as well as to locate mineral deposits [39,43]. In engineering and environmental geophysics, the method is highly effective for detecting subsurface voids—such as abandoned mine workings, shafts, and karstic features—because the physical contrast between the host rock and an empty or water-filled cavity generates distinct localized negative gravity anomalies [11–13,19,61,62]. However, a fundamental challenge in gravity interpretation is its inherent mathematical non-uniqueness, meaning that an infinite number of subsurface density configurations can produce the exact same surface anomaly. Furthermore, as highlighted in [63], these anomalies rarely represent idealized, sharp-walled open voids; instead, they often encompass broader zones of “low-density ground” caused by partial structural collapse, fracturing of the overburden rock mass, or poorly consolidated migrated material. Consequently, evaluating alternative models, sensitivity to geometry, and assumed density contrasts is mandatory, and final interpreta-

tions must be strictly coupled with independent geological constraints or complementary geophysical datasets [61].

In this study, a Scintrex Autograv model CG-5 gravimeter (Concord, Toronto, ON, Canada) was used, with a precision of up to 0.001 mGal. The positions of the measurement stations and the elevations were measured with the Topcon Hiper SR Differential GPS equipment (Livermore, CA, USA), with centimeter-level accuracy. The acquired data were processed and modeled with the Oasis Montaj software version 9, applying the corrections described above. The data were acquired along two lines coinciding with profiles ERT 2 and ERT 3. The spacing of the measurements was 2 m in both profiles, which was reduced to 1 m in the central zone to maximize lateral resolution and capture steep gravity gradients. The length of each profile was 100 m.

To overcome the non-uniqueness inherent to gravity data inversion, a forward modeling approach was adopted. The structural boundaries and depths obtained from co-located ERT profiles were used as initial geometric constraints rather than fixed boundary solutions. While microgravity data alone require a physical mass deficit, they cannot uniquely resolve sharp geometry. Thus, gravity modeling served as an independent physical validation to confirm that a mass deficit exists at the targeted locations, while accounting for density contrasts that may represent open voids, partially backfilled structures, or highly fractured, low-density host rock.

4. Results and Discussion

4.1. Electrical Resistivity Tomography Results

The ERT profiles were analyzed to deduce the geological model of the sector. Thus, in Profile ERT 1 (Figure 5A), the most superficial zone presented generally low resistivity values (30–70 Ω m). This set was interpreted as a detrital sedimentary cover, consisting of sandstone bodies immersed in lutitic facies (Triassic materials), which agrees with direct observations made in the outcrops. Small variations in the thickness of this sedimentary cover in nearby sectors were observed between 1 and 2 m. These variations in thickness are justified by the irregular morphology of the roof of the basement [64]. Under this sedimentary cover is the Paleozoic basement, which consists of granitoids with very high resistivities, with values between 400 and 2000 Ω m. However, the contrast in the resistivity values between the two units was not completely abrupt but increased rapidly and progressively with depth. This is because the granite roof is altered. This transition zone had resistivity values ranging between 250 and 400 Ω m. It was also determined from profile ERT 1 that the resistivity values in the granite were not laterally uniform. Thus, approximately in the central zone of the profile, a decrease in values was detected that coincided with the trace of the San José vein. This anomaly can be attributed to subvertical fractures associated with this vein, water circulation or even the mineralization itself. This decrease in resistivity values seemed more pronounced in the deepest part of profile ERT 1. The length of the remaining profiles was increased by using a greater number of electrodes and increasing the interelectrode spacing (maximum distance AB increased from 79 m in profile ERT 1 to 142.5 m in Profile 1B).

Although profiles ERT 1 and ERT 1B were obtained at sites very close to each other (Figure 4), the greater depth reached in profile ERT 1B (28.8 m versus 16.9 m) allowed better detection of the zones that coincided with the trace of the vein. This was characterized by a substantial drop in resistivity values, which decreased from 2000 to 400 Ω m. Adjacent to this zone and only 2–4 m deep, a closed and well-defined zone was identified, characterized by a sharp increase in resistivity values, which exceeded 20 k Ω m (GL-01 in Figure 5A). Another anomaly with similar values and depths was detected in the final part of the profile (between 120 m and 130 m from the origin; CV-01 in Figure 5A). Equivalent values have

been obtained in other mining districts with air-filled voids [9,10]. These two anomalies likely reflect small, very shallow exploitation pits with limited lateral extent, suggesting undocumented, small-scale mining operations. The first aligns with a possible shallow gallery following the vein trace, whereas the second exhibits a more irregular geometry consistent with a mining cavity.

In the remaining profiles, the sedimentary cover and the granite basement were clearly defined because of the marked contrast in resistivities (profiles ERT 2, ERT 3, ERT 4, ERT 5 and ERT 6). In various sectors, the contrast in resistivity within the Triassic facies was greater, which was associated with a greater development of detrital levels (sandstones and siliceous microconglomerates, with resistivities of up to 400 Ω m) alternating with lutites (10 Ω m). In the subsidence areas, the increase in surface resistivity was linked to anthropogenic fillings composed of granite blocks from old spoil heaps (Figure 3A).

In profiles ERT 2 and ERT 3 (Figure 5A), a strong positive resistivity anomaly was also identified, with values reaching 20 k Ω m. Unlike that observed in profile ERT 1B, this anomaly presented larger dimensions and a tendency to develop vertically. This vertical morphology could correspond to the mining voids of the vein (CV-02 in Figure 5A). In the historical mine plan of 1910 in Figure 2A, the existence of mining voids between levels 2 and 4 was confirmed at this position, and only punctual mining was recorded at level 2. However, the ERT profiles reveal that the positive resistivity anomalies were higher near the granite roof. This suggests mining activity after 1910 in the second gallery (GL-02 in Figure 5A). The vertical overlap of the three structures (GL-01, CV-02 and GL-02), characterized by strong resistivity anomalies, makes their differentiation difficult.

Profiles ERT 4, ERT 5 and ERT 6 are shown in Figure 5B. In profile ERT 4, the positive surface resistivity anomaly (GL-01) was not detected. However, subsidence was observed in the outcrop, which could be associated with collapse. This phenomenon would lead to a decrease or complete disappearance of the cavity and, consequently, of the resistive anomaly in the profile. The discontinuity in the trace of the gallery could be due to collapse and partial filling, which are frequent in shallow areas. These small voids are partially filled with gangue (loose granite boulders) and Triassic clays carried by water from the surface.

The position of profile ERT 5 coincided with an unexploited zone of the vein below the second level (Figure 2A). This would explain the absence of the vertical resistivity anomaly. However, at a depth of 25 m, a strong positive resistivity anomaly was detected (at approximately 73 and 77 m from the origin of the horizontal axis of the profile). Compared with the historical mining maps (Figure 2B), this anomaly is correlated with the position of the gallery on the second level, where there were even bifurcations (GL-02 in Figure 5A). With respect to the subsidence observed at the surface (Figure 4), in both profiles ERT 5 and ERT 6, negative resistivity anomalies were detected in the upper part, which indicated strong subsidence of the granite roof. This could be associated with the collapse of a near-surface gallery not included in the historical mine plans (GL-01 in Figure 5B). In the central position of profile ERT 6, the strong positive vertical anomaly associated with the mining pit was again detected (CV-02 in Figure 5B), in accordance with the information on mining operations presented in Figure 2.

Finally, at the northwest end of profile ERT 1B (Figure 5A), strong, near-surface positive anomalies were detected (CV-01). Since this area lies outside the main trace of the vein, these features cannot be directly correlated with mining cavities associated with its exploitation. Nevertheless, the possibility that they represent undocumented shallow workings cannot be ruled out.

4.2. Ground-Penetrating Radar Results

Five details of the profiles obtained with the 100 MHz antenna are shown in Figure 7A, and three details obtained with the 250 MHz antenna are shown in Figure 7B. Using the software Reflexw, the analysis of the reflection hyperbolas revealed the velocity of the waves in these lithologies to be 0.098 m/ns, which facilitated the conversion from time to depth in the radargrams. In the profiles obtained with the 100 MHz antenna, the contact between the sedimentary cover and the granitic basement was clearly differentiated. The stratified levels of Triassic sandstones and clays generated reflections with strong amplitudes, which allowed them to be distinguished from granite, with a more uniform response. The contact surface was approximately one meter deep, which was corroborated by direct field observations. Occasionally, coinciding with the trace of the mining shafts (and subsidence areas), this surface could present a concave morphology, with slopes of 1 to 2 m in depth. The bending of the layers, fossilized by higher levels, suggests subsidence phenomena associated with these geometries [10]. Beneath these conical morphologies, reflection hyperbolas appeared at depths of 2–4 m. The strong dielectric contrast between the granite and the filling of a cavity (air or loose material) would explain this response, which could be associated with small old collapsed mines: Profile GPR 3 (53–54 m from the origin), Profile GPR 5 (44–46 m from the origin) and Profile GPR 8 (34–36 m from the origin). These profiles also indicated the theoretical position occupied by a near-surface gallery not included in the historical mining maps, aligning with the trace of the vein. Although associated reflections were present in some cases (for example, at 30 m along Profile GPR), it was generally difficult to observe clear hyperbolic events to easily detect these cavities. The fact that these geometries lie at relatively greater depths could explain the signal attenuation, limiting their detectability.

The profiles obtained with the 250 MHz antenna allowed much better visualization of the contact between the sedimentary cover and the underlying granitic basement. Figure 7B shows three details of these GPR profiles in the vicinity of the mining shaft traces, areas affected by subsidence phenomena. Coinciding with these phenomena, the depression of the granite roof and the bending of the sedimentary cover, fossilized by filling materials, were detected in all profiles. These features suggest the collapse of small, very superficial mining voids [10,65]. In this context, directly above the granite basement along the vertical axis of these phenomena, hyperbolic diffractions were detected that could be related to the remains of these cavities, i.e., at 36–38, 46–48 and 22–26 m from the origin in profiles GPR 11, GPR 12 and GPR 13, respectively (GL-01 in Figure 7B).

4.3. Frequency Domain Electromagnetic Results

The survey limits for the FDEM technique are shown in Figure 4. Data were collected continuously at 1 s intervals along profiles perpendicular to the trace of the vein, coinciding with the directions of the ERT and GPR profiles.

In the upper part of Figure 8, three resistivity maps are shown at depths of 2.2 m, 4.4 m and 6.6 m, corresponding to the three acquisition channels of the CMD-Explorer equipment. In all cases, an anomaly is aligned along the NE-SW direction, coinciding with the trace of the vein. The anomalies exhibit higher values in the southwest sector. This response is consistent with the ERT profiles and is associated with the presence of shallow cavities. As observed in the ERT profiles, the anomalies were attenuated towards the northwest, which coincides with the surface subsidence. This finding reinforces the idea that cavity collapse occurred towards the northwest.

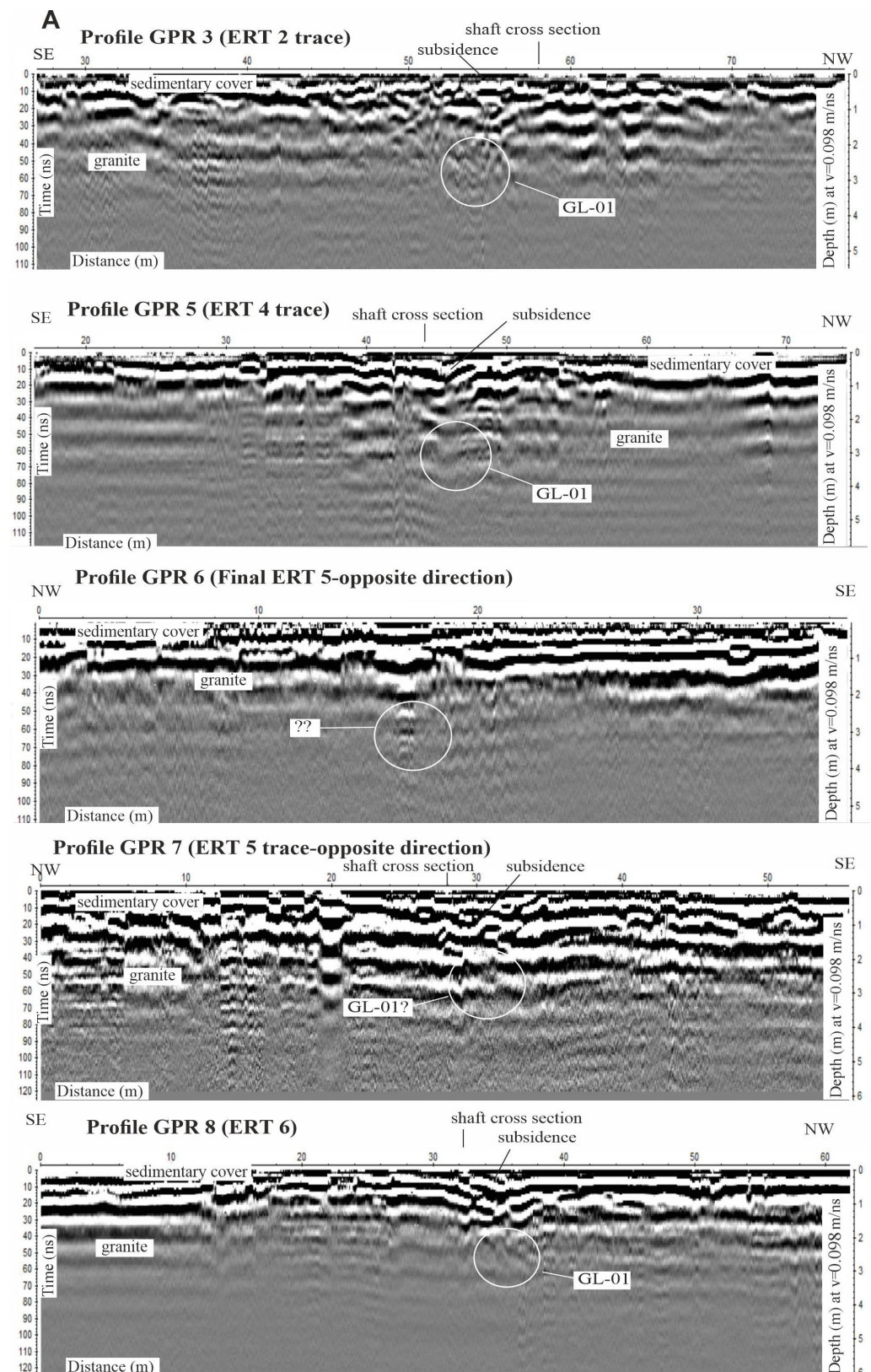


Figure 7. Cont.

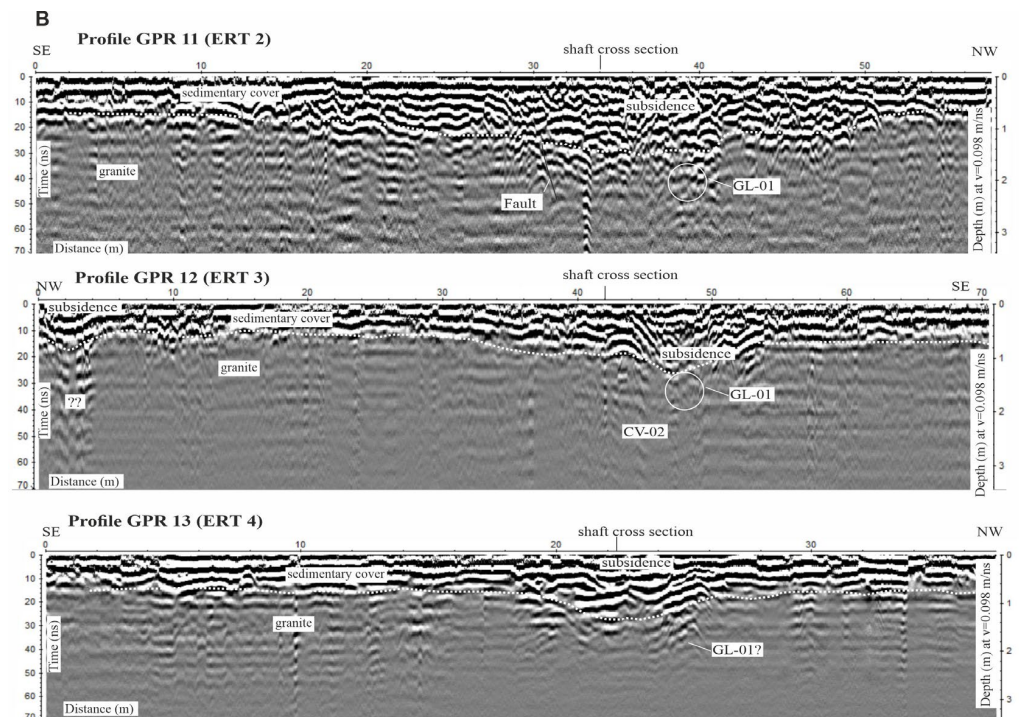


Figure 7. (A) Ground-penetrating radar (GPR) profiles acquired using a 100 MHz antenna. GL-01: near-surface gallery not included in the historical mine plans. (B) Ground-penetrating radar (GPR) profiles acquired using a 250 MHz antenna. GL-01: near-surface gallery not included in the historical mine plans. CV-02: cavity co-located with the mineralized vein (mining voids).

The slices at 7.5 m, 15 m and 30 m in Figure 8 correspond to the results obtained with the CMD-Duo equipment. In these images, higher resistive anomalies are observed coinciding with the trace of the vein in the southwestern sector. In the northeastern sector, between 15 and 30 m, strong anomalies are again detected, coinciding with those observed in profile ERT 6.

At depths of approximately 30 m (Figure 8), two disconnected conductivity anomalies were detected along the trace of the vein (one towards the southwest and another towards the outer northeast). Rather than resolving discrete void geometries at this depth, these broad anomalies delineate laterally extensive zones of mining-induced ground disturbance and fracturing along the structural strike of the vein. As illustrated in Figure 2, the main gallery workings were driven below the second level (>30 m depth), thereby approaching the upper resolution limits of the chosen FDEM configuration.

4.4. Gravimetric Results

Two gravimetric profiles were acquired along the same alignments as ERT Profiles 2 and 3, centered on the positions of the voids previously identified in those profiles (Figure 9). To facilitate comparison and joint interpretation, the distance scale of the gravimetric profiles was adjusted to coincide with that used in the ERT profiles, which served as the basis for their interpretation.

The interpretation of gravimetric data is inherently non-unique—a limitation known as the ambiguity problem—meaning that multiple density models can explain the same surface dataset. However, in this study, the gravimetric models were constrained by independent information provided by the ERT profiles, which reduced this ambiguity and yielded more realistic and geologically consistent solutions.

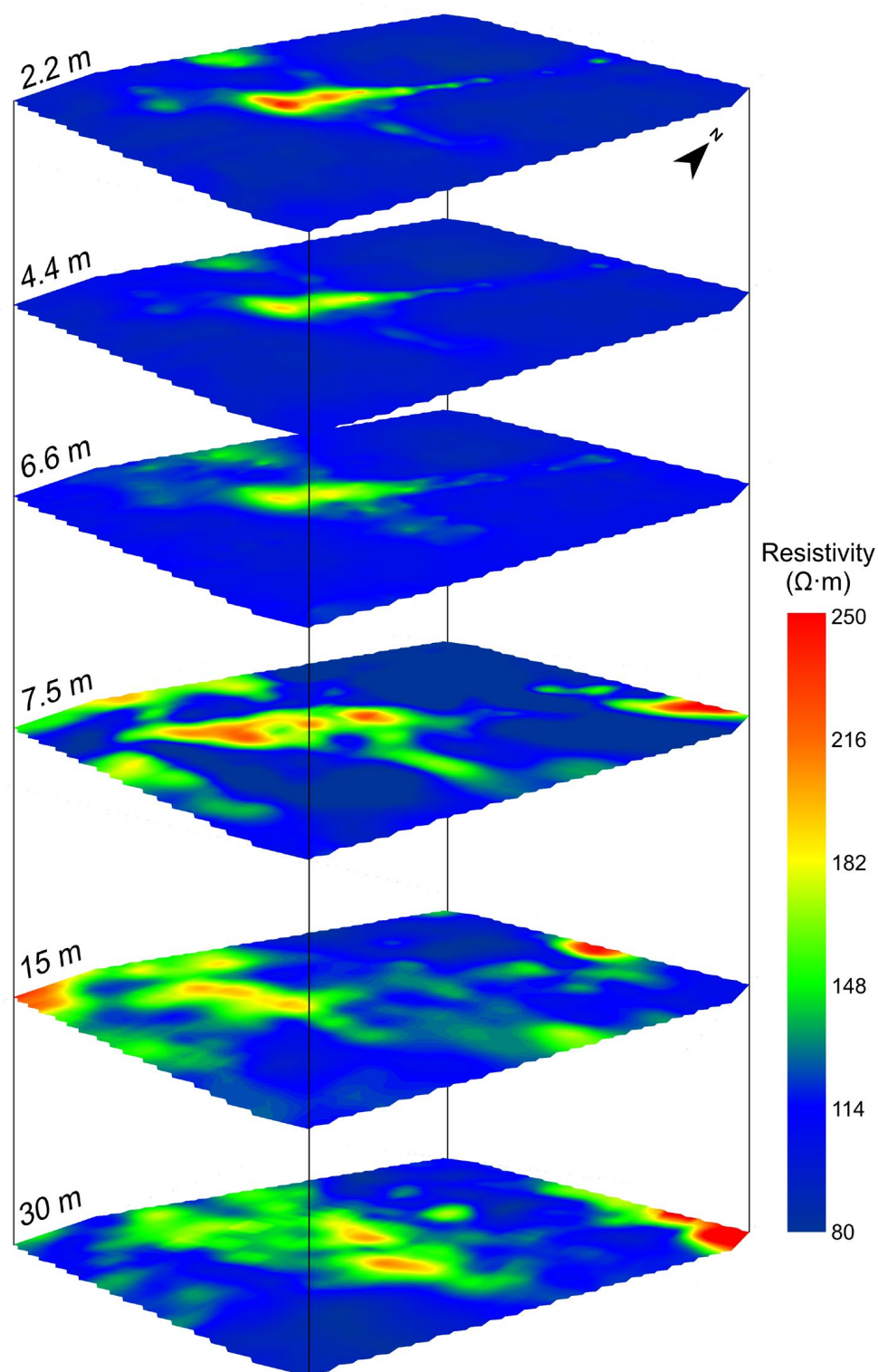


Figure 8. Depth slices derived from the frequency domain electromagnetic (FDEM) technique. Data for the maps at depths of 2.2 m, 4.4 m, and 6.6 m were obtained using the CMD-Explorer equipment. Data for the deeper slices at 7.5 m, 15 m, and 30 m were acquired utilizing the CMD-Duo system configuration.

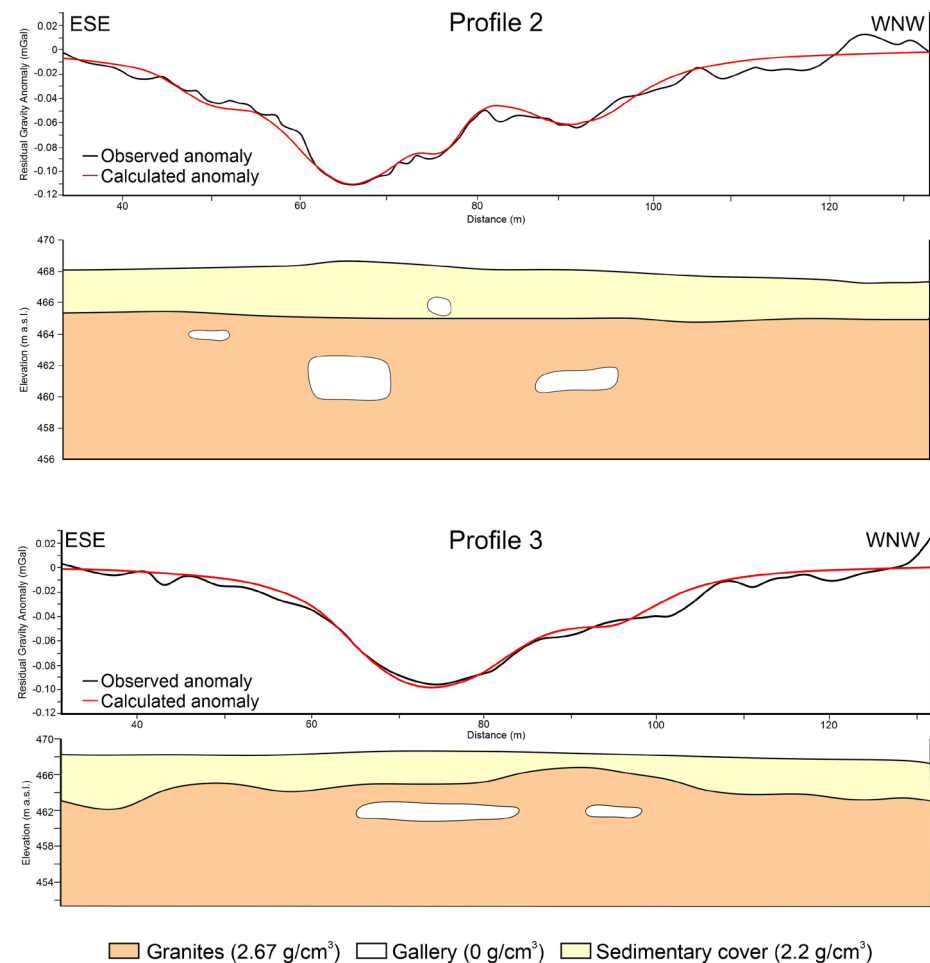


Figure 9. Profiles of the microgravimetric anomalies. The traces of Profile 2 and Profile 3 are co-located with the tracks of profiles ERT 2 and ERT 3, respectively.

In Profile 2, which has a total length of 100 m, a main gravimetric minimum of -0.11 mGal was obtained at approximately 65 m. This minimum spatially correlates with the gallery detected in profile ERT 2. This result suggests a structure approximately 10 m wide and 4 m high, located at a depth of 6 m, with an estimated strike extent perpendicular to the profile of 100 m. Additionally, several shorter-wavelength gravimetric minima were observed and interpreted as smaller, shallower cavities. Specifically, three secondary cavities located at approximately 50, 75 and 90 m were modeled, with the cavity at 90 m being the widest. These structures show a strong correspondence with the anomalies observed in the gravimetric profile.

In Profile 3, a gravimetric minimum of -0.09 mGal centered at approximately 75 m was detected. This anomaly coincides with the gallery identified in profile ERT 3, although it exhibits smaller dimensions than the one in Profile 2, which could be due to partial filling or structural collapse. The proposed model features a void of approximately 30 m in width, 3 m in height, and a strike extent perpendicular to the profile of 100 m. Likewise, an additional shorter-wavelength minimum was identified at around 95 m, which was interpreted as a smaller cavity.

The joint integration of gravimetric and ERT data allowed for more robust and realistic subsurface models to be obtained [17]. The relative resolution of each method can vary depending on acquisition parameters, such as the spacing of electrodes in ERT or the station spacing in gravity surveys. In this context, joint modelling was especially advantageous

since it allowed both methods to complement each other, providing mutual constraints that improved the reliability of the final interpretation.

4.5. Comparison of ERT/GPR/FDEM and Gravimetric Results

To maximize the practical utility for engineering applications and near-surface mining investigations, the performance metrics, operational boundaries, and synergistic deployment strategies of the four evaluated methods are synthesized below:

- Ground-Penetrating Radar (GPR): Delivers the highest vertical and lateral resolution for ultra-shallow features (2–5 m depth). It represents the optimal tool for defining exact void geometries, mapping the interface contact between the sedimentary overburden and the granitic basement, and delineating early-stage structural subsidence or sinkhole infills. Conversely, its primary operational boundary is severe electromagnetic signal attenuation in conductive media, such as the Triassic clay units overlying the granite basement in this district, which critically limits its depth penetration.
- Electrical Resistivity Tomography (ERT): Provides deep penetration capabilities (up to 25 m depth in this study) and continuous 2D profiling of the bedrock topography and deep gallery networks. While its spatial resolution inherently degrades in the shallowest subsurface compared to GPR, its main operational constraint stems from the logistical requirement of galvanic contact, specifically the challenge of achieving effective electrode coupling across highly resistive granitic substrates.
- Frequency-Domain Electromagnetics (FDEM): Functions as a rapid, non-invasive reconnaissance tool with high horizontal data density, serving as an ideal spatial complement to ERT profiling. Although its vertical resolution is inherently limited and smooth compared to ERT, it efficiently maps the lateral continuity of mineralized veins and macroscopic structural collapse trends across extensive survey areas.
- Microgravimetry: Serves as an unambiguous volumetric confirmation method. While it lacks the high-frequency boundary resolution of electrical and electromagnetic techniques, integrating ERT-derived geometries as a priori structural constraints yields highly robust density models. This approach directly links measured mass deficits (gravity minima) to subsurface voids and partially backfilled galleries, effectively mitigating interpretation non-uniqueness.

To avoid qualitative bias and establish a rigorous joint interpretation framework, all detected subsurface anomalies were classified into objective confidence tiers based on the principles of multi-geophysical integration [29,30]. Three distinct confidence categories were defined (Table 2):

1. Confirmed cavity/gallery: Anomalies corroborated directly by historical mining plans or surface evidence and verified by at least two independent geophysical datasets (e.g., a high-resistive ERT nucleus co-located with a microgravity mass deficit or a distinct GPR phase-reversal reflection). Alternatively, features showing a direct spatial correlation with active or documented geomorphological surface subsidence are also assigned to this tier.
2. Probable cavity/gallery: Anomalies exhibiting prominent, coherent signatures across two independent geophysical methods (e.g., co-located ERT and FDEM anomalies) but lacking historical map verification. This tier also includes structural features marked on historical mine plans that receive strong corroboration from at least one geophysical dataset.
3. Possible (speculative) cavity: Low-amplitude or isolated geophysical signatures detected by a single method without historical documentation or surface geomorphological expression. These features cannot be unambiguously distinguished from localized host-rock lithological variations or numerical inversion artifacts.

Table 2. Synthesis and confidence classification of interpreted subsurface anomalies. GL-01: near-surface gallery not included in the historical mine plans. GL-2: gallery (level 2 in the historical mine plans of Figure 2). CV-01: potential cavity located within the southwestern (SW) sector, exhibiting no spatial correlation with known vein trace mining voids. CV-02: cavity co-located with the mineralized vein (mining void). Three geometric uncertainty thresholds are defined: Low (0.0–0.5 m), Moderate (0.5–1.5 m), and High (>1.5 m).

Cavity/Gallery ID	Profile/Position (m)	Estimated Depth Range (m)	Supporting Methods & Evidence	Confidence Category	Geometric Uncertainty
GL-01	Profile ERT 1B (m 70–72)	2–4	ERT (High Resistivity)	Possible	Low based on ERT boundaries
GL-01	Profile ERT 2 (m 64–66) Profile GPR 3 (m 53–54) Profile GPR 11 (m 36–38) Profile gravimetric 2 (m 65–75)	2–4	ERT / FDEM (High Resistivity), GPR Hyperbolic and sagging reflectors Microgravity (Low ρ)	Probable	Low based on ERT/GPR boundaries
GL-01	Profile ERT 3 (m 70–73) Profile GPR 12 (m 46–48) Profile gravimetric 3 (m 72–78)	2–4	ERT and FDEM (High Resistivity), GPR Hyperbolic and sagging reflectors Microgravity (Low ρ)	Probable	Low based on GPR boundaries
GL-01	Profile GPR 5 (m 44–46) Profile GPR 13 (m 22–26) Profile ERT4 (m 55–65)	2–4	Surface Subsidence GPR sagging reflectors ERT: Triassic base collapse	Confirmed	Moderated based on ERT and GPR boundaries
GL-01	Profile GPR 7 (m 28–30) Profile ERT 5 (m 65–70)	2–4	Surface Subsidence Sagging GPR reflectors ERT: Triassic base collapse	Probable	Moderate based on GPR boundaries
GL-01	Profile ERT 6 (m 76–78) Profile GPR 8 (m 34–36)	2–4	Surface Subsidence ERT: Triassic base collapse Sagging GPR reflectors	Confirmed	Low based on GPR/ERT boundaries
GL-02	Profile ERT 2 (m 64–66)	24–26	Historical maps ERT (High Resistivity), Microgravity (Low ρ)	Confirmed	High (vertical overlap of two possible anomalies)
GL-02	Profile ERT 3 (m 71–73)	24–26	Historical maps ERT (High Resistivity), Microgravity (Low ρ)	Confirmed	High (vertical overlap of two anomalies)
GL-02	Profile ERT 5 (m 73–77)	24–26	Historical maps ERT (High Resistivity)	Confirmed	Moderate based on ERT boundaries
CV-01	Profile ERT 1B (m 130–135)	5–10	ERT and FDEM (High Resistivity)	Probable	Moderate based on ERT/FDEM
CV-02	Profile ERT 2 (m 64–66)	10–20	Historical maps ERT and FDEM (High Resistivity), Microgravity (Low ρ)	Confirmed	Moderate based on ERT boundaries
CV-02	Profile ERT 3 (m 70–72) Profile GPR 12	10–20	Historical maps ERT / FDEM (High Resistivity), GPR Hyperbolic reflectors	Confirmed	Moderate due to vertical smoothing

Synthesizing the operational performance, resolution limits, and multi-tiered confidence classification of these techniques, we propose a three-stage hierarchical geophysical framework for spatial planning and hazard assessment in legacy mining districts:

Phase 1 (Rapid reconnaissance): Frequency-domain electromagnetic (FDEM) mapping is utilized for extensive, rapid lateral conductivity characterization (0–30 m depth range) to delineate broad zones of structural ground disturbance, vein continuity, and major collapse features.

Phase 2 (High-resolution delineation): Targeted ground-penetrating radar (GPR) surveys are executed over critical shallow anomalies identified in Phase 1 to resolve precise void geometries and shallow subsidence boundaries (2–5 m), conditioned upon low-attenuation (low clay content) host media. Concurrently, electrical resistivity tomography (ERT) profiles are deployed across key structural axes to characterize deeper gallery networks (up to 25 m) and map discontinuities within the granitic basement.

Phase 3 (Physical mass-deficit validation and joint ambiguity resolution): Microgravity profiles are performed exclusively across coincident anomalies confirmed by Phase 2. Rather than duplicating spatial mapping, Phase 3 provides an independent bulk-density constraint. Geometric boundaries from ERT/GPR models serve as a priori structural constraints for gravity modeling. This coupling effectively minimizes the non-uniqueness inherent to standalone electrical/electromagnetic datasets, successfully distinguishes air-filled voids from low-density backfill, and enables rigorous mass-deficit/volumetric risk validation.

5. Conclusions

This study demonstrates the effectiveness of integrating four complementary geophysical techniques (ERT, GPR, FDEM, and microgravimetry) to locate, characterize, and prioritize shallow legacy mining voids in complex granitic environments. The main outcomes of this research are summarized as follows.

Methodological complementarity and depth capabilities: GPR (100–250 MHz) provides high-resolution imaging of shallow gallery roofs (2–4 m) and bedrock-cover contacts, although electromagnetic attenuation limits deeper investigation. ERT reliably maps deep gallery networks (down to 25 m) and tracks structural roof subsidence, effectively complementing GPR where galvanic contact allows. At a broader scale, FDEM serves as an effective spatial screening tool for rapid lateral mapping down to 30 m, identifying overall ground disturbance trends along mineralized veins, while microgravimetry acts as an independent physical validation metric that directly links subsurface mass deficits to void presence.

Reduction in inversion non-uniqueness: Integrating ERT-derived geometries as a priori structural constraints into microgravity modeling effectively resolves interpretation ambiguities. This cross-validation proves that the detected anomalies represent physical mass deficits (air-filled or partially backfilled voids) rather than numerical inversion artifacts.

Structural dynamics and hazard mapping: Spatial discontinuities and magnitude variations within the geophysical anomalies across the study area accurately reflect the structural collapse of shallow galleries, backfilling with mine waste, and clay migration processes—all of which correlate directly with surface geomorphological subsidence.

Engineering and practical value: This multi-method, hierarchical approach provides a robust decision-support framework for land-use planning and civil engineering, enabling the early detection and risk prioritization of subsurface hazards in legacy mining districts well before catastrophic ground failure occurs.

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Data Availability Statement: The datasets generated and analyzed during the current study (including profile spatial coordinates, processed resistivity and conductivity data, inversion model

parameters, and interpreted anomaly positions) are available from the corresponding author upon reasonable request.

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Conflicts of Interest: The authors declare no conflicts of interest.

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