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Multichannel GPR and multi-depth electromagnetic surveys for the study of *Villa Eucheria* and *Aquinum* at Castrocielo (Frosinone, Central Italy)

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ABSTRACT

The municipality of Castrocielo (Frosinone, Italy) is a historically significant center which includes several centers of great archaeological importance, including part of the archaeological site of the ancient Roman city of *Aquinum*. In this work, we show the results of geophysical surveys performed in two different areas: the first area is close to the Monacato of Santa Maria al Palazzolo, built on the foundation slab of a Roman villa dating back to the 1st-2nd century BCE; the second area is close to the charging station Casilina Est, where several burials, dating back to different periods from 4th century BCE to 4th century CE, were found. The aims of geophysical investigations is to identify structures linked to the ancient Roman villa (*Villa Eucheria*) in Area 1, and to identify the tombs of the necropolis in Area 2. The two areas were investigated in two different days, on 27th and 28 th March 2023 respectively, through a multi-channel georadar system (GPR). In the second area, an electro-magnetometric survey was also performed. This choise is to address the heavy rain developed during the night before the acquisition. Infact the GPR survey performed during the second day of the geophysical campaign did not provide good results.Based on the geophysical results, the archaeological excavation in Area 1 confirmed the detected anomalies, documenting a section of wall and other structures and elements brought to light over a length of approximately 9 m. The results obtained in Area 2 confirmed the cropmarks visible in the aerial photo, highlighting the traces of buried structures.

1. Introduction

Geophysics is a fundamental tool to explore and document cultural heritage. Geophysical methods are inherently non-destructive and thus are an essential support tool for archaeologists, to provide detailed geometric features of the buried structures, especially when there is no possibility of direct investigation, and to identify the areas of greater archaeological interest (Leucci, 2019; Giannino and Leucci, 2021). Several geophysical methods can be used in archaeological investigations, depending on purpose: the GPR has been applied for 25 years in archaeological prospections to map shallow subsurface targets (Conyers, 2006; Conyers, 2013; Conyers and Leckebusch, 2010); Electromagnetic prospecting techniques have been used for archaeological purposes since the late 1960s (Colani, 1966; Colani and Aitken, 1966).

The municipality of Castrocielo (Frosinone, Italy) is a center of great historical interest and the site of numerous archaeological finds. In this work, we considered two different areas (Fig. 1): the first area is to the east of the historical center of Castrocielo, at an altitude of 249 m above sea level, close to the Monacato of Santa Maria al Palazzolo, and built on the foundation slab of a Roman villa dating back to the 1st-2nd century BCE; the second area is close to the charging station Casilina Est, where several burials, dating back to different periods from 4th century BCE to 4th century CE, were found.

The district of *Villa Eucheria* includes the *Monacato*, a former Benedictine sisters' cloister (dating back to 1134) built on the base of a big Roman villa. The remains of the Roman Villa, dating back to the Republican Age, are the polygonal base against which the cryptoporticus of uncertain date leans¸ it perhaps belongs to a following period. It is a massive, polygonal wall in the 4th style, which forms the western front of a rectangular platform on which the ancient villa was built, over which were partially built the structures of a Benedictine monastery. The wall, almost 60 metres long, is actually made up of two different

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Fig. 1. The investigated areas fall within the municipality of Castrocielo, in central Italy (as shown in the left box by the red marker). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

parts, built using different techniques. At the southern end of the terrace wall, higher than the current ground level, there is a cryptoporticus set against the terrace wall of the stables. It consists of a long covered gallery with a barrel vault and twenty lancet windows. In the opposite wall and perpendicular to it, there is a narrow tunnel and the opening of the ramp leading to the upper platform. The interior walls of the gallery are completely plastered and decorated with squares, with reddish stripes on the vault and graffiti lines on the walls. The presence of small white limestone mosaic tiles not *in situ* suggests that the floor was originally mosaic. In the Middle Ages, the area of the villa was occupied by the convent of *S. Maria di Palazzolo*, the first reliable record of which dates back to 1134. The convent building with the adjacent church, recently restored, occupies the north-eastern sector of the stalls of the foundation of the Roman villa and proposes in its structures the orientations of the structures of the villa, which in some cases have been incorporated and are still recognisable. In the north-eastern sector of the stables, the cistern, which first served the villa and then the convent, has been preserved and is still fully functional. It is made up of three barrel vaulted galleries placed side by side and communicating with each other through two low and narrow openings with round arches (Nicosia, 2004; Cagiano De Azevedo, 1949). The few found ruins are elements not sufficient to make a satisfactory historical reconstruction of the site. Geophysical investigations were undertaken to investigate the ancient buried structure related to the Roman Villa.

The urban area of *Aquinum*, a Roman city located along the *Via Latina* between the cities Frosinone and Cassino (central Italy, Fig. 1a), was identified in 1998 through the interpretation of vertical historical coverage and aerial photographs. The archaeological site was investigated using aero-topographical studies, geophysical prospecting, and archaeological field surveys. Ancient *Aquinum* is characterized by the presence of an extensive defense system and a regular but not orthogonal road system of the town (Ceraudo, 1999). The excavations began in 2009 and continued following several geophysical campaigns (*e.g.* Piro et al., 2011; Piro et al., 2012). Halfway along the western side of the wall is one of the main gates of *Aquinum*'s urban layout, the *Porta Romana*. All that remains of the gate are a few huge opus quadratum blocks from the lower part of the eastern gate. All around are the collapsed blocks that formed the pillars and vaults of the structure. Just outside the *Porta Romana*, along the *Via Latina*, there must have been one of the most important necropolises in the city (Cayro, 1816). It extended as far as *Omomorto*, so called because of the large number of burials found there and the presence of a marble funerary statue, which has now disappeared (Grossi, 1907). Excavations, not always with purely scientific intentions, were carried out in 1859: a section of the necropolis along the *Via Latina* was studied, with numerous tombs, where many inscriptions and a marble statue, which disappeared shortly afterward, were found. Cagiano De Azevedo (1949) mentions a necropolis of poor tombs behind the western gate. The most recent misfortunes of this suburban area began at the beginning of the 1960s, when, in addition to the partial destruction of the amphitheatre (Ceraudo, 2020), it was disturbed by the construction of the Autostrada del Sole, with the Pontecorvo-Castrocielo junction and tollbooth, and the two service areas of Casilina Ovest and Casilina Est, the latter built right on the *Via* Latina. The archaeological excavations carried out between 2005 and 2009, with eight excavation areas opened at different points in the service areas, have made it possible to document funerary contexts dating from the 4th century BCE to the 4th century CE (Ceraudo, 2007; Bellini and Trigona, 2011). The most important core is made up of monumental chamber and caisson tombs, flanked by more modest capuchin tombs (Ceraudo, 2023). Fig. 3 shows an aerial photograph of Area 2, highlighting the traces (crop marks) of buried structures associated with the necropolis.

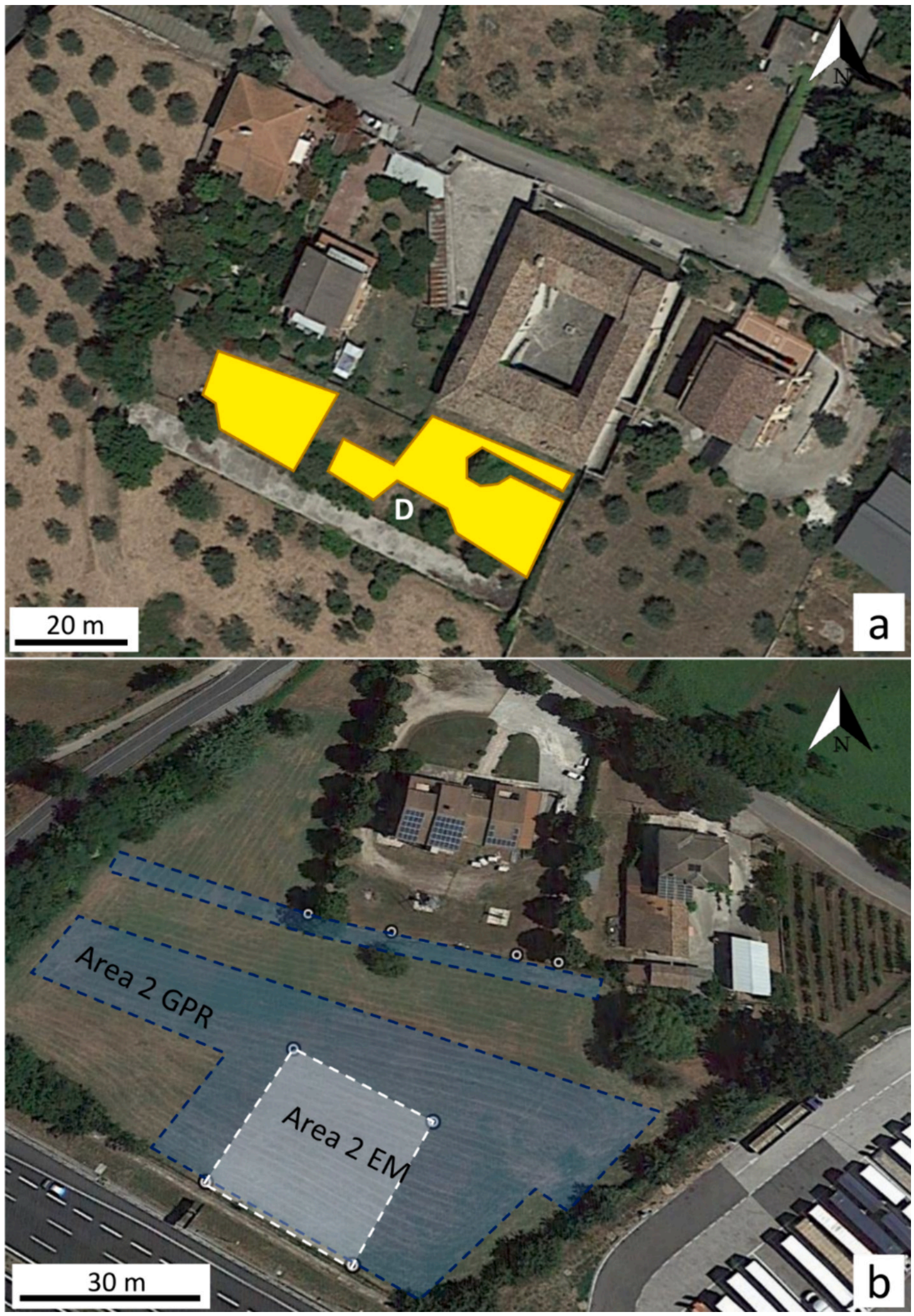

Fig. 2. Investigated areas: Area 1 is close to the *Monacato of Santa Maria al Palazzolo*, the lack of data is due to the presence of vegetation and a significant depression (D) to the south of the area (a); Area 2 is close to the charging station Casilina Est and is investigated through GPR method (delimited by the blue polygon) and EM method (delimited by the white polygon) (b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The studied area, falls in the wider context of the Latina Valley, in the alluvial plain of the middle valley of Liri River, at the base of the mountain system dominated by Mount Cairo. It is placed in correspondence with extensive cropmarks of travertine of hydrothermal origin, whose average thickness is of the order of 5 m. The stratigraphic base of travertines is characterized by alluvial and lacustrine Pleistocene deposits. Some areas are characterized by Messinian to Tortonian foredeep clayey sequence (geological map available online: https://geoportale.regione.lazio.it/; Praturlon et al., 2002).

The geophysical research activity was carried out by the Geophysics Lab of the Institute of Heritage Science of Lecce (CNR), within Project *Ager Aquinas* coordinated by the Laboratory of Ancient Topography and Photogrammetry of the University of Salento. The geophysical surveys weredesigned according to some archaeological aspects highlighted on the site, employing a multi-channel Ground Penetrating Radar (GPR) system for both areas and frequency domain electro-magnetometry (EM) measurements in the second area. GPR surveys were carried out using a Stream C georadar equipped with a GPS system that allows to obtain a precision of 2–3 cm. The campaign was expedited on 27 and 28 March 2023. Heavy rain developed during the night did not allow to obtain good results from the GPR survey performed on Area 2 during the second day of the geophysical campaign.

Some preliminary results relating to this work were presented at MetroArchaeo conference 2023 (Barbolla et al., 2023).

Starting from the results of geophysical prospecting, archaeological excavation campaigns were carried out in Area 1, finding the presence of structures of high archaeological interest, correspondents to the anomalies identified by the GPR survey.

2. Geophysical investigations

In the last two decades, GPR was one of the most utilized tools for archaeological prospection due to its high-resolution data and 3D visualization capabilities (Conyers, 2013). Another geophysical method used for archaeological purposes since the 1960s is the low-frequency electromagnetic (EM) method (Colani, 1966; Colani and Aitken, 1966, which is able to identify a variety of archaeological features (Barbolla et al., 2024; De Giorgi et al., 2023; Rodrigues et al., 2009; Simpson et al., 2010).

The purpose of the geophysical investigation conducted in Area 1 (whose extension is about 64 × 21 m) is to identify the remains of an ancient buried Roman villa through the use of the GPR method with a multi-channel instrument (Fig. 4). As can be seen in Fig. 2a, it was not possible to carry out the GPR survey in some parts of the area due to the presence of vegetation and a significant depression to the south of the area (named D in Fig. 2a).

A different purpose has the geophysical investigation conducted in Area 2 (whose extension is about 120 × 65 m), in which is possible to localize the cropmarks of a necropolis from aerial photo. To identify the presence of buried chamber tombs, the GPR method with a multi-channel system was used. An electromagnetometric survey was conducted as well with parallel profiles, equally spaced 0.5 m, based on the average dimensions of the chamber tombs found in an adjacent area (Fig. 4).

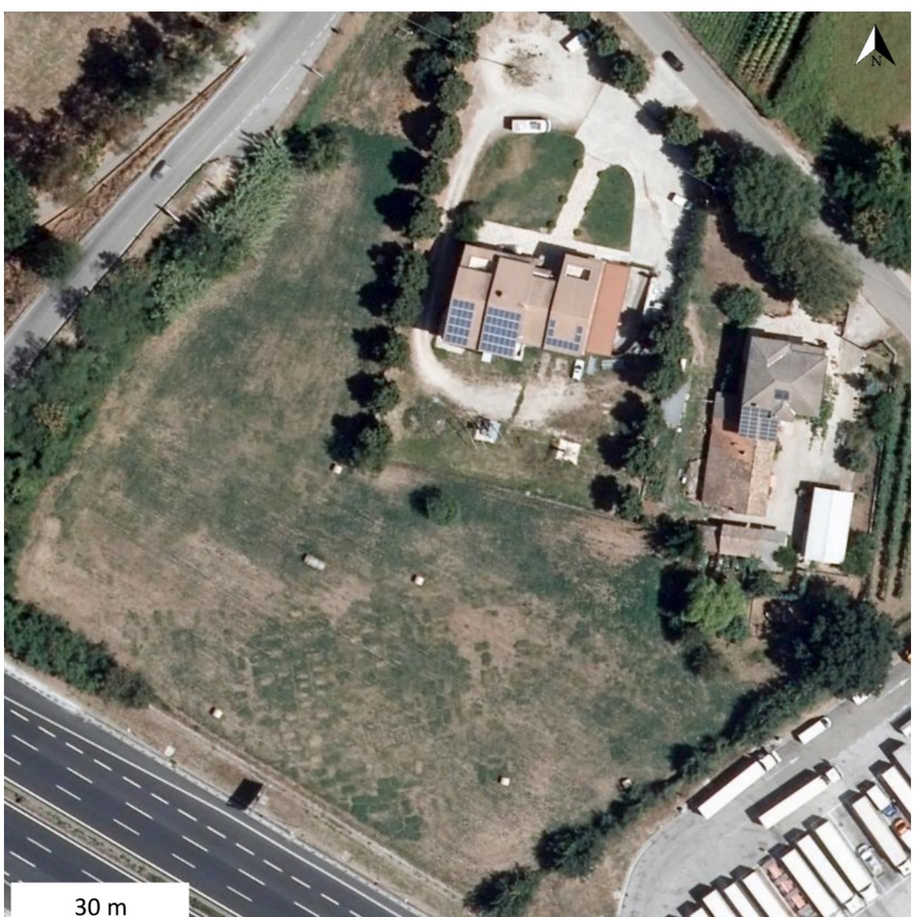

Fig. 3. Aerial photo of Area 2, close to the charging station Casilina Est (c), where the traces of the tombs are clearly visible (cropmarks).

2.1. Multichannel GPR survey

In this work, we used a multichannel antenna array (Fig. 4 on the left), IDS Stream C - Ground Penetrating Radar (GPR) which detects buried objects in real-time and produces subsurface GIS-based digital maps. It is equipped with a massive array of 34 antennas in two polarisations: the vertically and horizontally polarised antennas deliver high-quality results and an accurate 3D reconstruction of the underground structures in a single scan. The antennas have a central frequency of 600 MHz.

The raw data quality was moderate. Data were processed to improve the signal-to-noise ratio and to allow simple interpretation (Leucci, 2019). Multi-channel systems require radargram signal processes to balance the channels. The multi-channel processing was performed through the following steps: removal of DC drift, 0 ns editing, gaining, spectral whitening, background removal, migration and Hilbert transform.

We estimated the average velocity of electromagnetic propagation using the diffraction hyperbola method. Once the average velocity is known, the time scale of the radar section can be converted to depth. The data analysis highlighted a good penetration of the electromagnetic signal, which allowed investigation up to a time window of 70 ns, corresponding to a depth of about 2.4 m, considering an average velocity of propagation of electromagnetic waves in the subsoil equal to about 0.07 m/ns. The results of the analysis of data acquired in Area 1 highlighted some hyperbolic reflections of the electromagnetic signal (signed with yellow circles on the radargram in Fig. 5a-b) which suggest the presence of structures of probable archaeological interest at depths between 0.5 m and 1.1 m.

The acquisition of data profiles in a grid with a step of 0.1 m, allows to spatially correlate (3D) the anomalies present on each radar section through the analysis of the amplitude of the reflected events within assigned time intervals, obtaining the time slices (Giannino and Leucci, 2021).

The type of analysis applied to the studied Area 1 gave satisfactory results. Figs. 6–8 show the depth slices of Area 1 at different depths: the blue colour indicates a weak amplitude of the reflected signal (substantially homogeneous material); the colors from light blue to more intense red indicate variations in the amplitude of the reflected signal and therefore the presence of significant electromagnetic discontinuities. The variations in amplitude (therefore in colour) in the same slice indicate horizontal variations in the electromagnetic characteristics of the investigated halfspace. It is possible to identify alignments related to probable archaeological structures (walls).

Area 2 was investigated during the second day of the geophysical campaign, after heavy rain and the GPR investigations, as expected, did not identify the structures highlighted in the aerial photo (Fig. 9). Fig. 5c shows a radar section acquired in this area: the signal can reach a depth of less than $z = 0.4$ m. A portion of this area was investigated with the low-frequency EM method as described below.

2.2. Multi-depth electromagnetic survey

The low-frequency EM instruments operate at a frequency lower than 300 kHz, and their ability to identify archaeological structures is determined by physical issues, such as coil geometry and sensor height, and the physical properties of the soil (Bonsall et al., 2013). In our work, we used a multi-depth instrument, the CMD Mini-Explorer by

Fig. 4. Geophysical instruments: Stream C multichannel GPR on the left; electromagnetometer mini explorer on the right.

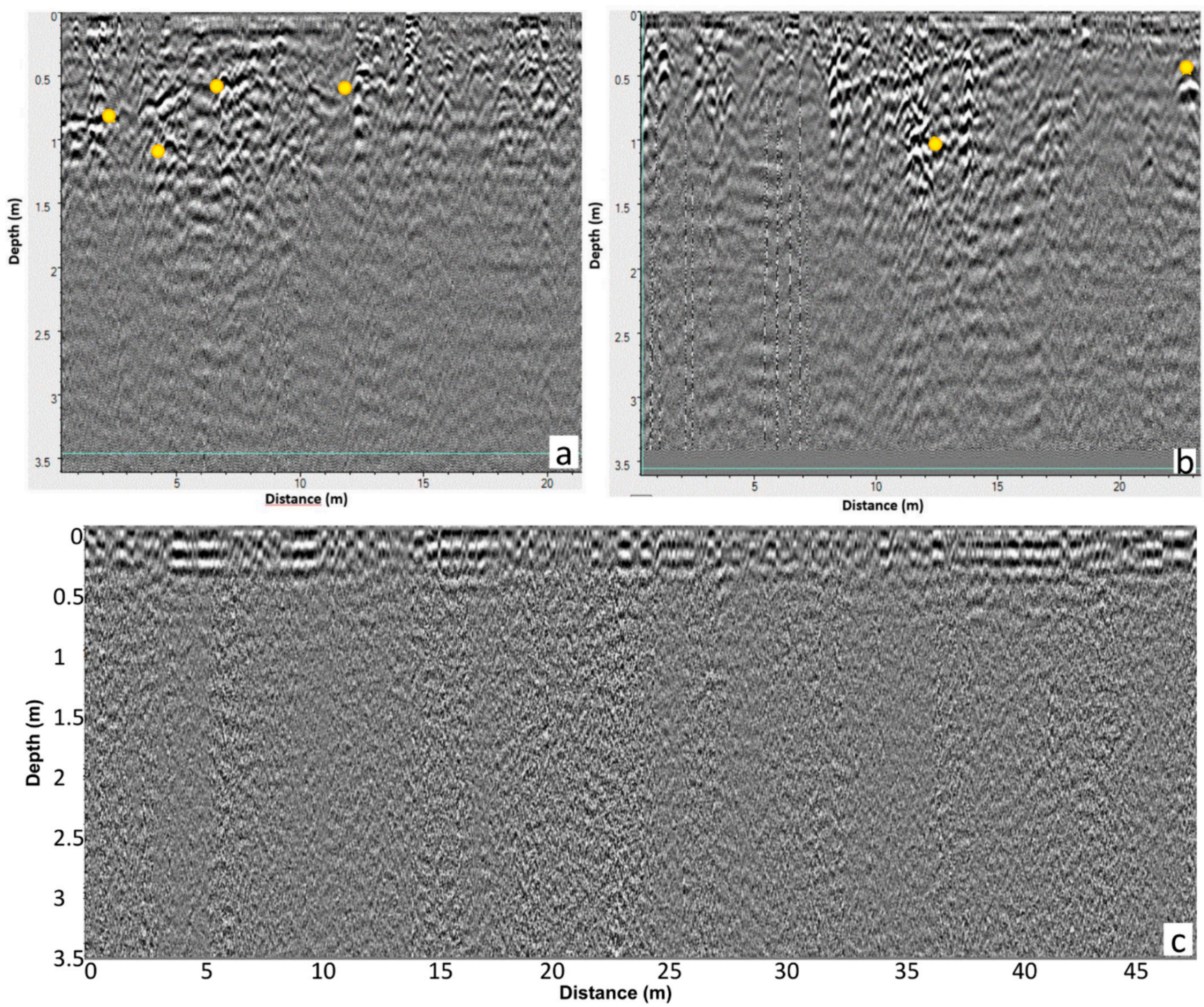

Fig. 5. Processed radar sections acquired in Area 1(a and b) and Area 2(c). Yellow circles identified some hyperbolic reflections of the electromagnetic signal. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

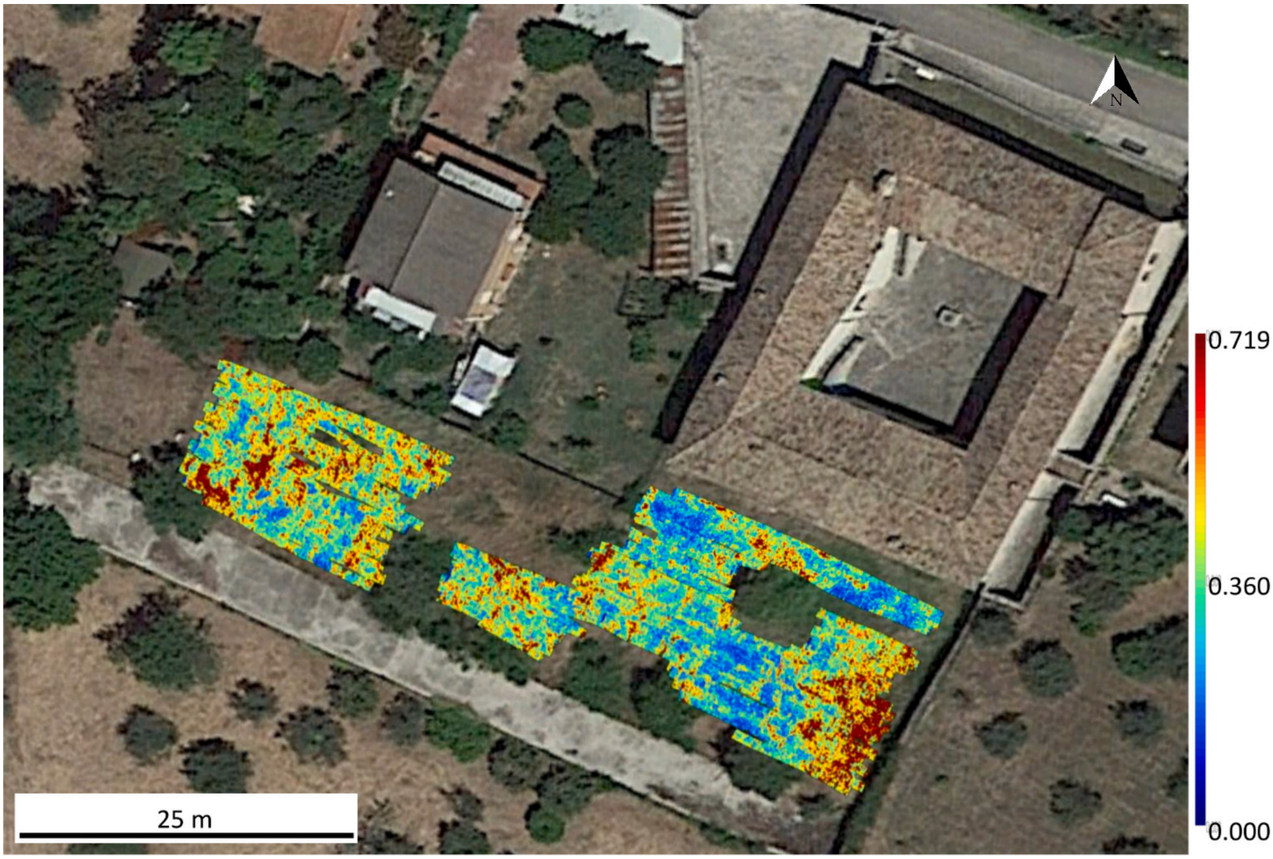

Fig. 6. Area 1: depth slice at z = 0.70 m.

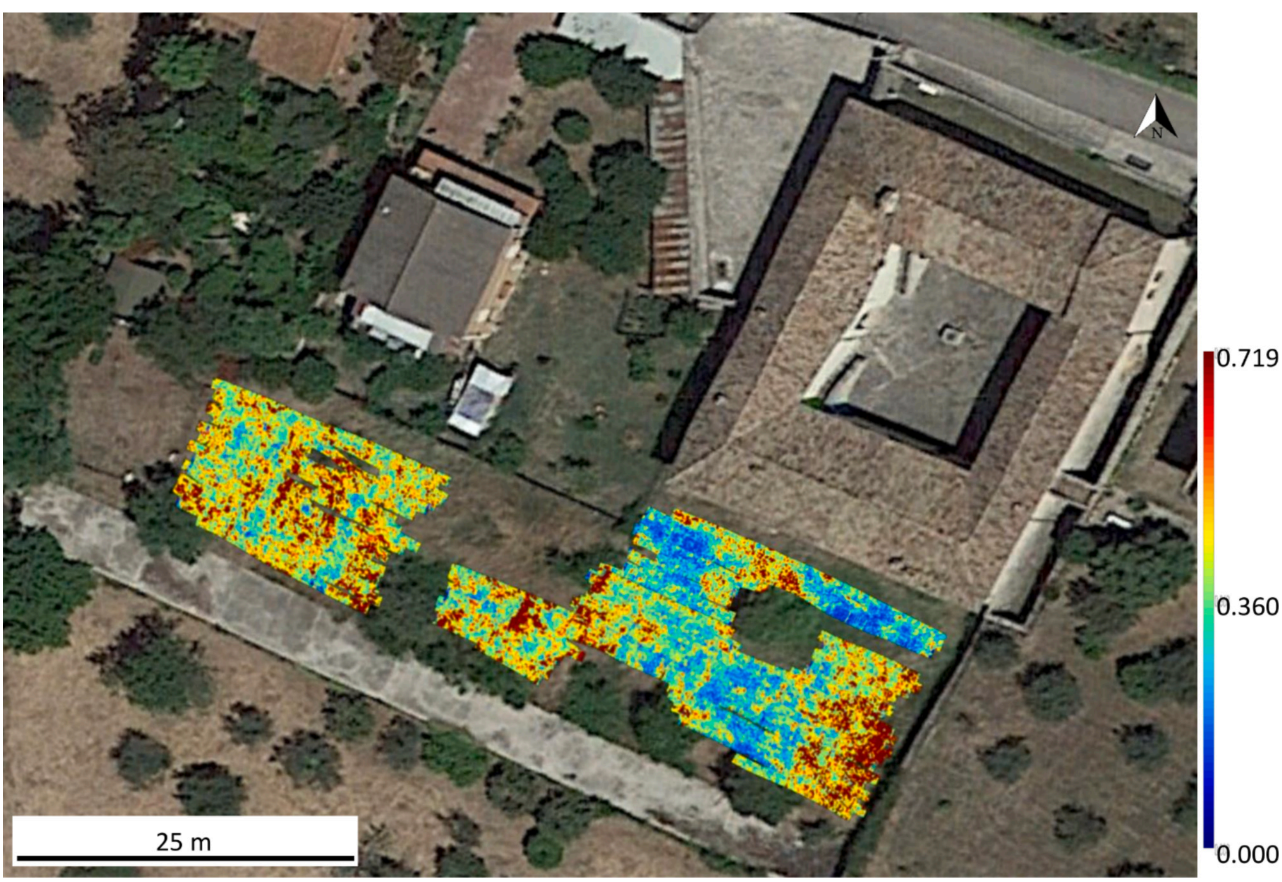

Fig. 7. Area 1: depth slice at z = 0.90 m.

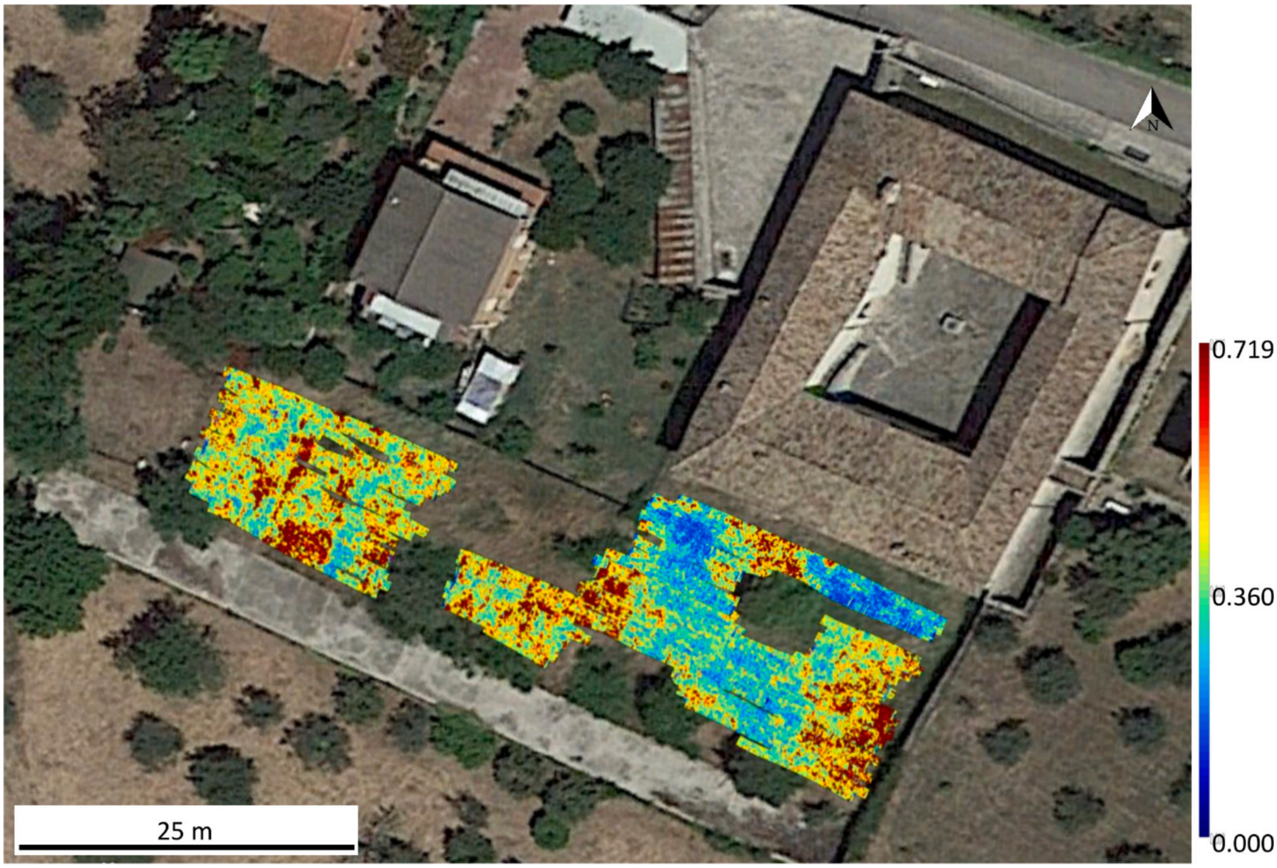

Fig. 8. Area 1: depth slice at z = 1.10 m.

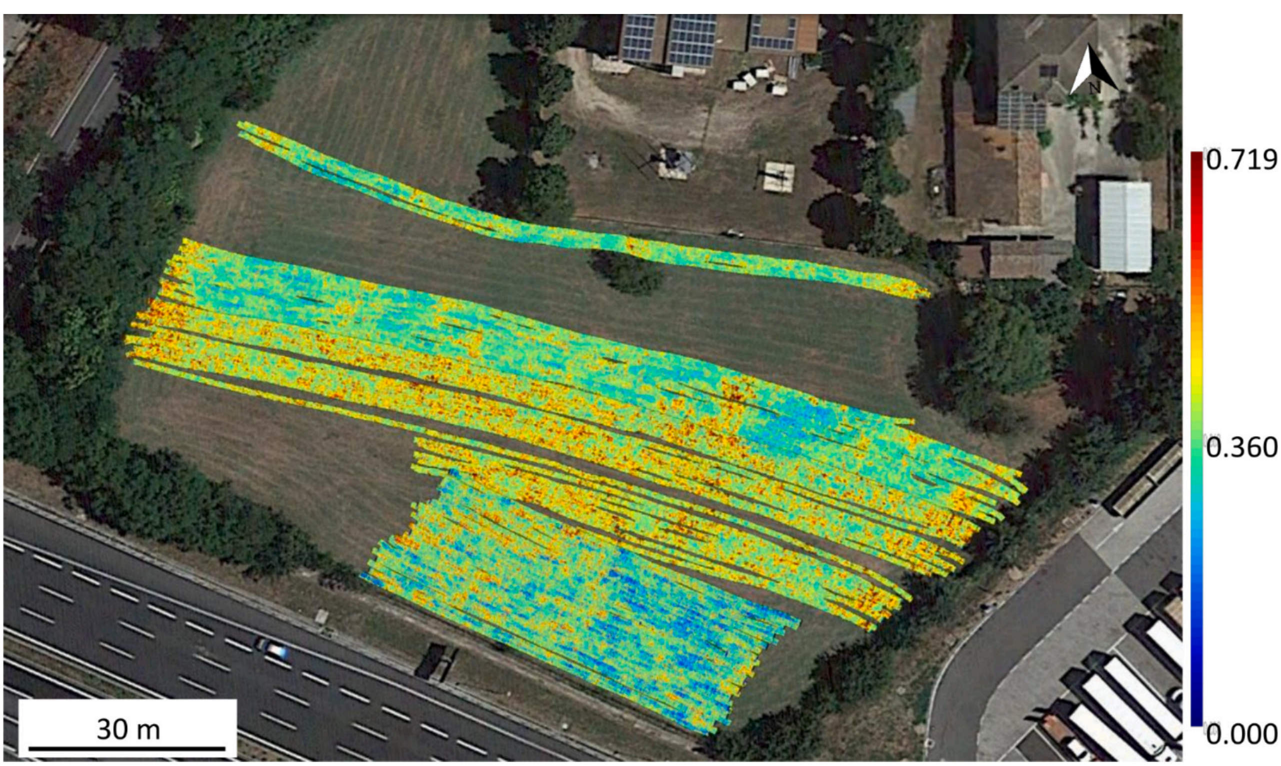

Fig. 9. Area 2: depth slices at z = 0.5 m.

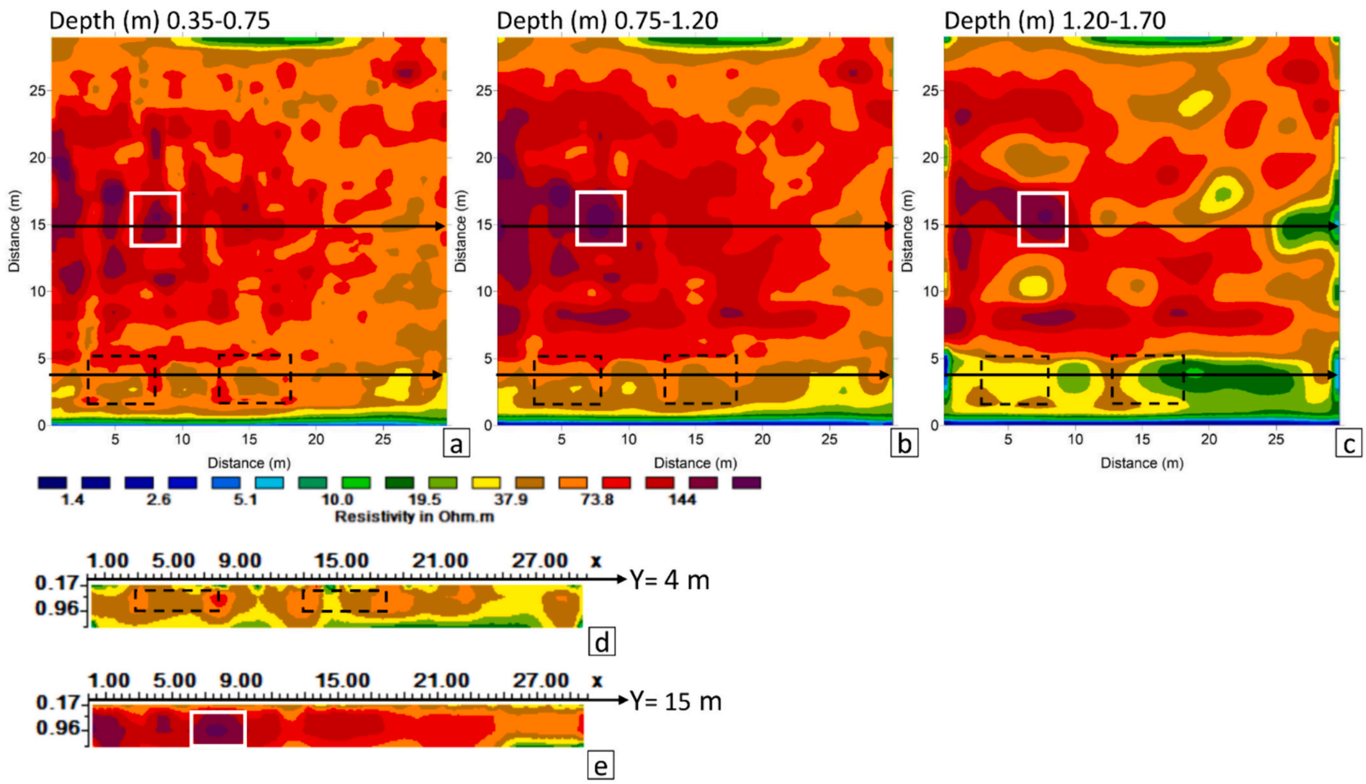

Fig. 10. EM results. Resistivity maps at several depth ranges: 0.35–0.75 (a); 0.75–1.20 (b); 1.20–1.70 (c); resistivity sections at y = 4 m (d) and y = 15 m (e); the dotted black rectangle interprets the resistivity anomalies assuming the presence of tombs partially filled with soil material; the white rectangle could indicate the presence of a chamber tomb with high resistivity for all the depths range probably due to the presence of voids.

GFInstruments (Fig. 4 on the right). It operates at a frequency of 30 kHz and has three receiver coils spaced 0.32 m, 0.71 m, and 1.18 m from the transmitter coil. There are two coil arrangements: a horizontal coplanar configuration with vertical dipole orientation and a vertical coplanar configuration with horizontal dipole orientation. We choose to use the EM with the vertical coil dipole orientation, which allows a greater investigation depth: the effective depth ranges are 0.5 m, 1.0 m, and 1.8 m. The transmitting coil generates a time-varying primary magnetic field, which propagates generating alternating currents (eddy currents) within the soil and the buried structures. The eddy currents create a secondary magnetic field, proportional to the rate of change of the primary magnetic field, measured by receiving coils. The received secondary magnetic field consists of the quadrature component, proportional to the ground conductivity, and of the in-phase component, influenced by magnetic properties.

Acquired data are processed and interpreted to characterize the subsurface EM properties. Electrical conductivity and magnetic susceptibility govern the magnitude of the received EM signal and, therefore, are used to understand the electrical properties of subsurface materials (Leucci, 2019). In our work, the data were collected in the continuous mode along 61 profiles equally spaced 0.5 m, setting the measuring period to 0.2 s and maintaining a constant speed of movement which not exceeds 9 km/h.

Although the electromagnetic method provides information about both electrical and magnetic properties, we focus on the interpretation of the quadrature component, since the in-phase one did not provide any additional information in this specific case study. The data interpretation is made using the inversion process. Acquired data are exported to Res3DInv software (Loke, 2024) to obtain two-dimensional resistivity models of the subsoil. Considering the quadrature component, negative values of apparent conductivity were removed and the inversion routine was applied, obtaining the xy and yz distribution of the electrical resistivity values at several depth ranges. We used the L1-norm based optimisation method, with a minimum damping factor equal to 0.01 and an initial damping factor equal to 0.10. The RMS misfit error obtained between theoretical and measured data after 5 iteration is equal to 6%.

EM results shown in Fig. 10 provide the identification of several resistivity anomalies related to the presence of significant buried archaeological structures. The resistivity depth slices (Fig. 10) show relatively high resistivity anomalies (about 160 Ohm m) which create a distribution of semi-rectangular shapes probably related to the presence of chamber tombs. The presence of these anomalies is visible in all the layers obtained through the inversion process (Fig. 10a to 10c), thus at shallow depth ($z = 0.35$ m) up to a depth of $z = 1.7$ m. Analyzing 2D sections (Fig. 10d-e), we observe the alternation of relatively high resistivity with slightly lower resistivity: this could be interpreted assuming the presence of tombs that maintain an intact structure, showing high resistivity due to the presence of voids and others in which probably the soil material has partially filled the chamber, returning a relatively lower resistivity value.

3. Discussion

The results obtained from the GPR survey in Area 1 allow us to observe the orientation of the buried structures. The main anomalies highlighted by the GPR surveys in the SW sector of the terrace where the Roman villa stood, were investigated stratigraphically with the opening of a 10 × 10 m excavation trench (Fig. 11).

The anomalies were interpreted together with the archaeologists and overlapped on the drone image after the archaeological excavation: as shown in the georeferenced time slice (Fig. 12), reflections from the tops of buildings draw the shape of some structures linked to the Roman villa. Immediately below the surface layer (about 20 cm below the current ground level) some structures pertinent to the villa were brought to light: part of an environment characterized by a lithic-based cement floor with leucitite inserts located in the northern portion of the

Fig. 11. Area 2: the drone image after the archaeological excavation (black square). At the top left the zoom on the excavation area.

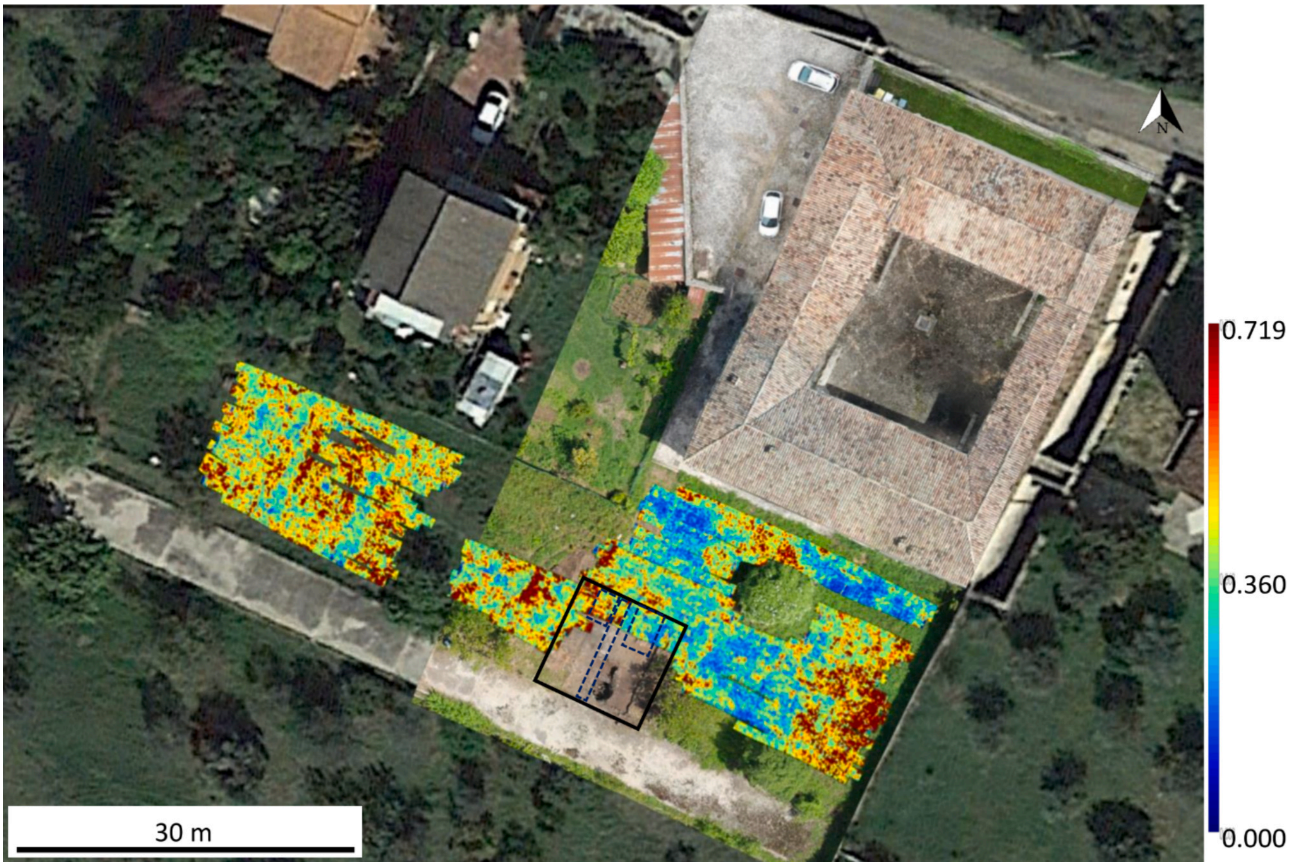

Fig. 12. Area 2: the depth slice at z = 0.90 m is overlapped on the drone image after the archaeological excavation (black square). The blu dashed rectangles indicate structures previously detected by the GPR surveys.

excavation. The room is delimited on the SW by two walls in opus incerta, oriented NE-SW, of different thickness, separated by a threshold which allowed to entry to the room from the SW. The wall retains traces of white plaster coating, preserved to a maximum height of 10 cm. In the southern portion of the excavation area, blocks of travertine (approximately 1 × 0.46 m) were found, with a NE-SW orientation, presumably pertaining to a substruction associated with terracing works carried out to facilitate the construction of the cryptoporticus, placed approximately 80 cm from the ground level. The excavation also partially brought to light 3 other wall structures, in the central sector of the excavation area, but at a significantly lower altitude (approximately 120 cm from the ground level) probably related to the works that allowed the passage between the cryptoporticus, located to the S of the terrace of the villa, and the terrace itself: a wall structure in travertine blocks bound with very friable yellowish mortar, oriented NE-SW; a wall structure in opus incertum with E-W orientation, located to the N of the entrance arch to the cryptoporticus; and a wall partition in opus incertum with NE-SW orientation.

Area 2 is close to the Casilina Est service area, built right on the *Via Latina*. The archaeological excavations carried out between 2005 and 2009 at different points of the service areas, document funerary contexts dating from the 4th century BCE to the 4th century CE, which include monumental chamber and caisson tombs, flanked by more modest capuchin tombs (Ceraudo, 2023). As shown in Fig. 9, in this area the GPR method did not give good results due to environmental factors:the weather (heavy rain preceded the survey) and the type of soil mostly clayey. Fig. 13 shows the georeferenced resistivity map at $z = 0.35–0.75$ m overlaid on the aerial photograph, where distinctive archaeological cropmarks are shown. This photograph highlights the traces of the tombs, identifying a part of the western necropolis of *Aquinum*. The EM method revealed anomalies that can be linked to the presence of the tombs: high resistivity anomalies align with the cropmarks visible on the aerial photo. The alternation of relatively high and low resistivity arranged in quadrangle regular shapes can be linked to tombs partially filled with soil.

4. Conclusions

Geophysical investigations provided good results regarding the identification of structures present in the shallow subsoil. The GPR method in Area 1 allowed to extend the investigation up to a depth of approximately 2.4 m, highlighting anomalies related to the presence of the buried Roman Villa. On the basis of the geophysical results, an archaeological excavation was carried out which revealed some important elements such as walls, travertine blocks, and pavements associated with the ancient Roman villa (*Villa Eucheria*).

Low-frequency EM method performed in Area 2 allowed us to locate the tombs, showing the alignment of relatively high resistivity anomalies in regular semi-rectangular shapes, confirming the hypothesis of the presence of the necropolis.

The presented study highlights the importance of geophysical methods as a tool for planning excavation activities saving time and money.

Fig. 13. Georeferenced map of resistivity at depth range 0.35–0.75 m.

Statements and declarations

The authors did not receive support from any organization for the submitted work. The authors have no relevant financial or non-financial interests to disclose.

CRediT authorship contribution statement

Dora Francesca Barbolla: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ivan Ferrari:** Investigation. **Francesco Giuri:** Investigation. **Ilaria Miccoli:** Investigation. **Giuseppe Scardozzi:** Investigation. **Veronica Ferrari:** Investigation. **Giovanni Leucci:** Writing – review & editing, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

All authors declare that they have no confict of interest.

Data availability

Data associated with this research are available and can be obtained by contacting the corresponding author.

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