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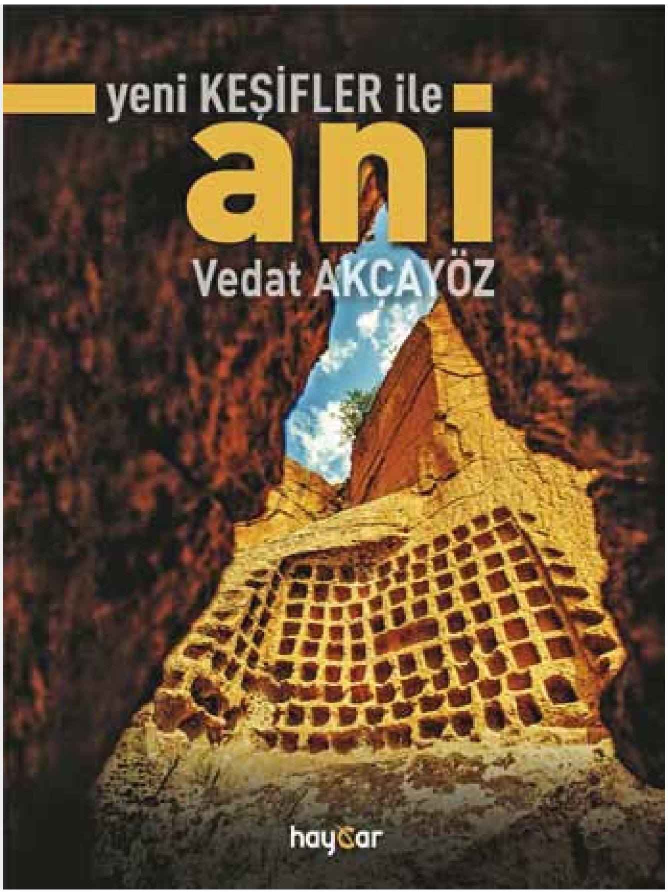

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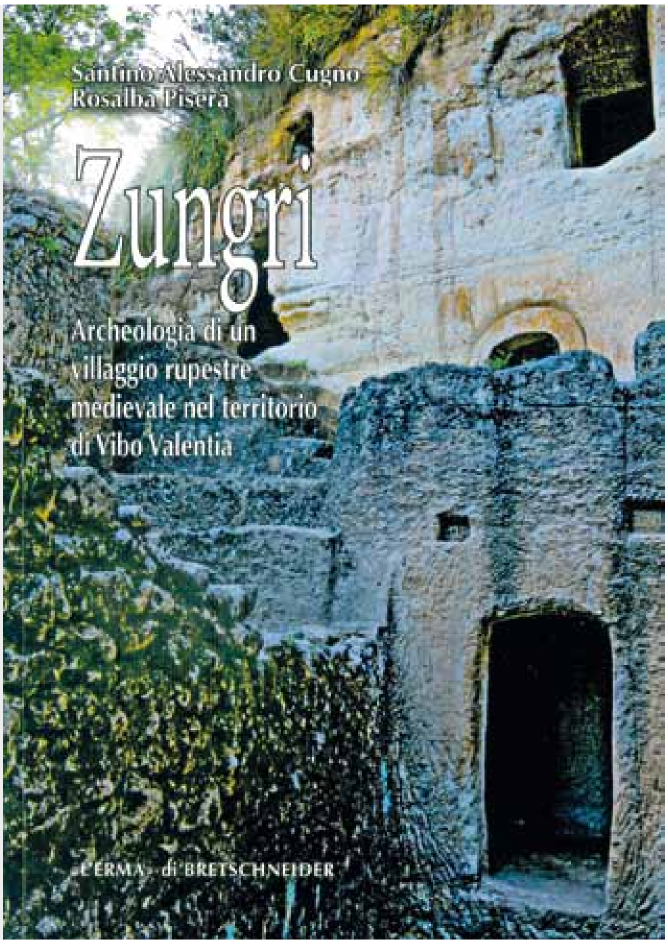

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The contribution of geophysical prospection in the recognition of artificial cavities

Il contributo della prospezione geofisica nella individuazione di cavità artificiali

Marilena Cozzolino[1], Vincenzo Gentile[1], Paolo Mauriello[1]

Abstract

Underground cavities, whether natural or artificial, have an important naturalistic, historical and cultural value. Knowing these places is fundamental for their conservation and enhancement from a tourist and attractive point of view. On the other hand, they can represent a hazard as collapse phenomena involve a high risk for public safety, both in an urban and extra-urban environment. It follows that their prior identification is essential to protect this heritage, ensure safety and manage building planning projects through careful assessment and risk mitigation. Alongside direct speleological observation, an important role is played by geophysical exploration. In recent years, significant technological advances have introduced numerous innovations in the field of applied geophysical prospecting, in both data acquisition and processing techniques, allowing the three-dimensional features of buried structures and surfaces to be identified quickly and accurately. This represents a great advantage, in terms of safeguarding the underground environments, since all the necessary elements are provided to prepare interventions that avoid or minimize the impact with them. The main property of geophysical methodologies is their non-invasiveness. In fact, geophysical methods are able to describe underground structures of interest present in the ground through measurements, carried out exclusively from the surface, which do not involve intensive mechanical work and which therefore do not endanger the structures that are intended to be located. This is possible because the physical properties of rocks or structures present in the ground are measured, based on their effects on the surface. What lies beneath the surface is described in physical terms such as density, electrical resistivity, magnetism, etc. From the more or less regular trend of the measurements and, above all, from the identification of the so-called geophysical anomalies it is possible to hypothesize the presence of hypogea and, in the most favorable cases, it is even possible to evaluate the directions and trends of the structures themselves, up to draw, with a good approximation, their three-dimensional spatial distribution. This contribution aims to briefly expose the active (seismic, electromagnetic, geoelectric and GPR) and passive (magnetic and gravitational method) geophysical techniques most useful for this purpose. For each of the methods, the operating principles are briefly described and, on the basis of the physical parameters measured, the potential for identifying cavities in different geological contexts are underlined. Finally, in order to highlight the effectiveness of these techniques, some case studies are presented relating to the use of geoelectric, electromagnetic and GPR prospecting for the identification of artificial cavities such as hydraulic works and buildings of worship. In particular, the applications with positive results in the identification of cisterns in the Municipality of Frigento (Avellino, Italy) and in the UNESCO archaeological site of Umm ar-Rasas (Jordan), of the hydraulic system of the Chapultepec Park (Chapulín, City of Mexico), of Roman aqueducts in Alba Fucens (Massa d'Albe, L'Aquila, Italy) and in Vasto (Chieti, Italy), of a *giacciara* at the Castle of Zena (Carpaneto Piacentino, Italy), of an unknown tunnel in the territory of Pomigliano d'Arco (Naples, Italy) and of probable voids attributable to burials around the Tomb of Laris in Città della Pieve (Perugia, Italy).

Key words: geophysical prospections, electrical resistivity tomography, electromagnetic survey, georadar, artificial cavities.

Riassunto

Le cavità sotterranee, siano esse naturali o artificiali, hanno un importante valore naturalistico, storico e culturale. Conoscere questi luoghi è fondamentale per la loro conservazione e per la loro valorizzazione dal punto di vista turistico e attrattivo. Di contro essi possono rappresentare un pericolo in quanto fenomeni di collasso implicano un rischio elevato per l'incolumità pubblica, sia in ambiente urbano che extra-urbano. Ne consegue che la loro individuazione a priori è fondamentale per proteggere questo patrimonio, garantire la sicurezza e gestire progetti di pianificazione edilizia attraverso un'attenta valutazione e mitigazione dei rischi. Accanto all'osservazione speleologica diretta, un ruolo importante è svolto dall'esplorazione geofisica. Negli ultimi anni i notevoli progressi tecnologici hanno introdotto numerose innovazioni nel campo della prospezione geofisica applicata, sia nelle tecniche di acquisizione che nell'elaborazione dei dati, consen-

[1] University of Molise, Department of Agricultural, Environmental and Food Sciences, Via De Sanctis snc, 86100 Campobasso, Italy

Corresponding author: Marilena Cozzolino - marilena.cozzolino@unimol.it

tendo di individuare i lineamenti tridimensionali delle strutture e delle superfici sepolte in maniera veloce e accurata. Ciò rappresenta un grande vantaggio, in termini di salvaguardia degli ambienti ipogei, poiché vengono forniti tutti gli elementi necessari per predisporre interventi che evitino o riducano al minimo l'impatto con essi. La proprietà principale delle metodologie geofisiche è la loro non invasività. Infatti, i metodi geofisici riescono a descrivere strutture ipogee di interesse presenti nel sottosuolo tramite delle misure, effettuate esclusivamente dalla superficie, che non implicano un lavoro meccanico intensivo e che quindi non mettono in pericolo le strutture che si intendono localizzare. Questo è possibile in quanto vengono misurate le proprietà fisiche delle rocce o strutture presenti nel sottosuolo, in base ai loro effetti in superficie. Ciò che si trova al di sotto della superficie viene descritto in termini fisici quali densità, resistività elettrica, magnetismo, ecc. Dall'andamento più o meno regolare delle misure e, soprattutto, dall'individuazione delle cosiddette anomalie geofisiche è possibile ipotizzare la presenza di ipogei e, nei casi più favorevoli, è addirittura possibile valutare le direzioni e gli andamenti delle strutture stesse, fino a disegnarne, con buona approssimazione, la loro distribuzione spaziale tridimensionale. Questo contributo si propone di esporre sinteticamente le tecniche geofisiche attive (prospezione sismica, elettromagnetica, geoelettrica e GPR) e passive (metodo magnetico e gravitazionale) più utili allo scopo. Per ognuno dei metodi vengono brevemente descritti i principi di funzionamento e, in base ai parametri fisici misurati, vengono sottolineate le potenzialità di individuazione di cavità in diversi contesti geologici. Infine, allo scopo di evidenziare l'efficacia di tali tecniche, vengono presentati alcuni casi studio relativi all'uso di prospezioni geoelettriche, elettromagnetiche e GPR per l'individuazione di cavità artificiali quali opere idrauliche e edifici di culto. In particolare si riportano le applicazioni con esito positivo nell'identificazione di cisterne nel Comune di Frigento (Avellino, Italia) e nel sito archeologico dell'UNESCO di Umm ar-Rasas (Giordania), di sistema idraulici del Parco Chapultepec (Chapulín, Città del Messico), di acquedotti romani ad Alba Fucens (Massa d'Albe, L'Aquila, Italia) e a Vasto (Chieti, Italia), di una "giacciara" presso il Castello di Zena (Carpaneto Piacentino, Italia), di un cunicolo sconosciuto nel territorio di Pomigliano d'Arco (Napoli, Italia) e di probabili vuoti attribuibili a sepolture intorno alla Tomba di Laris a Città della Pieve (Perugia, Italia).

Parole chiave: prospezioni geofisiche, tomografia elettrica di resistività, indagine elettromagnetica, georadar, cavità artificiali.

Introduction

The scientific community has always had a great interest in the study of underground cavities for their naturalistic, historical and cultural value. On the other hand, public administrators consider them to be elements of high value for their touristic attractive capacity. At the same time, however, due to possibility to generate collapse phenomena (Gutierrez *et al.*, 2014; Parise, 2019, 2022) they can be considered a hazard and having a vulnerability map is of fundamental importance to guarantee public security and allow civil engineers to build safely (Abidi *et al.*, 2017). Hence the need to increase the knowledge of these places. Cavities can have a natural or an artificial origin. Natural cavities are mainly formed in soluble karst rocks and, following Ford and Williams (2007), they can be classified by internal characteristics (size, vertical and horizontal dimensions, plan form, passage cross-section form, relation ti local or regional water table, categories of deposits) or in relation to external factors (modes of geological control, topographics setting, relation to topography, role in fluvial system, acquifer type, role in geomorphological and hydrological cycles, climatic setting). Artificial cavities are widespread in the word and, according to their intended use, they are classified in the following categories (Galeazzi, 2013; Parise *et al.*; 2013): works of worship, transit routes, hydraulic, civil, military and mining works.

In support of direct speleological exploration, an important contribution in cavities' identification is given by the application of non-invasive geophysical investigation techniques. There is a wide range of methods useful for these purposes including electrical resistivity tomography (ERT), electromagnetic prospecting (EM), ground penetrating radar (GPR), seismic, magnetic and gravimetric methods. All approaches are potentially useful even if the success of a prospection depends on the type of cavity (excavated in the rock/soil or built), its filling (air, water, filling material and the degree of its consolidation), the nature of the enclosing rock, the size, the depth, the conditions of the surfaces on which to operate, the available investigation spaces and the presence of environmental disturbances on the surface. Such disturbances may be due to various causes: intrinsic soil (inhomogeneity), topography (irregular topography can generate unacceptably effects), anthropic action (electric lines, piping or other objects buried) (Mussett & Khan, 2003). A common way to improve the signal is the acquisition of a large number of data in order to analyse the deviation of each individual measure from the average value. When environmental disturbances are minimized, measures must be treated by a reverse procedure, a process that allows to trace back to the physical model and hence to the cavity model.

Geophysical anomalies can sometimes be larger than the real dimensions of the cavities because of the so-called "halo effect" due to the presence of fractured rocks at the edges. Therefore, the seismic velocity can be reduced, but being of small thickness, there are no significant variations in the reflections. In the conductivity measurement it is possible to notice a reduction of the acquired values if the cracks are dry, an increase if they are filled with water. In gravimetric prospections, fractures increase the volume at reduced density, while in magnetic surveys no effects are observed.

In this paper, a brief review of the potentialities of the methods are described and some examples of successful applications of selected methods in the definition of artificial cavities are shown.

Geophysical methods for cavity's detection

Generally, geophysical methods are classified into two main categories: passive methods and active methods. In the first ones, the intrinsic properties of the soils are directly measured as in the magnetic method and the gravitational method; in the second ones, the terrains are energized with artificial fields and the resulting disturbances are measured. This category includes seismic, electromagnetic, electrical and GPR.

Passive methods

Among the passive methods, the microgravimetric method is the one that has had a wider application in cavity detection (Neuman, 1977). It consists in measuring the mass difference between a feature and a surrounding mass (Reynolds, 1977). The difference between real and theoretical value of the gravity acceleration at each measurement point, the so-called gravity anomalies, determines density contrasts. In order to remove the effects of temporal (sun and moon attraction, instrumental drift) and spatial variation (latitude, altitude and relief) it is necessary to make several corrections to the measured values.

Minor variations in gravity are due to changes in the density of underground materials or in the presence of underground constructions. If there are dense and compact rocks in the stratigraphy, gravity is greater than areas where smaller densities are present, such as sand, clay or untied material. Depending on the filling of the cavity, different anomalies can be detected: empty cavities full of air generally give rise to strong negative amplitudes; cavities filled by water generate anomalies reduced by 40% and cavities collapsed or filled with dense materials (rocks or soils) by 60% (Owen, 1983). As the value of the gravitational field measured in a given instant, at a certain point, can be influenced by a large number of factors, an accurate data acquisition, data correction and digital data analysis is required to determine the nature of the anomalies (Debeglia & Dupont, 2002). In addition, final interpretation must take into account the geological and historical features of the site.

Successful applications of microgravity technique in cavity exploration can be found in different papers. As regards natural cavities, Arzi (1975) and Butter (1984) successfully used microgravimetric surveys for delineating a zone of small karstic cavities and shallow air-filled and deep water-filled cavity systems, respectively. Other studies focused on the application of this method to target subsurface cavities and karst features are reported by Berrino *et al.* (1982) and Omnes (1977). Recently, the microgravity technique is often combined with different types of prospections (Mochales *et al.*, 2008; Leucci & De Giorgi, 2010; Martínez-Moreno *et al.*, 2013).

Since the 1970s, the method was also used for the identification of artificial cavities. Linnington (1966) applied it for a test on Etruscan chamber tombs at Cerveteri, Fajklewicz (1976) detected shallow abandoned mine workings in Poland and Bishop *et al.* (1997) presented case histories in mine environments. In addition, Lakshmanan and Montlucon (1987) observed different anomalies in the Great Pyramid, which conceal the real tomb and treasures of Cheops and Linford (1998) was able to locate suspected archaeological void features at Boden Vean, Cornwall. Recently, Styles *et al.* (2006), Martinez-Moreno *et al.* (2016) and Florsch *et al.* (2021) proposed the microgravity as a tool for the characterization of ancient mine voids. Finally, Pánisová and Pašteka (2009) and Fais *et al.* (2015) tested the effectiveness of the technique, respectively, for the identification of a crypt in the St. Nicolas Church in Pukanec (Slovakia) and for detecting cavities in an archaeological site in Sardinia (Italy).

The magnetic method generally produces successful cavity detection only under certain conditions and for this reason it is used when these conditions occur or in conjunction with other methods.

Underground rocks have magnetizations that differ from the surrounding ones and thus produce anomalies in the magnetic field on the surface. The magnetization is due to induction by magnetizing forces associated with Earth's field and in part remnant magnetization (Parasnis, 1997). The first is based on the difference between the magnetic properties of the abnormal source, as an anthropic structure, and those of the soil in which the structure is embedded; the second phenomenon is influenced by the characteristic of materials to assume a permanent magnetization after being subjected to very high temperatures. It allows the identification of certain artificial structures in which the material has been subjected to very high temperatures.

Water and air are not magnetic elements and in non-magnetic rocks, such as limestones, it is likely that they are not identifiable at all. In case the cavity is filled with a relatively magnetic sediment surrounded by non-magnetic rocks, some variations are measured (Mussett & Khan, 2003). The greatest success of magnetic surveys is found in the identification of artificial cavities where there may be an abundance of iron (pipes, mining wells) or the wall coverings are made with fired bricks (furnaces, tombs, thermal structures) or with volcanic rocks (such as slate, granite and basalt) (Piro *et al.*, 2007, Argenteri *et al.*, 2015).

Active methods

Active geophysical methods are more widely used in explorations of cavities.

Geoelectrical surveys are among the most suitable geophysical tools for the study of the stratigraphy, acquiring information regarding geometry and localization of buried targets considering their intrinsic electrical resistivities. A geoelectrical field survey is carried out measuring on the ground the potential difference across a pair of electrodes, generated by a direct current injected in the subsoil through a second pair of electrodes. By changing position and spacing of the electrodes according to specific rules, horizontal and vertical resistivity changes in the subsoil can be investigated. Nowadays, the 3D Electrical Resistivity Tomography (ERT) approach is used routinely, thanks to the latest technological developments that make it a fast, versatile and cost-effective method for depicting resistivity structures. The dipole-dipole (DD) electrode configuration moved on the ground along a profile is the most suited array for gathering ERT data and its layout is also largely more sensitive to lateral resistivity contrasts than other conventional arrays. For this reason, it can be particularly effective in highlighting cavities that cause strong lateral resistivity contrasts at the boundary with the hosting subsoil (Putiška *et al.*, 2012).

An air cavity has higher resistivity than the surrounding rock but, if the rock is dry, its resistance can be so high that the contrast is too small to exploit. Conversely, a water-filled cavity usually has lower resistivity than its surroundings (Mussett & Khan, 2003). When planning the survey it must be considered that the length of the profile must be wide enough to penetrate to the depth of the cavity (the greater the length of the traverse, the greater the depth reached). Furthermore, if a supposed deep cavity is at the edges of the profile and there are not enough spaces to centre it with respect to the traverse, it is not identifiable. In the realization of 3D tomographies, obtained by acquiring data on profiles arranged on regular grids, it is necessary to arrange sufficiently close traverse so as not to neglect any interposed cavities. Since the 1950s, electrical resistivity techniques were widely used in cavity detection. Cook and Nostrand (1954) interpreted resistivity data over filled sinks, Dutta *et al.* (1970) detected solution channels in limestone and Militzer *et al.* (1979) conducted theoretical and experimental investigations for cavity research. More recent works report the use of this technique for mapping karst hazards (Zhou *et al.*, 2002), to recognize buried cavities in urban environment (Cardarelli *et al.*, 2006) and to detect sinkholes (Van Schoor, 2022).

Electromagnetic (EM) methods are based on the measure of electromagnetic fields connected with alternate induced currents into the ground by a primary magnetic field. In different methods, the induced field is produced by the passage of the current through a transmitter coil or a metallic antenna. The primary magnetic field spreads above and below the ground and therefore through probable target bodies. The induced currents generate a secondary electromagnetic field that usually differs in intensity, phase and direction from the primary field and allows detecting probable hidden targets. A receiving coil receives the secondary field. The signal depends on multiple factors such as the type of material (higher is its conductibility, stronger is the current), the form and the depth of the hidden target and the position of the transmitter and the receiving coil.

EM methods are particularly suitable for identifying cavities, especially when the matrix that incorporates them has very high resistivity. The opposite is true when the material is highly conductive. However, the method is particularly sensitive to lateral variations of the near-surface karst features. Light-weight equipment with high resolution and fast measurement progress are preferential aspects over other methods especially for a preliminary assessment of a large-scale site. EM have proved useful in identifying and locating several cavities including air-filled drainage gallery (Ogilvy *et al.*, 1991); karst structures (Bosch & Müller, 2001) and large groundwater-bearing fracture zones (Sharma *et al.*, 2005).

The Ground Penetrating Radar (GPR) is capable to detect shallow alternation in the stratigraphy by transmitting an induced electromagnetic field into the ground that is then viewed through a contour map of the subsoil. Certain anomalies shown in such maps reflect changes of basic properties of the electromagnetic field, in its conductivity, electric permittivity and magnetic permeability; those parameters that are interrelated and therefore correspond to alterations caused by voids and/or are products of the interfaces between different soil types. The factors that affect system performance are above all the electromagnetic properties of the medium propagation that determine the depth of investigation, which therefore varies from point to point. However, as medium mitigation is a function of frequency radiated, the use of low-frequency antennas can generally extend the depth of penetration of GPR signals but can also generate the loss of resolution. During data acquisition, two parameters are measured: the time in which the electromagnetic wave fulfils the path transmitter antenna-discontinuity-receiver antenna (two-way time) and the amplitude of the wave. The two-way time depends on the velocity with which the wave spread into the geomaterials and gives information about the depth of reflectors. The amplitude represents the amount of energy that returns to the surface and depends on the energy of the transmitted wave, on how much of it is dissipated along the path and on the contrast in the electromagnetic properties of the materials that determine the reflection surface.

GPR is very efficient for describing surface cavities in details. The method has been used successfully for imaging of collapsed paleocave systems (McMechan *et al.*, 1998), cave detection in limestone (Chamberlain, 2000), shallow caves (Beres *et al.*, 2001), potential sinkhole (Batayneh *et al.*, 2002) and other karst features (Pueyo-Anchuela *et al.*, 2009). The method is also very efficient if they are artificial such as pipes, tombs, hydraulic works, but its applications are extremely limited when the overburden is electrically conductive.

The seismic refraction method is a method based on the measurement of the first arrival times of the seismic waves generated on the surface by a seismic source and picked up by receivers, also at the surface, arranged on an alignment at different distances from the source. The first arrival times, correlated to the different source-receiver distances, allow the estimation of the subsoil geometries (topography or morphological arrangement of the interfaces) and of the propagation speeds of the seismic waves. A cavity can have very low seismic velocity compared to the surrounding matrix and therefore this may not ensure the success of a seismic survey. Conversely, horizontal limits of cavities can be detected if there is a velocity contrast at the top or the bottom of the medium. Seismic refraction methods can provide important knowledge, especially as concerns near-surface heterogeneities and cavities (Belfer *et al.*, 1998, Chalikakis *et al.*, 2011 and reference therein).

Integration of methods

All mentioned methods are frequently applied to a case study individually or using a combined approach. The latter is the most recommended with the aim of obtaining high quality information through a global assessment of the convergence of data subject to different physical factors. Thanks to the integration of several techniques, it is possible to find the same geophysical anomalies, which, despite having been detected through various physical behaviours, identify the same buried target. In peculiar geological contexts, often some methods indicate consistent inhomogeneities, while other methods detect a situation of partial uniformity. For this reason, the multi-methodological approach gives the general analysis of the site greater completeness and accuracy.

In the literature there are many papers dealing with the integration of methods for the study of cavities. Beres *et al.* (2001) integrated GPR and microgravimetric methods to map air filled shallow caves in western Switzerland. Piscitelli *et al.* (2007) successfully mapped shallow cavities through a joint use of GPR and microwave tomography in the historical area of "Sassi of Matera" (southern Italy). Mochales *et al.* (2008) conduced gravimetric, magnetic and GPR surveys that led to a successful detection of air filled karst cavities in the Zaragoza area in northeastern Spain. Gambetta *et a*l. (2011) confirm the ability of Vertical-gradient microgravity and ERT surveys to give the precise location of the shallow voids, even in complex environments, such as in the Italian Armetta Mountain karst area, close to the Liguria-Piedmont watershed. The integrated results of the two surveys show a clear geophysical response through the exhibition of high resistivity values and a negative gravity anomaly over the large cave passages. In Chalikakis *et al.* (2011) a state of the art of the contributions by geophysical methods to karst-system exploration, based on extensive analysis of the published scientific results is presented. The paper represents an interesting overview that can be used as a preliminary methodological approach. Abbas *et al.* (2012) conducted a combined application of GPR, ERT, magnetometry and Very Low Frequency Electro Magnetic (VLF-EM) technique at the archaeological site of Tap-Osiris Magna in Egypt. The best results were obtained from VLF-EM interpretation that, correlated with 2-D resistivity imaging and drilling information, showed a highly resistive zone at a depth extending from about 25 to 45 m, which could be indicated as the tomb of Cleopatra and Anthony. Martínez-Moreno *et al.* (2013) reports the combined application of microgravity and electrical tomography, including ERT and induced polarization (IP) techniques, for the study of the deep Algaidilla cave (Southern Spain) buried in carbonates. Microgravity was able to detect the caves, but it alone failed to estimate the geometry. ERT results delineate the cavity both above and below the water table and the IP method was useful for detecting decalcification clays, often present at the base of karstic caves. Argentieri *et al.* (2015) followed a multi-methodological approach reporting measurements of GPS-altimetry, magnetic, gravity, geoelectrical, seismic, and soil gas for the study of a sinkhole near the Guidonia military airport (Italy). Due to the presence of vertical cavities formed in flanks of the depression, the research aimed to reveal the extension of the phenomena and to monitor the sinkhole's evolution. The measurements revealed a wide and deep ellipsoidal depression and a border characterized by a topographic scarp with near vertical geophysical discontinuities of the subsurface. Júnior *et al.* (2015) successfully mapped collapsed paleocaves at the western border of the Potiguar Basin in Northeastern Brazil combining the analysis of ERT and GPR sections by identifying high-resistivity zones and high-amplitude ground-penetrating radar reflectors. In contrast, the host rocks were marked by low to intermediate resistivity and ground-penetrating radar reflections that range from low amplitude to almost transparent. The results of the study showed the detailed internal geometry of this paleocave system enabling the identification of the connectivity pattern among these karst features and the porosity and total volume of the reservoir. Pazzi *et al.* (2018) carried out 2D- and 3D-ERT, microgravity and single-station seismic noise measures at "Il Piano" (Elba Island, Italy). In this place, at least nine sinkholes occurred due to erosion of sediment caused by water circulation between the aquifer hosted in the upper layer and that in the lower. The results of the integrated geophysical surveys suggested the presence of paleochannels and that the sinkhole-prone area boundaries correspond to these landforms. Mohamed *et al.* (2019) integrated ERT, GPR and MASW for detecting near-surface caverns at Duqm area, Sultanate of Oman. The results showed good agreement in terms of depth and dimensions of the detected caverns two cavern systems of varying thicknesses. The caverns, not completely hollow, were well delineated: they are separated at the top, but at some locations, they become a one-unit cavern system. Florsch *et al.* (2021) used ERT and microgravity for the detection of ancient mine voids at the Castel-Minier in southern France. Microgravity allowed the detection of a deep hypothetical cavity and a shallow one that was confirmed by ERT.

Experimental sites

Geophysical prospecting, under certain conditions, can be decisive in the indication of cavities in the stratigraphy. Beyond the method used, the necessary condition for the success of an investigation is that there is an adequate physical contrast between the target and the enclosing geomaterial. In this session, some examples of successful applications of geophysical prospecting, limited to geoelectric methods, electromagnetic technique and GPR, for the identification of artificial cavities are shown. The categories presented fall within the scope of hydraulic works and structures of worship.

A Roman cistern in the Municipality of Frigento (Avellino, Italy).

In the historic centre of Frigento (fig. 1a, b), in southern Italy, there are some known cisterns, wells and tunnels dating back to the Roman republican period (fig. 1c). They had the function of collecting rainwater or groundwater that, after being purified, was distributed in various points of the city for domestic or public use, but also to the inhabitants of the neighbouring territories.

Today, four tunnels are known of the articulated hydraulic system of cisterns (only three can be visited, because the fourth is obliterated by filler material) as reported by the Central Institute for Catalogue and Documentation (ICCD), Ministry of Cultural Heritage and Activities[1]. In particular, the three parallel tunnels have a rectangular in shape and a NW-SE orientation and the following dimensions: 21 m long, about 2 m wide and 3.90 m high. The galleries are connected by two arch-shaped openings perfectly aligned.

Fabio Ciampo (1760-1846), a local historian, in two manuscripts, respectively preserved in the Provincial Library of Avellino and in the Library of the Neapolitan Society of National History of Naples, carefully described all the environments that make up the cisterns and he formulated the hypothesis of the location of the other environments. According to Ciampo, the cisterns consisted of 11 arms connected through intercommunicating tunnel systems. They must have headed for some wells, currently located in gardens of private homes. In addition, the orientation of the road axes, which attest to the settlement phase of the Roman period in Frigento, follows the alignment of the cisterns.

As part of a collaboration between the University of Molise and the Archaeological Superintendence of Salerno, Avellino and Benevento, geophysical investigations were carried out inside the gardens of Palazzo De Leo (fig. 1d). The intervention was carried out in

[1] https://catalogo.beniculturali.it/detail/ArchaeologicalProperty/1500875170

Fig. 1 – a): location of Frigento (Avellino, Italy); b): location of surveyed area on a Google Earth™ satellite image; c): a tunnel; d): Palazzo De Leo.

Fig. 1 – a): localizzazione di Frigento (Avellino, Italia); b): indicazione dell'area d'indagine su immagine satellitare di Google Earth™; c): un tunnel; d): Palazzo de Leo.

the frame of a redevelopment project of the historic centre through the discovery of any other Roman pre-existing structures of the cistern complex and was promoted by the Municipality of Frigento.

The whole area has been investigated with a series of parallel ERT profiles thus obtaining a 3D matrix of data of the volume underlying the investigated surface from which the horizontal sections are extracted at various depths in which the various buried structural features are displayed. Figure 2a shows the slice relative to 3 m in depth, where an anomaly with high resistivity values attributable to a buried cavity is evident. In figures 2b and 2c, instead, three-dimensional views of the tomospaces were realized, and all the values lower than the average measured value were made transparent. From these images, the three-dimensional structure of the cavity can be easily obtained. As part of the renovation of the building, these results were taken into account and reinforcement of the structure was planned on the side affected by the vacuum to avoid collapses, especially in view of natural hazards such as seismic events.

Ancient cisterns at the site of UNESCO archaeological site of Umm ar-Rasas (Jordan).

The archaeological site of Umm ar-Rasas is located 30 km SE to the town of Madaba in Jordan, north of the Wadi Mujib and it covers approximately 10 ha on the Moab's plateau (fig. 3a). From 1986 to 2007, the archaeological researches were conducted by the Franciscan Archaeological Institute of Mount Nebo (Piccirillo, 1994, 2008) under the patronage of the Department of Antiquities of the Hashemite Kingdom of Jordan. In 2004, it was inscribed in the UNESCO's World Heritage List. From 2013, the Institute for Technologies Applied to Cultural Heritage (now Institute of Heritage Sciences), Italian National Research Council, in collaboration with University of Molise for the geophysical research, started a research project with the aim of reconsidering previous researches, documenting the standing structures and preparing the bases for conservation, restoration and use of the site. Galatà *et al.* (2017), Cozzolino *et al.* (2018), Malinverni *et al.* (2019), Piertidica *et al.* (2021) report parts of the multidisciplinary results in their papers.

The remains consist of a huge area, fortified by a massive wall that measures 158x140m, on which numerous buildings are located and that once was a Roman Castrum (fig. 3b). Towards the northern part of the archaeological site, housing and sacred structures have been identified, which can be dated from the Byzantine to the Early Islamic period, up to the IX century A.D. (Piccirillo, 1994). The most relevant religious complex is Saint Stephen's, by the name of the proto-deacon and proto-martyr to whom it was dedicated. It was developed between the VI and VIII

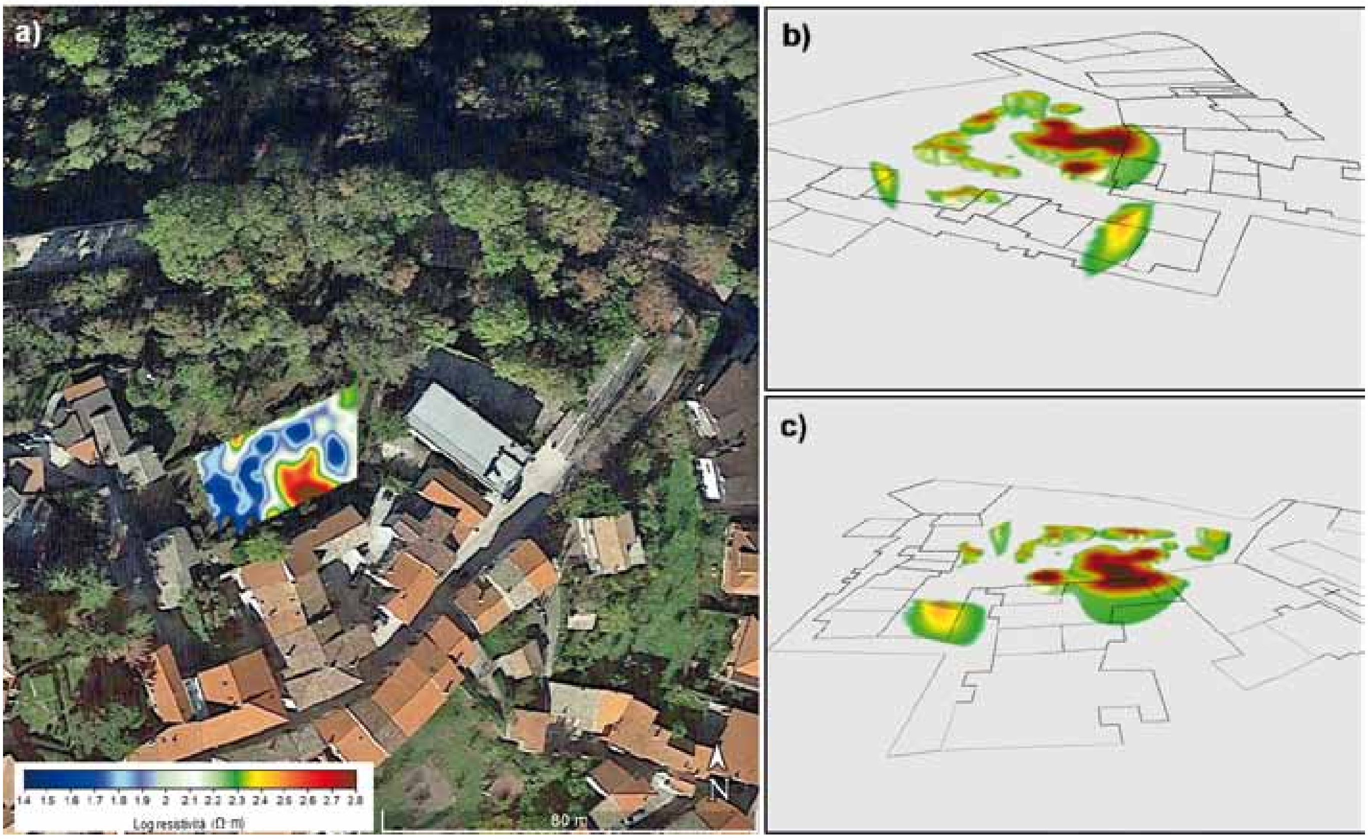

Fig. 2 – a): resistivity map relative to 3 m in depth; b), c): three-dimensional views of the tomospaces.

Fig. 2 – a): mappa di resistività relativa a 3 m di profondità; b), c): viste tridimensionali dei tomospazi.

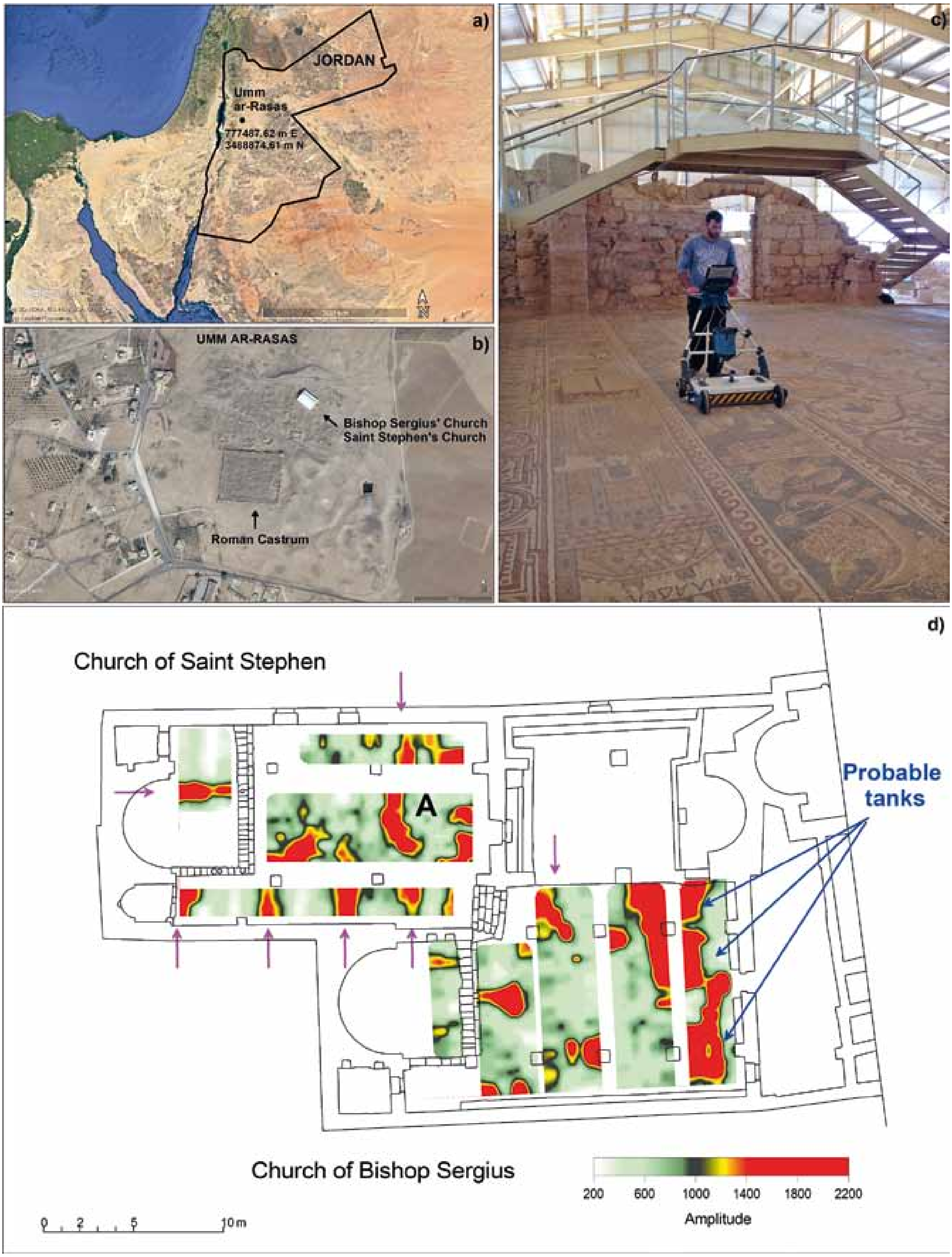

Fig. 3 – a): location of Umm ar-Rasas on a Google Earth™ satellite image of Jordan; b): detail of the site with indication of the roman castrum and the two Byzantine Churches; c): GPR prospection; d): horizontal slices related to the depth window of 0.5-0.7 m overlapped on the map of the churches (the blue arrows indicate the location of probable tanks, while the pink arrows highlight probable buried archaeological structures).

Fig. 3 – a): localizzazione di Umm ar-Rasas su immagine satellitare di Google Earth™ della Giordania; b): dettaglio del sito con indicazione del castrum romano e le due Chiese Bizantine; c): prospezione GPR; d): sezioni orizzontali relative alla finestra di profondità di 0.5-0.7 m sovrapposte alla planimetria delle chiese (le frecce blu indicano la localizzazione di probabili cisterne, mentre the frecce magenta evidenziano probabili strutture archeologiche sepolte).

century A.D., formed by at least four communicating churches: the the Tabernacle that is the most ancient, Bishop Sergius with its baptistery and the funerary chapel to the front, Saint Stephen and the Courtyard, raised between the other three places of workships.
The research has focused on Sergius' and Saint Stephen's Churches (fig. 3c), both with three aisles and one apse and with the chancel rose by two steps. The two churches host mosaic floors of exceptional quality and rich with inscriptions, portraits, everyday life scenes, geometrical and plant motifs and nonetheless the representation of many towns from Palestine, Egypt and Jordan. In Bishop Sergius' Church those mosaics are dated with precision to 586 A.D. by an inscription located to the front of the altar's base, where it is mentioned the name of the commissioner, Bishop Sergius of Madaba (576-603 A.D.). Through time, they have been subject to modifications both for restoration and iconoclasm's reasons, such as in the case of many other contemporary religious complexes.
During 2016, a GPR survey was conducted at the archaeological site of Umm ar-Rasas inside the Churches of Bishop Sergius and Saint Stephen. Taking into account the probable type, dimensions and depth of submerged bodies and the surface on which the research group was working (i.e. on the mosaics), the GPR was preferred to other methods. Standard bidimensional radargrams relative to single transects were processed through band pass filters, background removal and the Gain Control in order to remove high and low frequency anomalies that occurred during the data acquisition, normalize the amplification and remove reflections generated by noise due to the different signal attenuation.
Then, using a sequence of parallel lines, a three-dimensional matrix of averaged square wave amplitudes of the return reflection was generated and time-slices were realized for various time windows. In the examined context, supposing a soil with velocity v with which the wave spread into the materials equal to about 0,1 m/ns, the depth h of the reflectors could be approximately derived using the equation h = vt/2 (where t is the time necessary to the electromagnetic wave to fulfil the path transmitter antenna-discontinuity-receiver antenna).
Figure 3d reports the results of GPR investigations relative to the depth window of 0.5-0.7 m, overlapped on the map of the churches. The anomalies seen in these representations depict the spatial distribution of the amplitudes of the reflections at specific depths within the grid. Within the slice, low amplitude variations express small reflections from the subsurface and, therefore, indicate the presence of homogeneous material. High amplitudes denote significant discontinuities in the ground and evidence the presence of probable buried objects. Regarding the Church of Saint Stephen, in the most superficial map, various anomalies perpendicular to the left aisle, a longitudinal anomaly in the centre of the median body of the church, and an anomaly in the space in front of the apse (at the right edge) are highlighted; they are indicated with pink arrows in figure 3d. In the Church of Bishop Sergius, the prospection showed, at the entrance of the structure, where traces of a water channel are visible, anomalies of regular shape probably attributable to voids and therefore to possible underground cisterns belonging to a more ancient chronological phase. Works are still ongoing and the main objective of the research is to produce a full map of hidden structures inside the walls of the city useful to promote archaeological excavations and project of valorisation of the site.

The hydraulic system of Chapultepec Park (Chapulín hill, Mexico City)

The Chapultepec Park (fig. 4a) is located at Mexico City on the Chapulín hill where the ancient city of Tenochtitlan was. It was the largest city in the pre-Columbian Americas and the capital of the expanding Aztec Empire in the 15th century. It was captured by the Spanish in 1521. When the city began to grow, there was the need to supply water to the surrounding territories starting from the springs on the hill (Villasenor 1987). Thus, in 1466, the aqueduct of Chapultepec was built. Canals and reservoirs to water, the so-called baths of Moctezuma (fig. 4b), which were also intended to increase the water level and the water pressure in the aqueduct pipeline, supported it. Here, one of the modern metal pipes for conveying the water into the cistern is clearly visible.
As part of a wider project on the hydraulic system of the castle, in the frame of a collaboration with the National Autonomous University of Mexico, different ERTs were carried out to test the resolution capability of geoelectrics over a small sized target buried at very shallow depth. In figure 6c, a three-dimensional view of the geoelectrical results is proposed. They show, starting from the top of the hill, where the castle of Chapultepec is, the location of different conductive nucleus (in blue in the sections) that are plausibly traces of ducts intercepted transversely. As a result, the network of water channels can be therefore inferred.

The aqueduct of the Latin colony Alba Fucens (Massa d'Albe, L'Aquila, Italy)

The Latin colony of *Alba Fucens* in the Abruzzo region (fig. 5), in central Italy, was founded by Rome at the end of 4th century BC. In the late-republican age, it was supplied by an aqueduct capable of providing water to the city from a distance of 10 km thanks to a channel and an inverted siphon. Mentioned in two inscriptions inherent some restoration works dated to the first half of 1st century AD, there is still little known about the Alba aqueduct's complete course and function (Parise 2007); it is one of the earlier aqueducts with a siphon in Italy. In the frame of a collaboration with the University La Sapienza of Rome, geophysical surveys were performed in order to understand the development of the aqueduct in Piani de

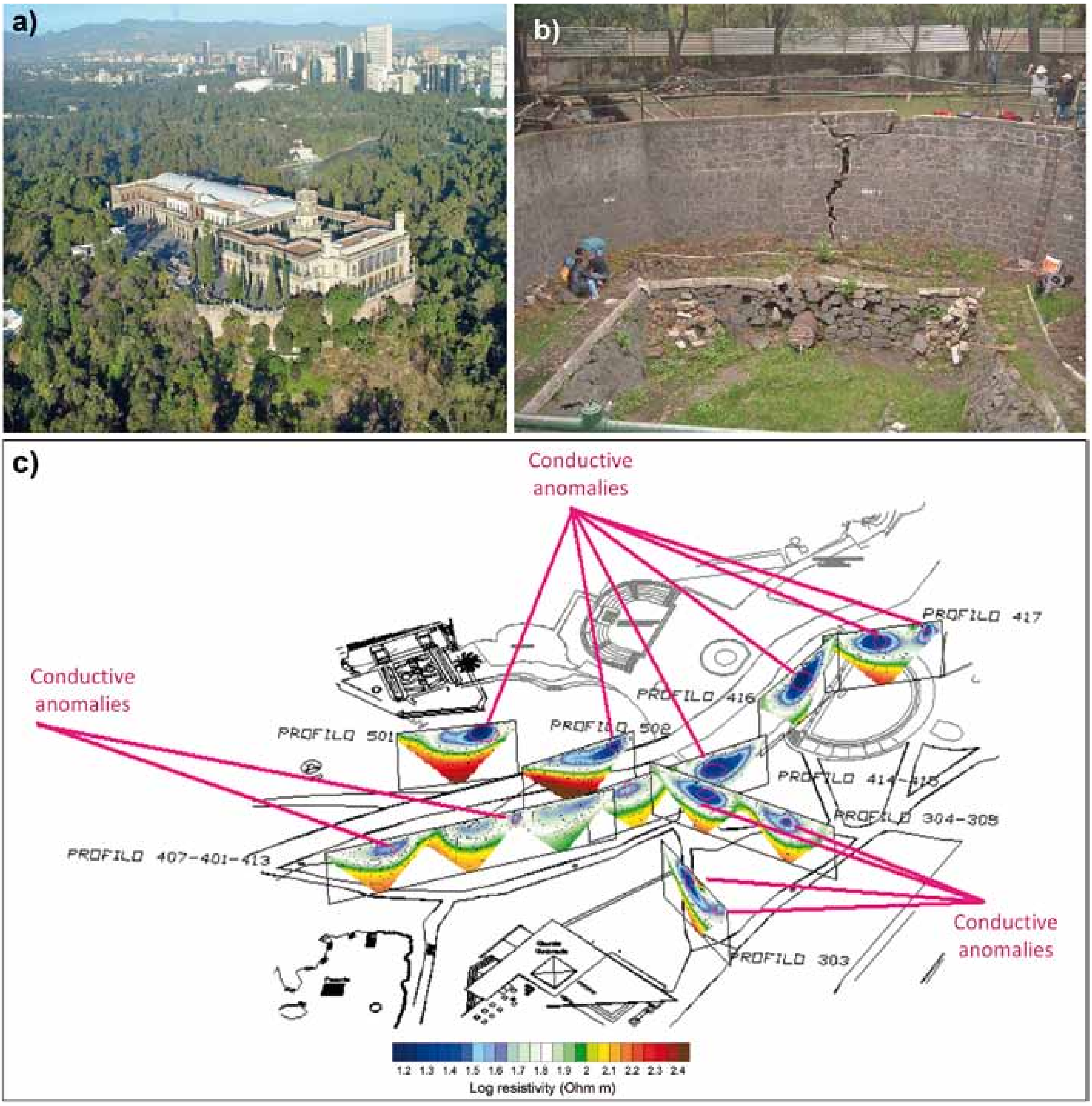

Fig. 4 – The castle of Chapultepec Park (a) and the Bath of Monteczuma (b), on the Chapulín hill, Mexico City. The network of water channels as resulting from ERT survey (c).

Fig. 4 – Il castello del Parco di Chapultepec (a) e il Bagno di Monteczuma (b), sulla collina di Chapulín a Città del Messico. La rete di canali idraulici come risultanti all'indagine ERT (c).

La Vara, Via del Tratturo (Rose *et al.*, 2016). Here, the morphology of the area shows the aqueduct, after a 1.2 km NE-SW long straight stretch with a constant 0.26 percent gradient, and in order to avoid the glacial valley of La Vara was forced to suddenly bend to south, crossing the contour line: maintaining the same gradient a free-flowing channel in few more than 800 m would have had to rise 33 m above the ground. The aqueduct bends toward south, following a constant descent from 1,010 m asl to 933 m (at Arci plain) and the free-flowing channel disappears in favour of a long platform made of *opus caementicium* where the pipes were probably mounted. The large structure in polygonal masonry of Arci, an embankment 11.90 m wide and 14 m high, over which the pipes were mounted, represents the only trace of the aqueduct visible today.

Different geoelectrical sections in this area were realized taking into account a section of the *specus* recently brought to light by archaeological excavation.

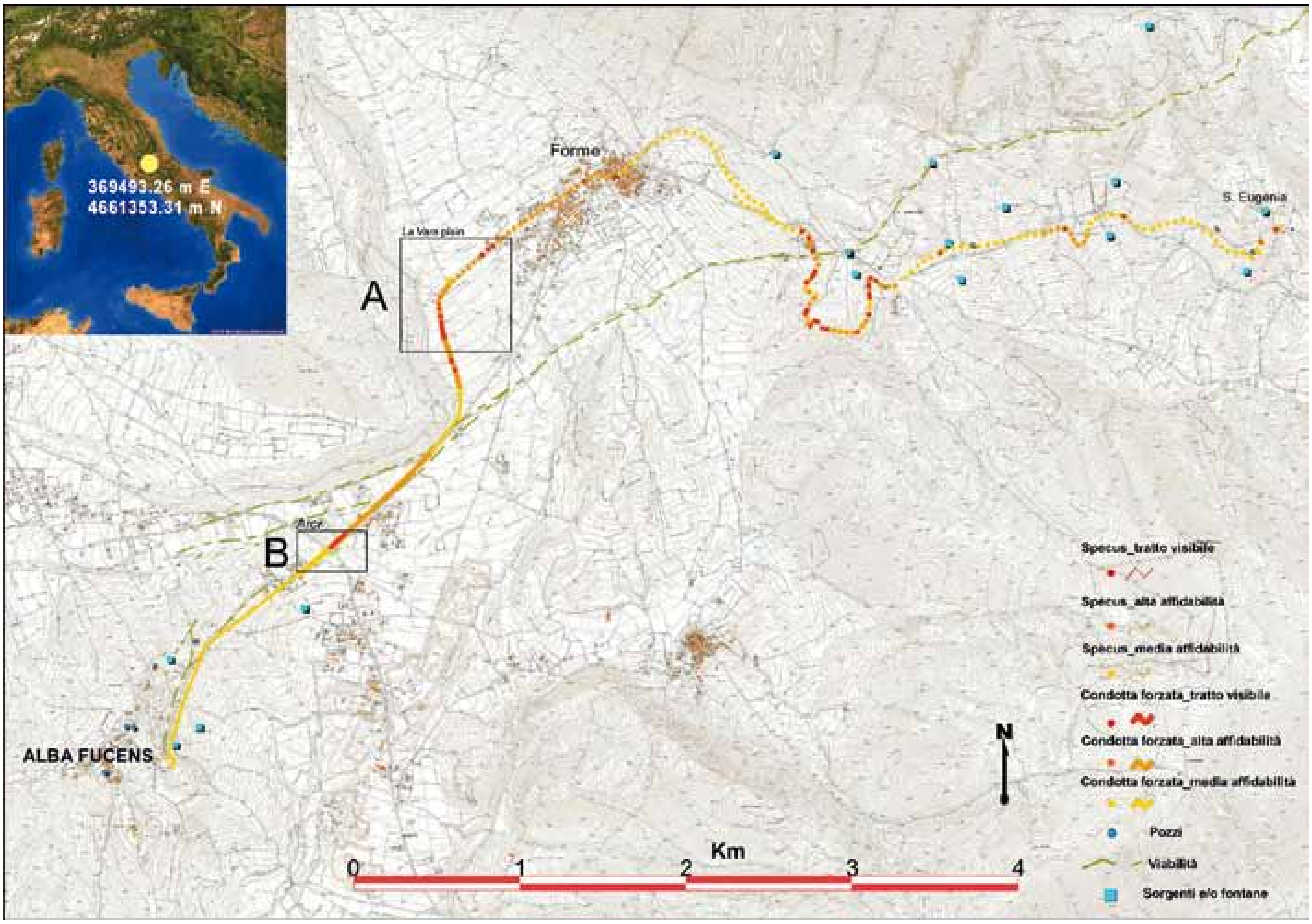

Fig. 5 – Map of Alba Fucens territory with indication of the roman aqueduct course and the surveyed areas (modified after Rose *et al.*, 2015).

Fig. 5 – Mappa del territorio di Alba Fucens con indicazione del percorso dell'acquedotto romano e dell'area d'indagine (modificato da Rose et al., 2015).

Its bottom lying at 1.87 m from the present ground level, was built in a filled-up trench and covered by a barrel vault. From this point, step by step, we narrowed the area where the header tank of the inverted siphon should have been positioned. We reported the results of the resistivity tomography realized as a test near the specus (fig. 6a and b): it is possible to note that the channel is represented by a low resistivity anomaly (blue colored anomaly, highlighted with a magenta circle) at 2 m in depth and with dimension similar to the excavated structure. In this case, the survey allowed determination of the direction of the hidden channel and its correlated structure. Five consecutive vertical tomographies (P2-P6) have allowed us to recognize the path to the specus towards SE (fig. 6d). The first two sections testify also the passage of the channel upstream of the road, while the third, interpreting the first anomaly as the noise/disturbance of the road itself, indicates the presence of the pipeline on the southern side of the road (with axial centre place around the meter 25 of the profile). The last three profiles delineate a path roughly rectilinear, well collimated for direction and depth with the upstream portion. Profile P7 has highlighted a new and different stratigraphic situation. In order to be able to represent data in horizontal sections, the investigated areas were properly covered by a grid of electric profiles (P7-P21), densely prepared with the purpose to obtain an appropriate resolution. We report as an example in figure 6d the P12 section in which a large conductive area is visible. It is approximately 10 m wide and appears about in the range 8-18 m and 1.5-4.0 m along the x- and z-axis, respectively. The processing of the whole resistivity data set allowed us to obtain a tomospace of the investigated volume from which series of horizontal maps with increasing depth were extracted, with the idea to better underline the spatial relationships among the anomalies present in the subsoil. In all horizontal resistivity slices a low rectangular resistive structure, about 10 m wide and 15 m long, appears, well delineated at 2 m in depth (fig. 6c). The apparent confluence of what we have identified along with the continuation of the open canal aqueduct on the northern narrow side of the structure, the orientation of this latter, makes it identifiable with the header tank. Downstream of the rect-

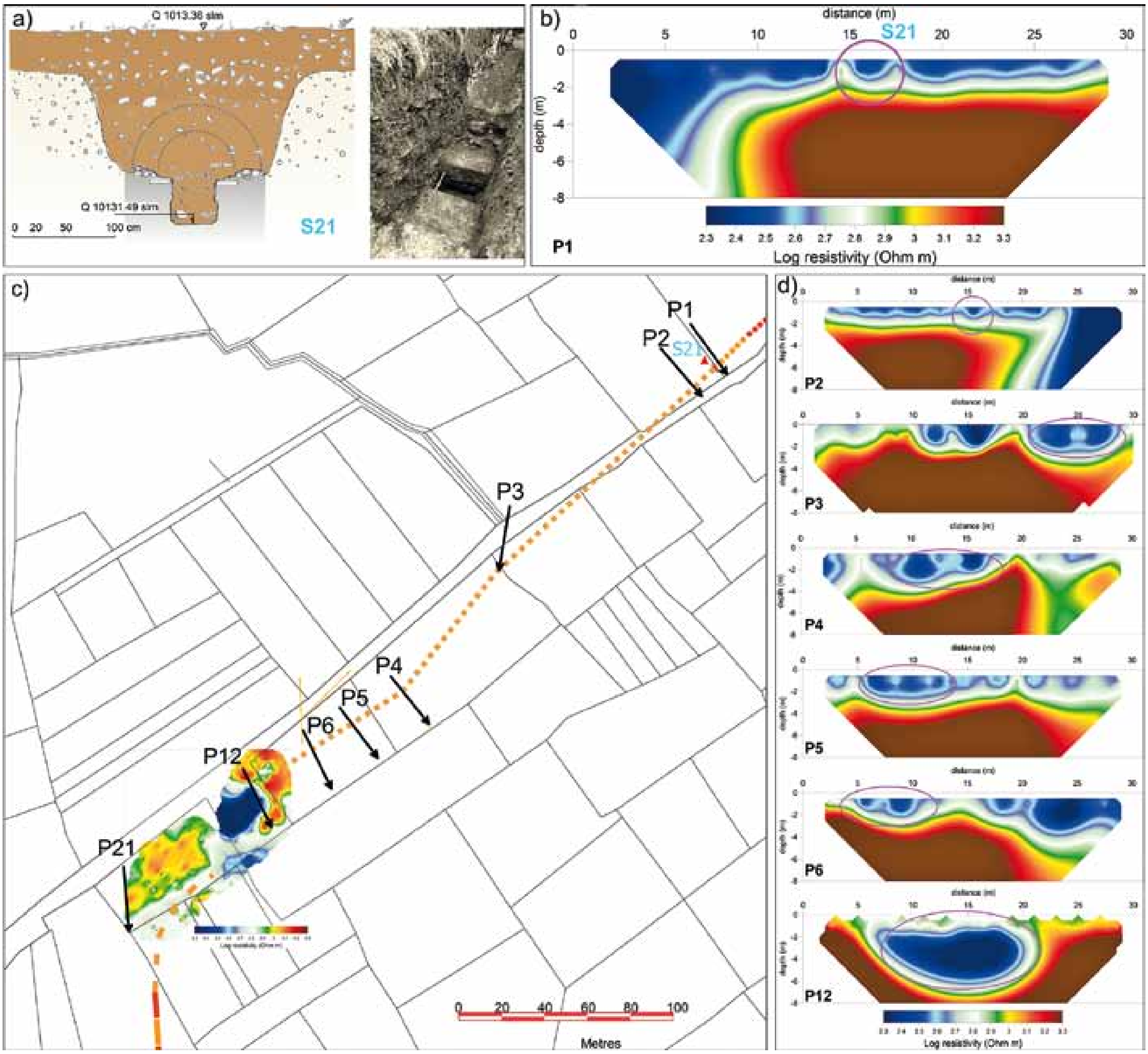

Fig. 6 – a): archaeological section of the specus (drawing and photo of Dario Rose); b): results of electrical tomography P1; c): results of electrical tomography P2-P6 and P12; d): electrical tomography; tomography relative to 2 m in depth with indication of the probable shape of the aqueduct (modified after Rose *et al.*, 2015).

Fig. 6 – a): sezione archeologica dello specus (disegno e foto di Dario Rose); b): risultati delle tomografie elettriche P1; c): risultati delle tomografie elettriche P2-P6 e P12; d): tomografia relativa a 2 m di profondità con indicazione della probabile forma dell'acquedotto (modificato da Rose et al., 2015).

angle the presence of a conductive alignment suggests the existence of a rectilinear structure. It is about 3 meters wide, and well comparable with the platform in concrete, highlighted further downstream.

The "Acquedotto delle Luci" in Vasto (Chieti, Abruzzo Region).

The Acquedotto delle Luci is located in the city of Vasto, once the city of Histonium. With other hydraulic works, it supplied the city with water for domestic, productive and leisure uses such as spas and fountains (fig. 7a). Aquilano *et al.* (2011) provided a detailed description of the underground path with a particular focus on the area of the *caput aquae* and the *puteus* destroyed on August 28, 2007 during the construction of a building. Immediately south of this, three *putei* are still preserved and visible today. Starting from these, the speleological explorations have partially investigated the hypogeum by identifying two parallel branches: branch C and branch D are characterized by a maximum depth, in the southernmost point investigated, of 10 m and 5.36 m, respectively.

Fig. 7 – Location of the “Acquedotto delle Luci” in Vasto (Chieti, Italy): a) - indication of the surveyed area; b) - indication of the geophysical grid; c) - indication of the electrical resistivity tomography relative to 3 m in depth (Aquilano *et al.*, 2011).

Fig. 7 – Localizzazione dell’“Acquedotto delle Luci” a Vasto (Chieti, Italia): a) - indicazione dell’area d’indagine; b) - indicazione della griglia geofisica; c) - indicazione della tomografia di resistività elettrica relativa a 3 m di profondità (Aquilano et al., 2011).

Recently, as part of a building project, a verification of the aqueduct was requested in order to locate it exactly. The geophysical survey took place through the realization of nine ERT profiles (fig. 7b): seven were almost parallel profiles (1-7), planned with the aim of intercepting the more superficial branch D, in the entire investigated area; the two crossed profiles (8-9) trying to make the most of the limited spaces to intercept branch C.

The depth of the anomalies seems to decrease from north to south where the aqueduct is detected at the maximum depth of 5 m. Given the limited operational space, it was not possible to detect traces of branch C. Profiles 8 and 9 did not show, at the presumed depth of about 10 m, significant anomalies, and this was probably due to the low contrast between the encompassing matrix and the buried target. Figure 7c shows the horizontal section of resistivity relative to about 3 m of depth. From the analysis of the electrical tomography the trend of branch D of the Roman aqueduct is clearly outlined, which however seems to stop immediately south of the *puteus*.

The "*giacciara*" of the Castle of Zena (Carpaneto Piacentino, Piacenza, Italy)

The castle of Zena (fig. 8a, b) is located in the area of Carpaneto Piacentino, in the lowland between Fiorenzuola and Piacenza (Emilia Romagna, Italy). It is an abridgment of six historical buildings covering a general surface of about 4.000 m^2. The foundation date of the Castle of Zena is still unknown, though the first document attesting its presence dates back to 1216. The whole complex, despite the several repairing phases in past ages, still preserves the ancient character of a fortress of square plan, as documented in the drawing of figure 8c, dating back to 1701 and based on a land map of 1591. The southern wing of the building is attested to have been demolished in the 18th century, thus leaving the courtyard of the castle partially exposed. On the western front, where the entry is situated, the traces of a drawbridge, replaced afterwards by a bridge in masonry, and the ditch that surrounds the castle, are visible.

The work was developed within the project S.O.C.R.A.T.E.S., which priority was the study of the castle and the surrounding areas together with the construction of models and methodologies of general interest, addressed to recovery and exploitation of the buildings of historical and architectural interest. The activity related to the geophysical prospections was assembled in three different areas that, according to

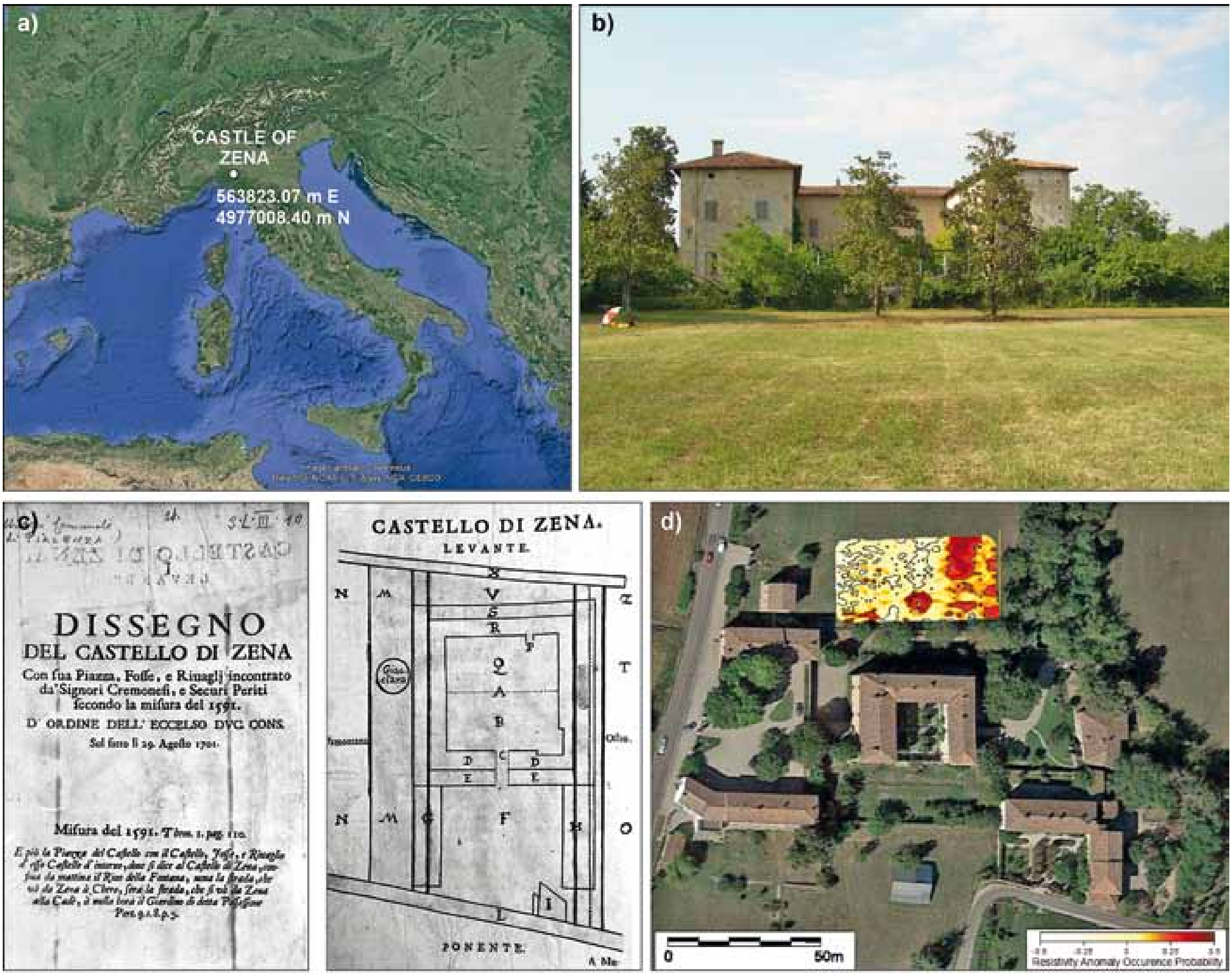

Fig. 8 – a): location of the Castle of Zena, Carpaneto Piacentino (Emilia Romagna, Italy); b); the northern facade; c): an archive document from Piacenza dating back to 1701, showing a drawing of the Castle of Zena based on land measurements of 1591; d): resistivity tomography relative to 1 m in depth on a Google Earth™ satellite image.

Fig. 8 – a): localizzazione del Castello di Zena a Carpaneto Piacentino (Emilia Romagna, Italia); b): la facciata settentrionale; c): un documento d'archivio, proveniente da Piacenza, datato 1701, che mostra un disegno del castello di Zena basato su misurazioni dei terreni del 1591; d): tomografia di resistività relativa a 1 m di profondità su immagine satellitare di Google Earth™.

the project of restoration and renewal of the castle, will have to change the original destination of use. The investigation was conducted using the geoelectrical method and the data were elaborated according to a 3D-elaboration program (Compare *et al.*, 2009). The nature of the geophysical anomalies, probably connected to remains of archaeological interest, was then verified through mechanical surveys and subsequently through a direct activity of archaeological excavation.

In this section a part of the results are reported, limited to the area close to the northern side of the fortress, where a car park had been planned underground. 37 parallel profiles, 31m long and spaced 1.5m apart, were realized. In this zone, a *giacciara* (icebox) is indicated with a circle in the old drawing of the fortress, close to its northern wing. The probable presence of the round structure, likely a brickwork room used in the past for the maintenance of food, is also suggested by the cropmarks easily visible on the ground (fig. 9a), nearly where it is indicated in the map of figure 8c.

Worthy of note appears the isolated rounded sequence of nuclei visible in figure 8d at the center of the A-zone, close to its right-hand borderline. The location of this source exactly corresponds with the cropmarks visible in figure 9a. The subsequent archaeological excavation allowed a circular structure with radius and height of 3.3m to be discovered (fig. 9d), immediately under the humus (Bondi, 2006).

It was found made of pebbles and bricks tied up with a mortar rich in sand in the top portion, made of disjointed bricks and slightly flared at the bottom, and externally surrounded by eight small buttresses, set at a regular distance of about 2.6 m. This regular and well-preserved masonry structure was readily ascribed to the circular plot indicated as *giacciara* in the ancient drawing reported in figure 8c (Bondi, 2006).

For a better appreciation of the resolving power of the exposed probability tomography method, Figures 9b and c show a zoom of the 3D image, under two different angles of view, limited only to the central round

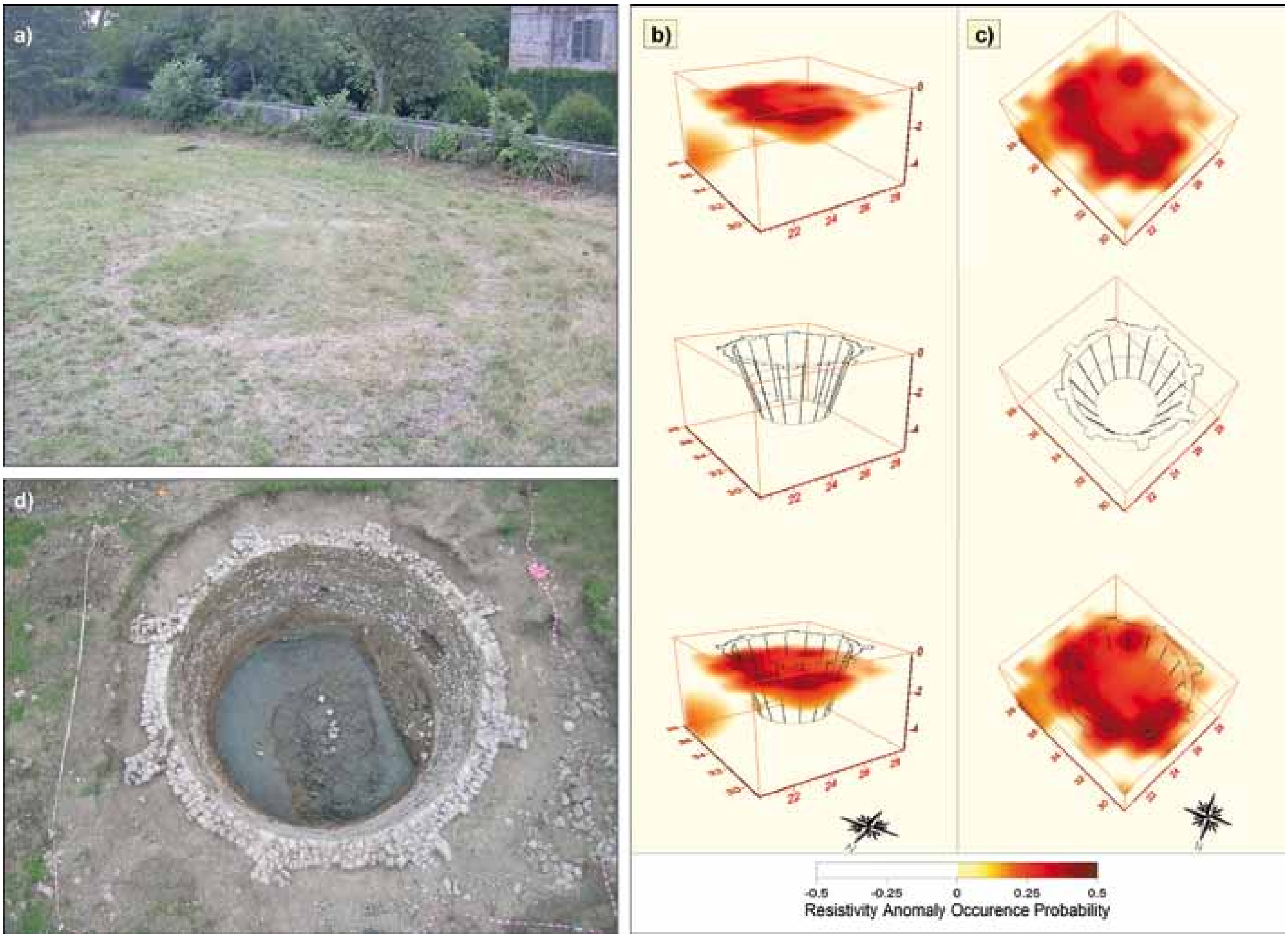

Fig. 9 – a): cropmarks in correspondence with the “giacciara” indicated in the map of fig. 8c; b), c): 3D images of the giacciara compared with the round sequence of nuclei from a lateral (b) and a top (c) view; d): the “giacciara “found in correspondence of the rounded sequence of nuclei in the resistivity tomography (modified after Compare *et al*. 2009).

Fig. 9 – a): tracce nella vegetazione in corrispondenza della “giacciara” indicata nella mappa di fig. 8c; b), c): immagini 3D della “giacciara” comparate con la sequenza di nuclei circolari visti di lato (b) e dall’alto (c); d): la “giacciara” rinvenuta in corrispondenza della sequenza di nuclei circolari nella tomografia di resistività (modificato da Compare et al. 2009).

sequence of nuclei. A sketch of the *giacciara* is also plotted at the correct place as from the digging. In both images, the round sequence of nuclei appears to correspond exactly with the trace of the *giacciara* on the horizontal plane through its center. Furthermore, in the lateral view, the full bowl-shaped set of source nuclei appears to smoothly conform to the very regular nest-shaped structure of the *giacciara*.

An unknown tunnel in the territory of Pomigliano d'Arco (Naples, Italy).

As part of the construction of a building in the Municipality of Pomigliano d'Arco (NA), non-invasive geophysical investigations were carried out with the aim of verifying the presence of cavities buried in the subsoil following the identification of a tunnel in the section excavation (fig.10a). The methodologies used were the GPR and the three-dimensional electrical tomography.
From the georadar sections (here for the sake of brevity, it is shown only the section relating to 1.5 m) the presence of an anomalous low-amplitude area, connected to the tunnel found in the section of the excavation (fig.10b), is clearly shown. The anomaly, visible from a depth of about 0.8 m, is attributable to the presence of material with different electromagnetic properties than those of the encasing ground.
The resistivity data obtained through the ERT profiles were overall processed according to a 3D tomographic scheme. Figure 10d shows a three-dimensional view of the investigated tomospace and in figure 10e the high resistivity values have been made transparent in order to create a 3D model of the low resistivity anomaly. As for the results of the GPR survey, the sections clearly highlight the presence of an anomalous area of considerable size with low resistivity connected to the tunnel found in the section of the excavation. The anomaly decreases in size beyond 2 m depth until it almost disappears at 4 m depth. There are also some small nuclei with low resistivity especially close to the wall where the cavity has been identified. As can be seen from the comparison of the horizontal sections relative to 1.5 m depth, obtained from the application of the two techniques (fig. 10c), it was possible to detect the same geophysical anomalies: although they were detected through different physical behaviors, they identified the same situation underground. Given the clear connection of the anomalies to the tunnel found in the section of the excavation, it was recommended to proceed with direct tests and checks to ascertain the nature of the materials present in the stratigraphy (probable, loose deposits) and / or the presence of voids.

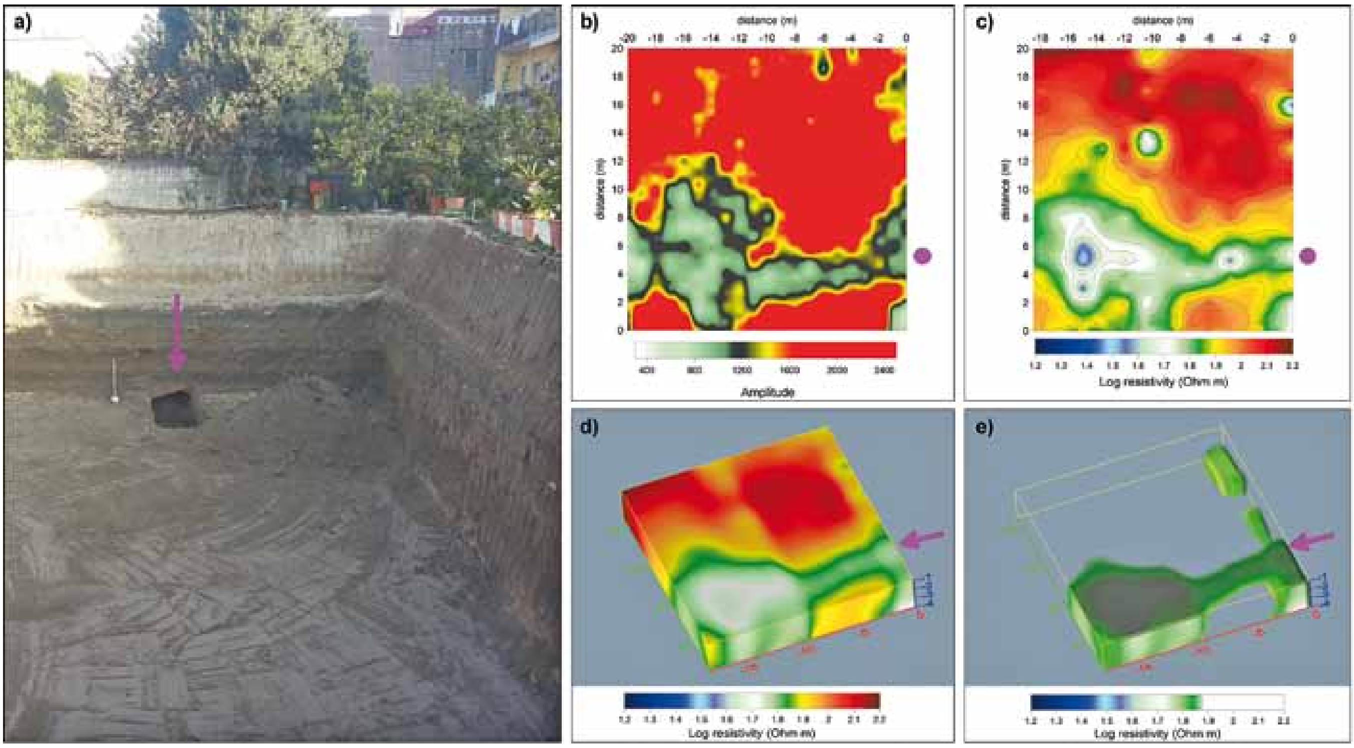

Fig. 10 – a): an unknown tunnel in the area of Pomigliano d'Arco (Naples, Italy); b): GPR horizontal section relative to 1.5 m in depth; c): ERT horizontal section relative to 1.5 m in depth; d): three-dimensional view of the investigated tomospace; e): three-dimensional view of high resistivity values.

Fig. 10 – a): un tunnel sconosciuto nel territorio di Pomigliano d'Arco (Napoli, Italia); b): sezione orizzontale GPR relativa alla profondità di 1.5 m; c): sezione orizzontale ERT relativa a 1.5 m in profondità; d): vista tridimensionale del tomospazio investigato; e): vista tridimensionale dei valori alti di resistività.

A survey around the Tomb of Laris at Città della Pieve (Perugia, Italy)

In 2015, fortuitously, during the plowing of a land in Poggio Valle in Città della Pieve (PG) (fig. 11a), a hole opened in the ground. Inside you could see the sculpted lid of a sarcophagus (fig. 11b) from an Etruscan tomb from the late 4th century BC. A long dromos was then found, with heavy double travertine doors were also found guarding the Chamber. One of the two sarcophagi had a long Etruscan inscription on the side, translated as “Laris Pulfnas son of Arnth” probably referred to the person buried inside the urn. In addition to the funerary objects, which include pottery, miniature votive vases, a strigil and a bronze olpe, two intact storage containers were found, a large Greek-Italic amphora, a double-handled Olpe and four large urns from a fine alabaster grain with cremated remains.

As part of a collaboration with the Archaeological Superintendence of Umbria, geophysical investigations were carried out with the aim of verifying the presence of further funerary structures buried in the areas adjacent to the tomb. The methodologies used were electromagnetic induction prospecting for a large-scale study of the site and three-dimensional electrical tomography for high resolution detail. In a first phase of the intervention, precise measurements were acquired on the surfaces above the tomb, in the few points free from obstructions, to verify the geophysical response of targets to be identified (voids filled with air) according to the geological materials that incorporate them. Very high electrical resistivity values were measured near the void corresponding to the main chamber and the side chambers, while very low resistivity values were measured in sterile soils. We then proceeded with the analysis of the irregularly sized area located east of the tomb.

In the electromagnetic survey, data were acquired within a grid in which the survey profiles were carried out at a distance of 0.5 m, in continuous mode. Figure 11c shows the result obtained using a frequency of 15000Hz. There are two large high resistivity areas, one in the northern portion of the investigated area and one in the south- eastern sector.

In the geoelectric survey a grid with dipole-dipole profiles spaced 1 m was carried out, using a dipole distance of 1 m, and acquiring measurements up to three meters deep. The tomography that best highlights the high resistive anomalies is that relating to a depth of 1.5 m, presented in figure 11d superimposed on the satellite image of Google Earth and on which interpretative lines have been inserted.

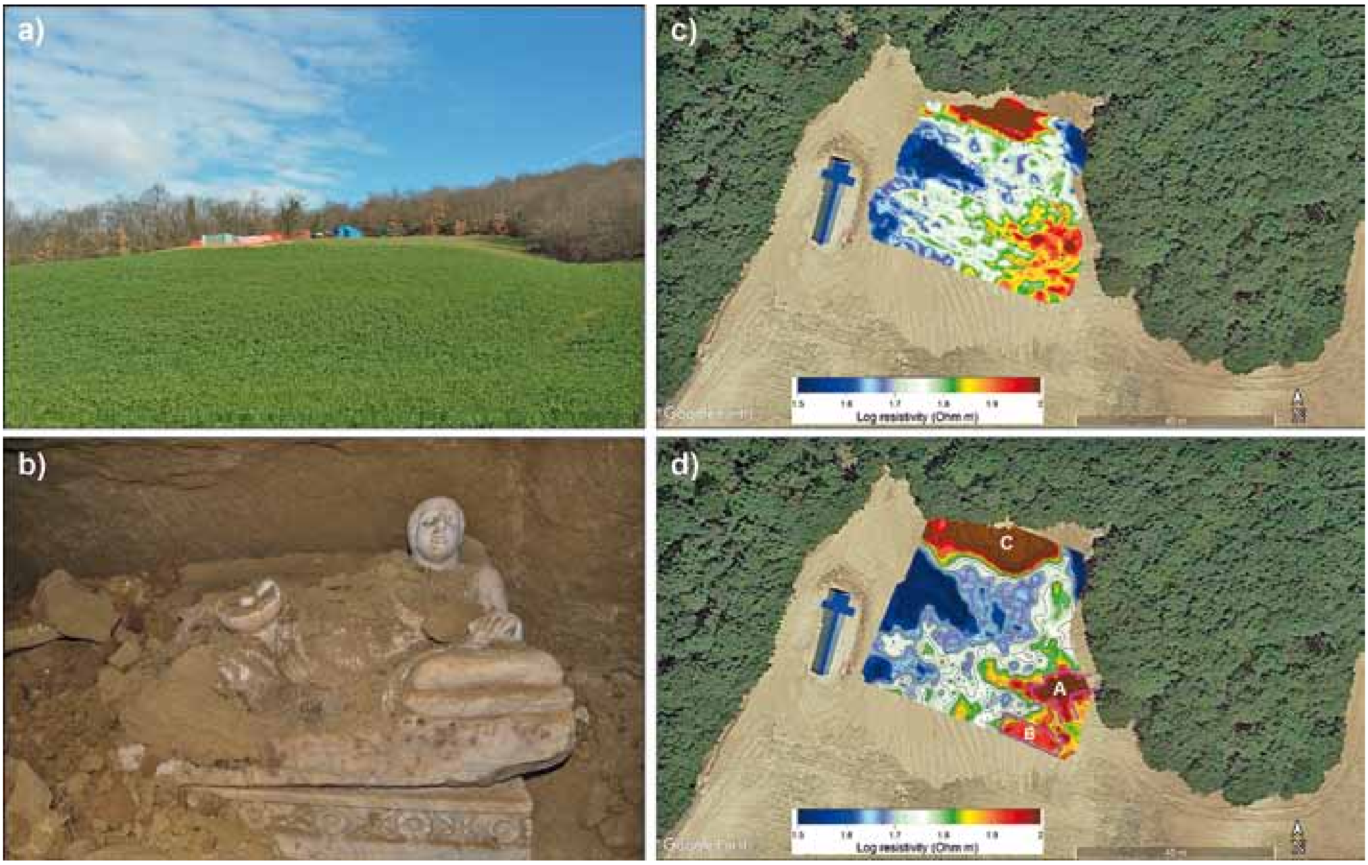

Fig. 11 – a): Poggio Valle in Città della Pieve; b): the sculpted lid of a sarcophagus (http://www.comune.cittadellapieve.pg.it/); c): EMI results; d): ERT results.

Fig. 11 – a): Poggio Valle a Città della Pieve; b): il coperchio scolpito di un sarcofago (http://www.comune.cittadellapieve.pg.it/); c): risultati EMI; d): risultati ERT.

There are three anomalies probably referable to underground tombs:
- Anomaly A has dimensions and shape almost similar to those of the tomb. The inhomogeneity was detected in a point where the ground slopes to SE: any burial would have been adapted to the morphology of the ground and therefore this would justify the different orientation compared to the known monument. At the point where the highest resistivity values were measured, a slight depression is noted at the surface.
- Anomaly B is located at the edge of the survey area, has a similar width to anomaly A and is located at the point where the ground begins to slope slightly to the south.
- Anomaly C has different dimensions to those of the previously described anomalies. The probable cavity has a width of about 20m and has been partially analyzed because it is located at the northern edge of the investigated area. However it seems to develop further below the wood.

All described anomalies develop at least up to 3m depth.

Conclusion

This contribution illustrated the potential of the most useful geophysical techniques for identifying cavities, and briefly described some application cases in the field of detection of artificial cavities. In the various case studies, limited to the application of GPR, EMI and ERT prospecting for the study of shallow artificial cavities, three-dimensional representations of the buried targets were shown, demonstrating the effectiveness of the appropriate methods.

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