# The role of historical-archaeological sources integrated into the GIS environment with geological and geophysical data in the mitigation of geological risks in some urban areas

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**Short Note**

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## ABSTRACT

**Numerous geological risks characterise urban areas, one of the most undervalued of which is the sinkhole risk connected to underground cavities. In the Lazio Region, the subsoil of many beautiful art cities like Rieti and Viterbo is rich in underground cavities, mainly anthropogenic because of their thousand-year history and the geological substrate's peculiar characteristics. These cavities have very different ages and types, the oldest dates back to the Etruscan and Archaic times. However, their excavation continued uninterrupted during the Roman and Medieval times until the Second World War, when many were readapted as bomb shelters. An interdisciplinary approach that combines geological and geotechnical aspects integrated by geophysics with historical and archaeological data in a GIS project can allow an efficient census of these cavities, defining not only their morphology and their functions but also hypothesising their continuation in unexplored or collapsed traits. Such a census is indispensable to estimate and, therefore, mitigate the sinkhole's risk and better define risk, including the seismic response of a subsoil articulated and altered by many levels of underground cavities.**

**KEY-WORDS:** Historical cartography, GIS, sinkhole, anthropic cavities, geophysics.

## INTRODUCTION

To mitigate the sinkhole risk in ancient art cities such as Rieti and Viterbo, an interdisciplinary approach was implemented employing a geographic information systems (GIS) for creating a geodatabase of cavities. This was accomplished by integrating multiple sources of information, including geological, geophysical, historical and archaeological data. This spatial database of cavities permits the definition of their morphology, functions and extension. "The study of underground cavities, especially anthropogenic ones, requires an interdisciplinary approach because they are complex systems that involve the interaction of multiple factors, including geological processes, human activity, and cultural and historical context. Geology allows for defining the stratigraphic and structural context and the characteristics of the units in which the cavities have been excavated or developed. Geophysics, calibrated with stratigraphy, allows identifying the presence of unknown cavities by defining their extent, size, and potential areas of weakness. However, only historical-archaeological research can define the functions of these cavities, the time in which they were made, and the alterations they have undergone. Historical cartography allows the reconstruction of the various phases of development of urban centres and the significant changes introduced to the original morphology of the territory, with particular reference to the hydrographic network that has often been diverted and channelled. Overall, an interdisciplinary approach is essential for understanding the complexity of anthropogenic underground cavities and ensuring their preservation for future generations because, once consolidated, they can be a resource more than a problem. The territory of the Lazio Region presents a great variety of volcanic geological units. From an anthropic point of view, some of these units are of great importance for recent and past human activities. In the pyroclastic units, cavities have been opened to create additional spaces for the houses built on the surface and to extract the building materials. The technical characteristics of these rocks also favoured the realisation of all the hydraulic works (cisterns, aqueducts, sewer tunnels, etc.) indispensable to the city and the necropolis and tombs.

## MATERIALS AND METHODS

The first step in analysing the investigated city (Viterbo, Rieti, and Bolsena) was a literature review of all available bibliographical data, not limited to geological ones but also historical cartography and archaeological data (Madonna et al., 2020a, 2020b, 2021, 2022, and reference therein). Then a detailed geological and geomorphological survey of urban areas was done, implemented by collecting the subsoil data (borehole of 364/84 law and other stratigraphies acquired by professional geologists, Entities, or Public Administrations). Where the Geological Map of Italy at a scale of 1:50.000 was available (Viterbo), the geological units were defined according to those established in the CARG project. In other cases (Rieti, Bolsena), a correlation with those of adjacent Geological Maps has been attempted. All data has been integrated into a GIS project realised with the open-source software QGIS.

Historical cartography, focused on analysing maps dated between the 17th and 19th centuries, is a key helpful tool highlighting the evolution of landscapes, hydrographical networks and anthropic presence in a territory. Those maps show several particulars at a detailed scale, so it is possible to reconstruct and evaluate the changes that occurred during the last 200 years.

The availability of historical-archaeological data varies significantly according to the type and age of the urban settlement considered. Unfortunately, in some cases, the information is scattered in many sources and can hardly be used and contextualised without the mediation of a specialist with the appropriate knowledge. Collaboration with state archives, libraries, museums, and local foundations is highly recommended for historical cartography and archaeological sources. In addition, monographs and publications by local scholars, generally excluded from academic circuits, such as (Bernardinetti & De Francesco, 1975; Bernardinetti, 2009) for the city of Rieti, can be very useful.

The use of geophysical surveys is to be considered the safest and fastest method for locating cavities and wall structures in the subsoil. Many techniques exploit different physical principles in order to obtain information passively and safely as microgravimetry and Ground Penetrating Radar (GPR) (Di Filippo et al., 2007, 2009; Di Nezza et al., 2015; Petitti et al., 2010) or Electrical Resistivity Tomography (ERT). So we will present some examples of applying these techniques in Viterbo town.

Penetrating radar (GPR) surveys were carried out in the San Lorenzo Cathedral to understand better the existing buried structures, such as cavities or other features such as tombs and tunnels, and to determine the variation of the density in the ground, microgravity and ground-

This study aimed to map and delineate the subsurface condition of the area with the view of revealing probable subsidence-prone zones within the study area. Microgravity observations were made on a 40 m×20 m grid with a spacing of 2 m. Globally, 200 points were positioned and measured on a floor in the nave. Each measured station position had been determined with sufficient accuracy in horizontal and vertical directions. Elevations of measured points have been determined utilising topographic levelling. Gravity data were collected using the relative gravimeter LaCoste & Romberg model D. For a correct determination of the short-term drift; the base station readings were recorded every hour during the survey on a selected base station. The base station was linked to the S. Angelo Romano Absolute Gravity Station (Di Nezza, 2007; D'Agostino et al., 2008) located on Meso-Cenozoic carbonate rocks of Mt. Cornicolani. The free air and planar Bouguer slab with a density of 2100 kg/m$^3$ corrections were applied to obtain the Bouguer anomaly map.

Additionally, the main negative and positive gravity anomalies of interest in the nave were also have been investigated by 51 GPR sections. A SIR10B (GSSI system) GPR was employed to collect all data presented here, together with antennas with a frequency of 400 MHz with a constant offset.

## RESULTS AND DISCUSSION

The territory of the Lazio Region, and in particular the volcanic area, is rich in underground cavities of anthropogenic origin, excavated in pyroclastic deposits since the Archaic and Etruscan times. We will present some examples of the application of the interdisciplinary methods used for the research and analysis of these cavities with particular reference to Viterbo (Fig. 1A) and Rieti (Fig. 2). For these urban areas, a geological map in scale 1:5.000 integrates the geological survey of surface data with those of the subsoil. The original urban hydrographic network (now largely channelled underground) and the main changes of the original morphology have been reconstructed using multiple sources, including historical aerial photos and historical cartography

With regard to historical cartography, the effectiveness of a map is related to the conservation status of the original format and, consequently, to the digitalisation process and the output resolution. The preliminary action to correctly use those sources of historical information is to apply the most appropriate georeferencing method that allows to conversion of the geometric coordinates of the maps into geographic ones for each pixel of the final digital format. The projection is usually effective when many ground

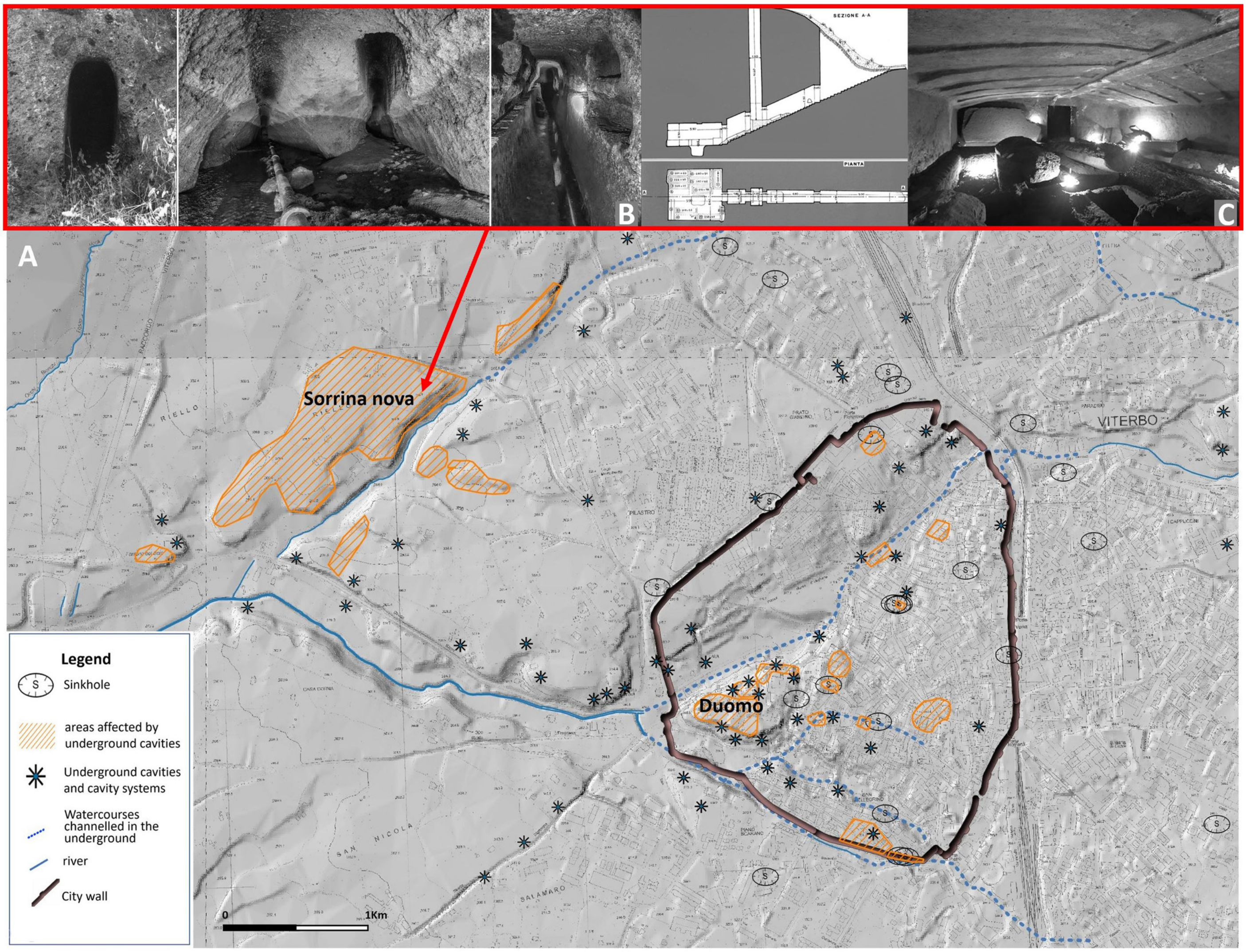

**Fig. 1 - A) Map of the underground cavities in the urban area of Viterbo and of sinkholes in recent years. Topographic base map: regional technical cartography(CTR) of the Lazio region on a scale of 1:5000, superimposed on the Digital Terrain Model (DTM). Examples of Underground archaeological remains in the Riello area, close to Viterbo: B), tunnels for drainage and water collection; C), chamber tomb.**

control points (GCPs) are identified on the historical maps and matched with a modern reference (satellite images, orthophotos, recent topographic maps, etc.). If the abovementioned criteria are respected, a historical map is a useful data source, especially when the investigation concerns the study of urban areas and punctual o linear phenomena such as hydrographical variations of anthropogenic origin. The city of Viterbo (Fig. 1A) and Rieti (Fig. 2) are valid study cases to confirm historical maps' usefulness for hydrogeological investigations. In particular, Rieti was called "The City of waters" due to a dense network of artificial canals that crossed the city centre since Roman times; the urban expansion of the last two centuries deeply modified the tracks of the canals in many points, with works of canalisation and covering; Rieti is also rich in natural underground cavities, sometimes anthropised, made by karstification of continental carbonate deposits of the cliff where the city centre rises; the intersections of natural cavities with ancient works of hydraulic derivation represent a risk factor to the structural stability of some buildings, even due to the high seismicity of the area; the covering of many traits of the canals might cause floods into different urban sectors. In view of this, the collection of historical maps available for Rieti covers a period of ca. 250 years, and investigations might rely on some detailed information at a scale of 1:2000, derived from the Gregorian Cadastre (made for Rieti in 1819), the Italian Cadastre (1859-1955) and the New Italian Cadastre (1930-1960), thus depicting the evolution of the hydrographic network until recent times.

Over the last two decades, the study of anthropogenic cavities and, more generally, of the rock-cut settlements has found important applications in archaeology - in both urban and rural areas -, thanks also to the use of increasingly sophisticated techniques for surveying and the refinement of stratigraphic and typological methods of analysis and documentation.

In Roman and Etruscan times, Sorrina Nova was the main settlement in the Viterbo area, located at the Riello hill, 1 km away from the present Dome's hill and where the Upper Medieval castrum was built as the core of the urban area today.

The Riello area, formerly crossed by the Via Ciminia and bordered to the west by the ancient route of the Via Cassia, is

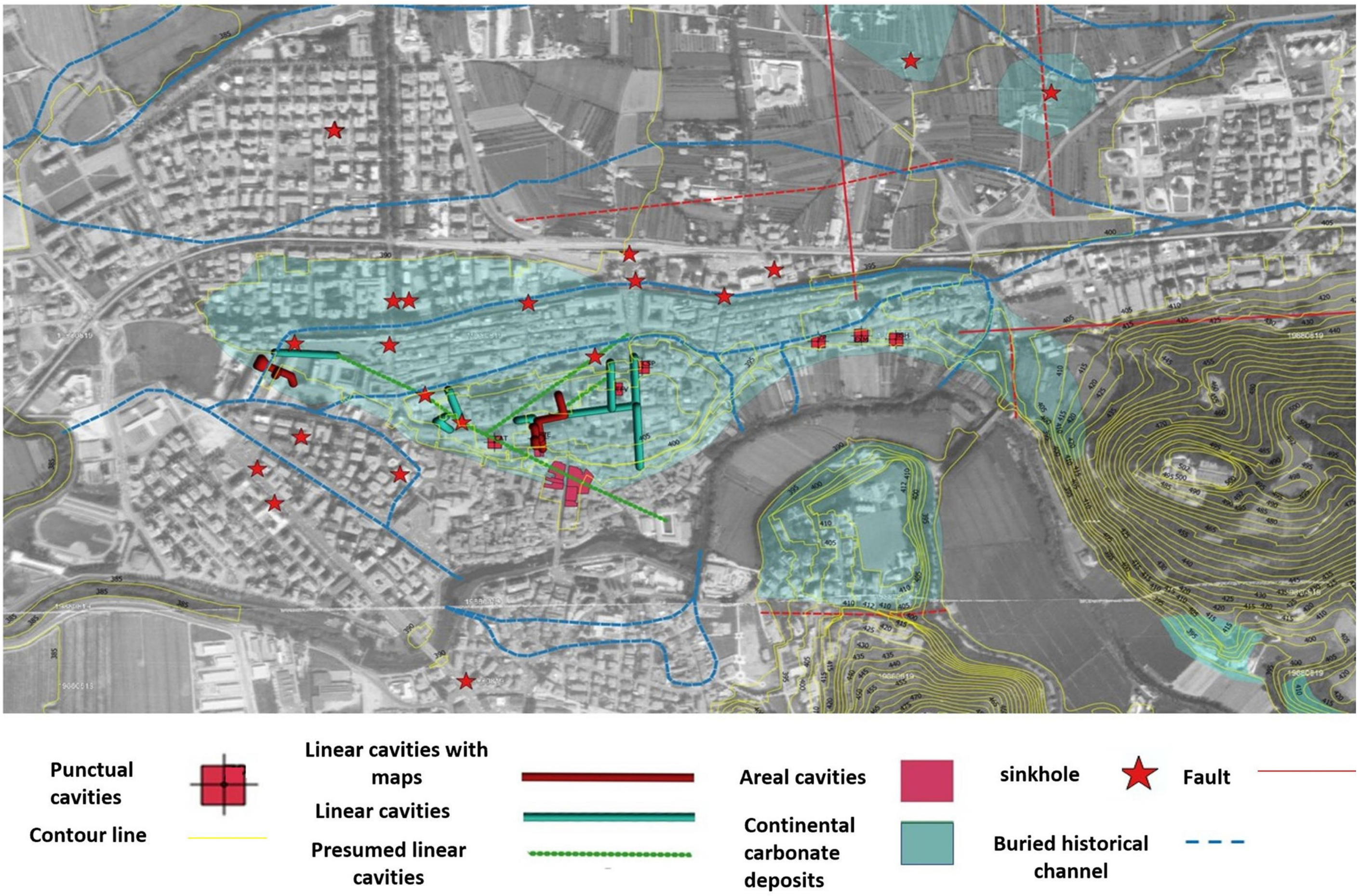

**Fig. 2 - Sinkholes surveyed in the urban area of Rieti with the distribution of cavities, continental carbonate deposits, the main tectonic discontinuities and the ancient hydrographic network and canal system. Basic cartography: BN 1998 orthophoto (national geoportal) with superimposed level curves highlighted in yellow.**

characterised by numerous archaeological remains from the Etruscan and Roman eras, many of which are of the underground type, excavated in the outcropping tufa. The area is now reached from the outskirts of Viterbo; indeed, starting from the second post-war period, it was progressively attacked by urbanisation. Most of these ancient underground cavities, archaeologically investigated and georeferenced (Fig. 1A), are closely connected to the presence of the ancient settlement of Sorrina Nova, which occupied a plateau of approx. 13 hectares; the inhabited area, probably called Surna in Etruscan times, was alive at least from the 6th century BC until late antiquity (Giannini, 2003, pp. 49-53, 57-64; Zucca, 2006, pp. 391-403; Milioni, 2007, pp. 11-12, 23-25, 37-92; Rovidotti, 2007; Proietti & Sanna, 2013, pp. 251-264; Pulcinelli, 2016, pp. 159-161; Fenelli & Scardozzi, 2020, pp. 279-304, 361-378, 449-464, 466-478). A part of these preserved hypogean anthropic cavities consists of tunnels with an ogival profile functional for the drainage of the land (Fig. 1B); along their paths are ventilation and inspection shafts. Other tunnels, on the other hand, had the function of water collection, such as those which, together with rooms dug into the tuffaceous bank along the north-eastern slopes of the Sorrina Nova plateau, constituted the articulated water collection system known as Grotte del Riello; it was used for a long period (even as a catacomb in the early Christian era), undergoing modifications and extensions until the modern era (Fiocchi Nicolai, 1988, pp. 127-130; Proietti & Sanna, 2013, pp. 253-254; Ceci & Proietti, 2019, pp. 335-337). Many of the archaeological cavities in the Riello area are hypogea (Fig. 1, C), most of which are chamber tombs in use between the archaic and early imperial periods (Barbieri, 1993-1995, 1996, 2002) during the medieval and modern age were reused as homes, agricultural shelters, and stables. In some cases, they are isolated, in others grouped in necropolis: among these, the most important is the necropolis of Riello (6th/5th-1st century BC), excavated along the edges of the plateaus located to the north-east (Bertarelli and Croce areas, partly destroyed by modern urban expansion), east (Riello and SS. Salvatore areas) and south-west (Fontanile del Boia area) of the Surna-Sorrina Nova plateau, and the necropolises of Poggio Giulivo (6th-century BC-1st century AD), Poggio Giudio (6th-1st century BC) and Casale Merlani (end of the 4th-beginning of the 3rd century BC), more distant from the ancient town (between 700 m and 1 km) and perhaps attributable to the settlement that was to arise, probably already in Etruscan-Roman era, on Colle del Duomo, from which medieval Viterbo would later originate. Most are made up of rather simple hypogea, with a single room. Still, there are some tombs with more complex layouts, characterised, for example, by two rooms in axis, with side platforms and niches on the walls for the deposition of the deceased; in the archaic phase there are generally tombs with a small chamber, which has three lateral platforms and a watershed ceiling with a raised central columen or a lowered vault. At the same time, in the Hellenistic and late-Republican era, there were tombs of larger dimensions characterised by the presence of numerous niches excavated at the sides of a central corridor (so-called "spina di pesce" pattern), originally closed by large tiles. Lastly, among the underground archaeological cavities in the Riello area, particularly linked to its geological characteristics, are some ancient pozzolana quarries, such as the one identified in the area of the IperCoop shopping centre (S. Croce area; Fenelli & Scardozzi, 2020, p. 487).

Another important archaeological structure of the hypogean type, of which, however, we still know very little, was located immediately outside the south-eastern sector of the historic centre of Viterbo: it is the aqueduct built in the 2nd century AD by senator Mummius Niger Valerius Vegetus, who had properties in the Viterbo area (Rovidotti, 2002; Maganzani, 2012; Bruun, 2015, pp. 136-141; Fenelli & Scardozzi, 2020, pp. 76-78, 350-351, 363). The work is remembered by a long and interesting inscription (CIL XI, 3003 and *additamenta*), of which two other fragmentary copies are known (CIL XI, 3003b and AE 2002, 471), which documents how Mummius Niger purchased from another senator, Publius Tullius Varro, the spring which was located in the "fundo Antoniano maiore" (identified at the site where the complex of S. Maria in Gradi was built in the Middle Ages) and with an aqueduct (the "Aqua Vegetiana") 5,950 passus long (= 8,794 km) he had brought the water to his Villa Calvisiana, set "ad Aquas Passerianas", i.e. at the statio of Aquae Passeris, along the Via Cassia, unanimously located by scholars in the Terme del Bacucco area, north-west of Viterbo (Fenelli & Scardozzi, 2020, pp. 68-70, 75-78, 342-344). The route of this aqueduct is not known, but some remains of pipelines and tunnels referable to it were seen at the end of the 19th century along the eastern stretch of the medieval walls of Viterbo, between Porta Romana, Porta della Verità and Porta San Marco. Finally, it should be remembered that starting from the same source to the east of the Church of S. Maria in Gradi, a shorter aqueduct was built in the Middle Ages which feeds the fountain in Piazza Fontana Grande, built in 1212 in the south-eastern sector of the historic centre of Viterbo.

Since the 11th century, many other settlements arose close to the castrum, in areas known as *fines viterbienses*; those of the 11th-13th centuries were included in the city wall.

From the 11th century onwards, the towns of the *Patrimonium Samcti Petri in Tuscia* experienced considerable economic and demographic development, reflected by the considerable increase in the area enclosed by the city walls. The considerable economic, demographic and urban development of the three major urban centres resulted in the progressive saturation of urban spaces and imposed the need to devise various solutions to increase the surface area available for housing, also by digging underground (Fig. 3). research conducted in Viterbo has been able to document the intensity of the exploitation of the areas underneath the houses for cellars (*cellaria* or *vincellaria*), water reservoirs, grain storage pits (*putei*) and then, from the 14th century onwards, also dump pits ("pozzi da butto"). Archaeological investigations in towns and rural centres well document the presence of domestic waste disposal structures; these are flask-shaped or cylindrical pits, not infrequently previously used as water reservoirs or grain storage. In the late Middle Ages, the network of hypogea was very articulated; during the 15th century, the statutes of the city of Viterbo tried for the first time to regulate digging underground, mainly for safety reasons. Similar measures were implemented by the statutes of

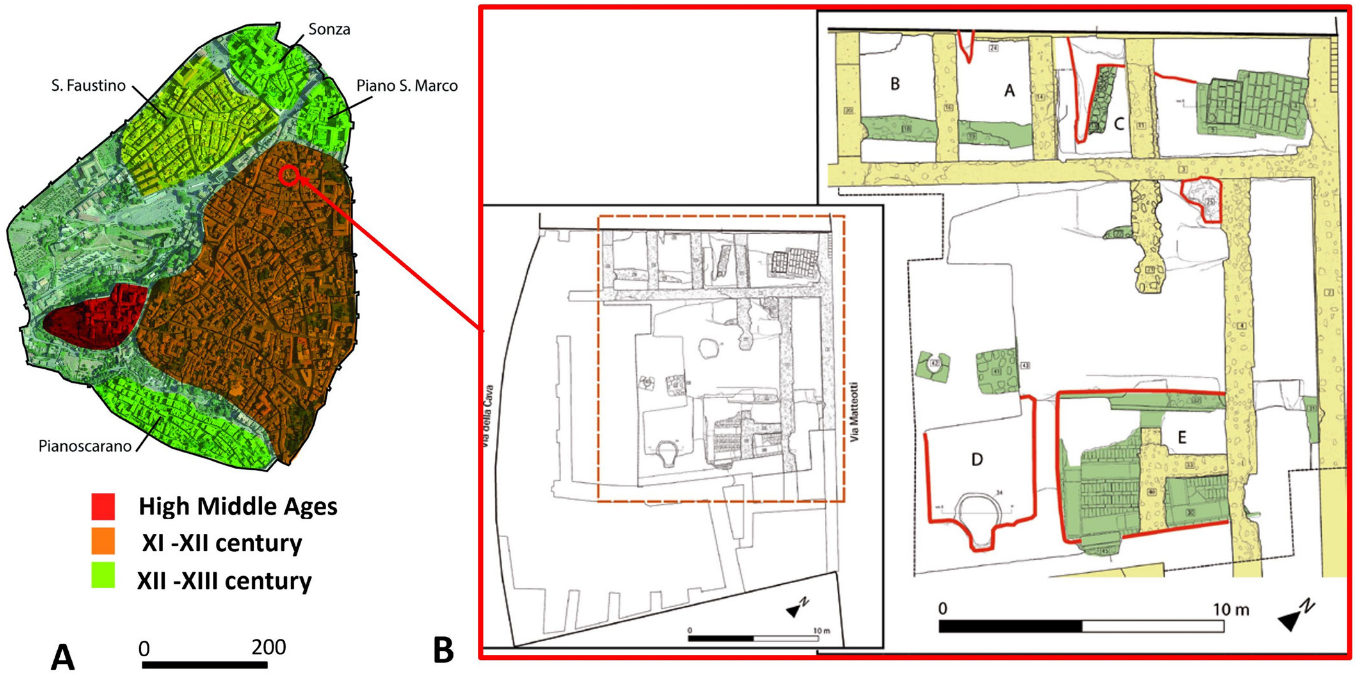

Fig. 3 - A) The urban development of Viterbo (G. Romagnoli); B) Caves in the area between Via Matteotti and Via della Cava (after Romagnoli, 2014).

Celleno, one of the castles subject to the control of the municipality of Viterbo: in this case, too, the excavation of caves was forbidden so as not to further weaken the tuffaceous cliff, already subject to landslides. Moreover, like other municipal towns in central and northern Italy, from the 13th century onwards, Viterbo was equipped with a system of underground water pipes and sewer collectors, which ran along the main roads. Some of them remained in use until the 19th century (fig.1A).

Geophysical investigations are widely considered to be the best methods of finding underground cavities (Fig. 4 A, B, C). These cavities represent an important risk when heavy machines are deployed on a new construction site and should be detected before starting construction works.

Electrical Resistivity Tomography (ERT) method is useful for subsurface imaging and detecting different underground voids such as corridors (i.e. underground buildings), crypts (underground burial chambers), cellars (any type of underground rooms), caves (natural underground chambers) etc. (Fig. 4A). These voids can be empty, full or partly water-filled or filled with a different kind of stuff. Other prospecting techniques have been employed to detect underground voids. Success depends on their ability to reach the target depth with the appropriate resolution for each problem. The ERT method aims to characterise the variations of underground formations' physical parameters (ground resistance vs depth). It measures a set of data in which various parameters (apparent resistivity, conductivity, depth etc.) are measured. Each of these parameters is related to one or more physical properties of the subsurface. ERT is a popular choice due to the low costs of the survey and the high resistivity contrast between the air-filled cavity and surrounding formation. The cavities are partially or wholly water filled and can have a resulting electrical conductivity ranging from very conducive to relatively resistive depending on the host rock.

In modern uses, data are generally acquired using at least two different electrode configurations: this allows you to check for anomalies, increasing the success of the investigation. Wenner-Shlumberger and dipole-dipole are the common protocol used in this kind of prospection.

Results suggest that electrical resistivity tomography is a state-of-the-art geophysical tool for detecting and interpreting mining voids and other subsurface cavities.

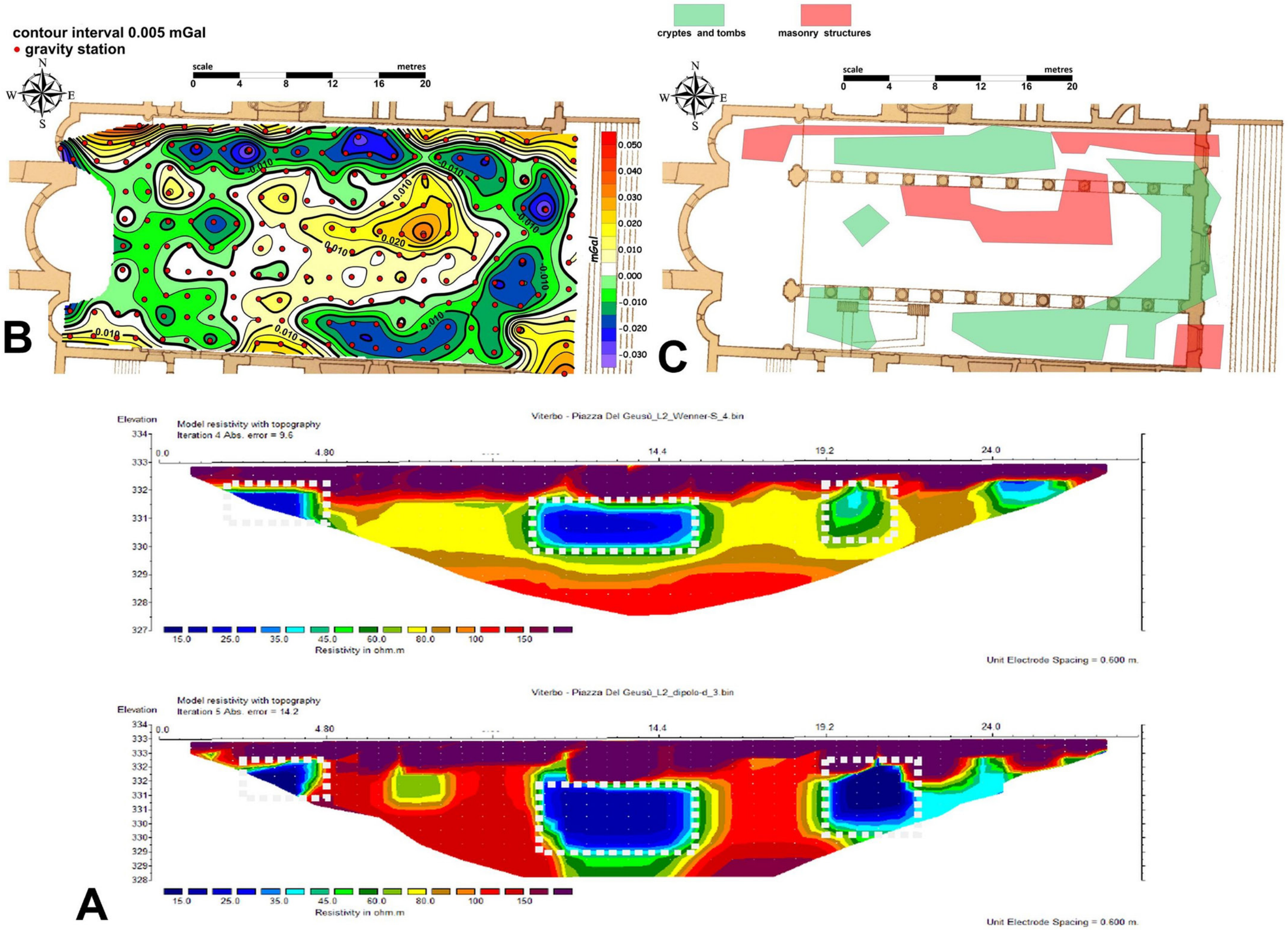

**Fig. 4 - A) Residual gravity anomaly map; B) The results obtained by integrated interpretation microgravity and GPR methods; C) Wenner-Shlumberger (top) and Dipole-Dipole (bottom) 2D resistivity sections. Blu areas (conductive) are related to filled cavities.**

The resolution capacity of joint inversion of Wenner Schlumberger and dipole-dipole array data for cavity detection is more suitable than that of the individual one.

Electrical Resistivity Tomography (ERT), Microgravity prospecting and Georadar (GPR) were used to identify the presence of cavities and structures in the basement of the Viterbo's San Lorenzo Cathedral. These explorations were made as part of a research project on the burial of Pope Alexander IV based on the historical and archaeological analysis carried out by Dr Alberto Picardo. The regional geological trend was approximated by a simple planar surface and removed from the data of the Bouguer gravity map. The difference between the Bouguer and regional anomalies is known as the residual anomaly. Figure 4B shows the residual anomaly map with a range from -0.035 to +0.055 mGal and a contour interval of 0.005 mGal. Interpretation of gravity data is rather simple, where negative anomalies represent low-density contrast and can represent cavities and tunnels. Meanwhile, positive anomalies represent high-density contrast and can be produced by buried walls.

Integrated interpretation of results from microgravity and GPR methods (Di Filippo et al., 2007, 2009), Figure 4C, has confirmed the presence of crypts and tunnels, negative anomalies, and some other masonry structures, positive anomalies.

GIS applications allow comparison layers with different types of data and an optimal integration between them. Examples of application of the methodologies listed above represent some of the best methods not only for locating underground cavities (both man-made and natural), but also for understanding and reconstructing the evolution of the urban fabric and the changes undergone to its geomorphological and hydrographic network. Unfortunately, the census of sinkholes that occurred in urban areas is limited only to recent decades. However, a remarkable correlation has been found between the sinkholes and the places where underground cavities have been recorded or where tracts channelled underground of the hydrographic grid were present.

Such integration is fundamental because geophysical investigations alone are not enough to give definitive answers on the presence of underground cavities.

In the case of geoelectric techniques, for example, a reference calibration stratigraphy is required, and the following limitations can be encountered: the difficulty of interpretation in morphologically uneven areas or with numerous underground utilities; identification of non-conductive contaminants or electrically undiversified from the surrounding soil; disturbances caused by the presence of underground ducts and/or pipes, overhead lines, earthing, surface metal bodies.

Microgravimetry, probably the most performing technique, can give unreliable results in the case of cavities that are partially or filled with debris. Due to these limitations, multidisciplinary approaches must be considered to mitigate errors essential to the study area's actual stratigraphic and geological knowledge. Geognostic perspectives also acquire importance; although they cannot be regarded as real cavity research tools, they provide essential information about the stratigraphy and, therefore, the location (if not directly mapped in special geological maps) of those formations known historically to have been affected by anthropic.

## CONCLUSIONS

In ancient urban areas, investigating underground cavities and the associated sinkhole phenomena requires an interdisciplinary approach due to their complex nature, involving various factors, including geological processes, human activities, and cultural and historical contexts. We have shown how an interdisciplinary methodology to studying the complex problems of the subsoil of cities of art like Viterbo or Rieti can contribute to identifying phenomena of geological hazard and an opportunity to protect and enhance the vast and almost unknown archaeological heritage concealed beneath them. The investigated cavities are sometimes placed on several levels and have varied sizes and extensions. The contribution of the historical-archaeological sources was fundamental for their preliminary identification. Geophysics has been indispensable in defining the characteristics of those not explorable, while their geological characterisation is the basis for any future geotechnical investigation. Over the course of modern and contemporary times, many of these cavities have been modified and repurposed for various uses.

For instance, numerous cavities were enlarged and interconnected during the Second World War to serve as bomb shelters. These cavities pose a significant risk factor, as their vaults may suddenly collapse, leading to sinkhole formation and potential damage to the structures and infrastructures above. Radon and Thoron gas could be stored in the cavities and reach high concentrations dangerous for the above houses if they are not adequately ventilated. Furthermore, localised collapses near rivers or anthropic embankments further contribute to the overall risk associated with these cavities. The proposed multidisciplinary approach can also be extended by incorporating contributions from other geophysical techniques, such as MASW (Multichannel Analysis of Surface Waves) and HVSR (Horizontal-to-Vertical Spectral Ratio), as well as photogrammetry techniques utilising Unmanned Aerial Vehicles (UAVs) and interferometry.

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