

# Structural detailing of buried Roman baths through GPR inspection

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**Abstract**— This paper deals with a geophysical experimental activity carried out in the Maxentius Complex, an archaeological site located in Rome, Italy. The objective of this study was to evaluate the feasibility of GPR for the structural detailing of buried roman baths structures. As a result, GPR allowed to confirm the literature-based information, i.e. to precisely locate the tanks of the thermal area. Their presents was already known through previous excavation then buried and no more visible. In addition, the tomographic analysis highlighted the presence of two further tanks, thereby suggesting the possibility of further rooms to be located close to the known ones. This assumption was also confirmed by tomographic analysis, which stressed out a wall pattern that seems to suggest the presence of further rooms in the top-right side of the area. In general terms, GPR demonstrated a great applicability to archaeological purposes, despite the reliability and productivity of the data interpretation are strongly influenced by the expertise of both the geophysicists and the archaeologists involved.

**Keywords**— *ArchaoTrack; GPR, archaeology; archaeometry; prospections; Roman baths; thermae.*

## I. INTRODUCTION

Baths are typical roman structures, a significant example of space articulation and composition with different shapes. It is commonly believed that they were born in Italy, precisely in Campania. However, it has been suggested that these structures have Greek origins: the Latin word *thermae* comes from the greek *Θέρμα*, deriving from the adjective *Θερμός*, meaning “warm”.

Ancient Romans considered baths spaces both for health and hygiene care and meeting places where anybody, regardless their social class, could go: indeed they were public and free.

*Thermae* were often also built for propaganda: evergetism played a very important role in the construction of these buildings, often provided with luxury furnishing and impressive architecture according to the possibilities of the client, who frequently coincided with the Emperor himself.

According to the specific function of these structures, which required the warming of entire pools and rooms for bathing, they were realized through remarkable technical solutions [1] that are nowadays object of study from archaeologists. Among the others, various scientific contributions have been published concerning the geophysical analysis of buried thermal structures [2-3].

Within the ArchaeoTrack project [4] an area occupied by a thermal building has been surveyed through Ground Penetrating Radar (GPR). The analysis of the outcomes has shown some significant results concerning the structural and functional features that could be useful to identify specific elements for easily recognizing this kind of structures by geophysical surveys.

### A. Breath evolution of the Roman bath complexes

Over the time baths were characterized by several planimetry changes according to different economic means and to the political condition in which they were built.

Up to now, the first *thermae* known are the *Thermae Stabiane* in Pompei dating back to 4<sup>th</sup> century BC and their scheme was very simple [5]. Over time, the baths were subjected to modifications up their complete planimetry, reached only in the 1<sup>st</sup> century BC. According to some scholars, the *hypocaustum* system was born right here in Campania. This system was perfectly described by Vitruvius as an underground space in which the hot air heated by *ad hoc* ovens (*praefurnia*) circulated. In this space the air flew among a network of small pillars supporting the floor (*suspensura*), where the tanks were located, and thanks to the wall cavities made by tubuli (hallow bricks). The whole system was insulated to prevent the formation of condensation on the walls and to maintain the temperature.

The invention of this heating system, which granted stable temperatures in the rooms, allowed the replacement of the individual tanks with wider *alvei* that could host several people at the same time.

The planimetric organization of the *Thermae Stabiane*, can be considered as a reference for baths complexes built during the following first phase of the Imperial age, throughout the Italian peninsula and in the Roman west. In the Imperial baths the consequent arrangement of the rooms was subjected to an increasingly criterion of axial symmetry. The satellite spaces multiplied and joined the three main rooms (*tepidarium*, *calidarium*, *frigidarium*). The baths were enriched architecturally and decoratively. During this age the *frigidarium*, with the adjacent *natatio*, became the central and main space of the planimetry composition. It was the point of arrival, convergence and return of each path, where the meeting occasion was multiplied.

Despite the evident evolution of this kind of buildings in the transition from the Republican period to the Imperial age, the planimetric scheme described by Vitruvius and the main spaces remained roughly unvaried.

The first room in which the Romans entered is the *apodyterium* (dressing room) in which all visitors must have met before entering the proper baths. From there it was possible to reach the *sudatio*, generally a circular space, covered by a dome and heated by a stove (the temperature was among 30° and 35°). Subsequently, it was possible to enter in progressively warmer spaces, namely, *tepidarium* and *calidarium*. The latter was generally a rectangular space, illuminated by the sun from noon to the whole afternoon. In both *tepidarium* and *calidarium* there were tanks with hot water inside heated by means of the *hypocaustum* system which originated from the furnaces placed in the *praefurnia* –structures made of bricks or stone built next to the rooms to be heated to avoid the heat dispersion. Crossing again the *tepidarium* there was the *frigidarium*, rectangular and uncovered space, the only one at room temperature. Normally the largest space of baths.

In addition to these places, there was another series of areas dedicated to the care of the body, such as gyms and saunas. Sometimes in the richer baths there were also spaces used as theaters, fountains, library, etc.

### B. Geophysical prospections in bath complexes

Geophysical non-destructive prospections are nowadays gaining momentum as viable solutions to major issues arising from the use of traditional trenching, i.e.: *i*) uncertainty of the archaeological findings and risk of false alarms; *ii*) high cost of the surveys; *iii*) prolonged work disruptions; *iv*) spot information and *v*) need for highly-specialised professional profiles. Understanding subsurface configuration in archaeological areas without affecting the buried materials has therefore become a prime focus of the archaeological community. Within this context, the science for analysis, measurement and quantification of archaeological structures has been designated as the area of Archaeometry [6].

Ground Penetrating Radar (GPR) is well known as a viable equipment for locating buried archaeological remains [7-11]. Its effectiveness is mostly due to a wide range of available antenna frequency systems, which implies different possible depths and resolution of investigation, as well as to the enormous amount of information retrieved and possibility to obtain a tomographic plan view of the area investigated.

Up to now, studies on the analysis of data deriving from GPR prospections regarding thermal complexes have mainly focused on retrieving and completing the plan-views and studying the different phases of the structures [2-3]. Scientific contributions concerning the identification of hidden bath among the other possible buried structures by means of GPR are still lacking.

Accordingly, the aim of this paper is to identify the anomalies deriving from the specifically bath-related structural characteristics, such as the *hypocaustum*, with its double floor, and the activity of the *praefurnium* from which the hot air started its circulation through an arch and after that below the floor and between the walls of the *calidarium*.

## II. GROUND PENETRATING RADAR

GPR operates by transmitting electromagnetic (EM) waves towards a surface, typically a soil, and receiving the transmitted or back-reflected signal. The dielectric properties of the medium passed through (i.e., the dielectric permittivity  $\epsilon$ , the electric conductivity  $\sigma$  and the magnetic permeability  $\mu$ ) rule the propagation of the EM waves.

GPR system is usually configured by one transmitting and one receiving antenna(s), a control unit, a data storage unit and a display unit. An EM impulse is emitted by the transmitting antenna towards the surface to investigate. Subsequently, the signal is reflected and scattered by the dielectric anomalies/interfaces in the subsurface and collected by a receiving antenna. A conventional analog-to-digital (A/D) converter is used to convert the extracted information in such a way that a real-time displaying of the data as well as additional processing can be performed.

To date, GPR is a well-established technology, widely applied in several applications, spanning from civil engineering to planetary sciences and including of course the Archaeology [10].

### A. Use of Ground-penetrating Radar in Archaeology

As has been already told, GPR in archaeology has been applied for the assessment of protected sites that can never be excavated, as well as for rapid and cost-effective planning and development of mitigation projects.

Within this context, preventive archaeology is a discipline, including GPR surveys, required for evaluating the risk of running across buried archaeological remains during excavation activities carried out within engineering works. This class of applications are nowadays carried out by an increasing number of geophysical consulting firms.

The first application of GPR in archaeology dates back to 1970s. Bevan and Kenyon [12] and Bevan [13] investigated radar reflections from buried walls and other historic structures. Similarly, Vickers and Dolphin [14] analysed radar reflections to identify potential buried walls associated with the native American Indian structures at Chaco Canyon.

A variety of GPR case studies were published in the 1980s and 1990s. Vaughn [15] used GPR to identify a sixteenth century Basque whaling station. Imai et al. [16] accurately locate pit house floors buried in volcanic soils. DeVore [17] investigated the Fort Laramie National Historic Site.

Other relevant GPR studies from the same time period can be found in [18-20].

These studies were mainly focused on locating targets rather than providing a computer-generated image of the area with spatial development of the buried remains.

On the contrary, time-slice analysis was mostly developed over the 90s, and first research was introduced by Nishimura and Kamei [21] and Milligan and Atkin [22]. Much more sophisticated imaging was presented later using data binning and interpolation procedures [23, 24].

Relevant advances in data imaging were reached much more recently, mostly focusing on interpolation methods [25-26].

Integration of GPR with other non-destructive testing (NDT) methods has been the main research focus over the last decade. Main aim of this approach is to integrate information from equipment with different physics and investigation scales. In this regard, GPR, electrical resistivity tomography (ERT) and magnetic techniques have been mostly combined and used in various different case studies.

A first study addressing the topic was proposed by Negri and Leucci [27]. The authors used two-dimensional ERT imaging to detect the presence of an active fault passing under a main historical temple. GPR was instead employed to detect potential man-made structures throughout the area.

Nuzzo et al. [28] presented an integrated investigation with GPR, ERT and magnetic gradiometry to improve interpretability of results at Hierapolis, Turkey.

Papadopoulos et al. [29] applied GPR and ERT techniques to archaeologically characterise a complex urban area. More recently, Zeid et al. [29] proposed a non-conventional geophysical approach for archaeological investigations. The authors employed the Horizontal-To-Vertical Spectral Ratio method (HVSr) to appreciate contrasts of acoustic impedance of inspected paleo-surfaces. In addition, the Induced Polarization tomography (IPT) was used to monitor trend of chargeability values to relate with a paleo-riverbed.

### *B. Advantages and limitations*

In the last years the use of GPR has been adopted in many fields. Its application involves mainly the underground surveys because of its fast data acquisition and for the consequent cost savings.

The GPR utilization in recent researches has shown its potential together with some limitations.

GPR is an extremely useful instrument for archaeology because quite large areas of ground can be surveyed quickly, producing information concerning buried cultural remains and related stratigraphy. Besides, GPR tests are relatively cheap and do not involve safety concerns for both the surveyors and the archaeological heritage.

However, it is worth to consider that the ancient structures situated in considerable depth are generally difficult to be detected because of the material dispersion. Penetration depth and resolution of the acquired dataset depend on various factors such as antenna frequency and electrical properties of the soil.

The antennas choice can derive from the earth features but also from the penetration depth to be obtained: this is inversely proportional to the resolution of the achieved information.

The main limitations in the data acquisition phase occur in presence of high-conductivity materials, such as clay- or salt-contaminated soils, or heterogeneous soil that can lead to complicated electromagnetic scattering phenomena. Indeed, in high conductive situations the effectiveness of the signal penetration could be very limited and can affect even the detection of superficial structures.

A further issue concerns the interpretation of acquired data and the consequent 3D reconstructions, as they require the presence of a skilled operator who also needs to know the archaeological features of the area quite well. Indeed, an archaeological structure might be difficult to understand only through a GPR survey, since it may present irregular shapes, different life phases and, therefore, different construction materials.

Accordingly, a close collaboration between the surveyor (typically geophysicist) and the archaeologist is fundamental. In addition, favourable soil conditions and the integration of the GPR with other non-destructive testing technologies can give way to an easier interpretation of the acquired data.

## III. EXPERIMENTAL ACTIVITY

The site selected for this study is the Maxentius complex, located between the second and the third miles of the ancient Appian Way (Rome). This complex is characterized by three principal focal points dated between the end of the 3<sup>rd</sup> and the beginning of the 4<sup>th</sup> century AD: the so called mausoleum of Romulus, the Imperial villa and the circus. However, this archaeological site is known to have been occupied by a large *villa rustica* since the previous Republican period (Fig. 1).



Fig.1. Aerial View of the Maxentius Complex.

Among the different zones considered suitable for GPR inspection, it has been decided to carry out the survey in the area stretching between the villa and the Romulus *quadriporticus* where a bath complex (2<sup>nd</sup> century AD) was partially brought to light and reburied during the second half of the last century [30] (Fig. 4).

The backfill was characterized, in this area, by a significant dampness and a remarkable slope towards west. As it is clearly shown in the plan, the actual remains of the bath complex are characterized by three rectangular tanks (15.50 m wide and 19 m long) of which the central one is larger than the other two (fig. 4). On the southern side another tank with an apse shape is located and part of its roof is still visible on the Romulus *quadriporticus* external wall at a height of 7.20 m.



Fig. 2. Scheme and data collection on Grid 1.

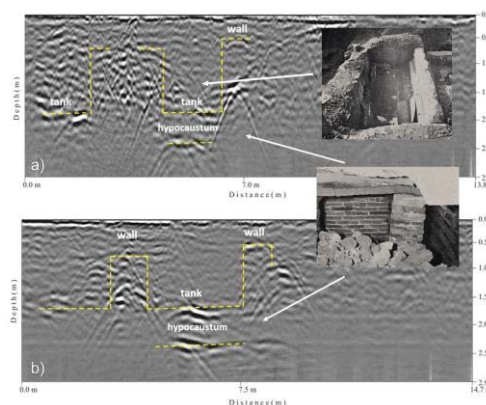
The inspection was carried out by covering the area following the trapezoid-like grid (cell size: 0,50 x 0,50 m) shown in Fig. 1 and 3. The data were collected using the Hi-Mod system, manufactured by IDS Georadar, equipped with two paired ground-couple antennas. The nominal frequencies of the antennas are 200 MHz and 600 MHz. The time interval was kept equal for the two antennas and set as 0.156 ns (512 samples per 80 ns). As transmitter and receiver are very close, they were considered to be approximately at the same position (i.e., a monostatic configuration). The horizontal resolution was set at 0.035 m. The encoder installed on a wheel of the cart permitted to track the exact distance covered by the antenna during the survey.

#### IV. RESULTS AND DISCUSSION

The analysis of the data acquired along the grid (fig. 2) has allowed the identification of the main ancient buried structures already detected during the last century's excavations. The first analysis of the acquired data has

shown that the archaeological remains are located between a depth of 0.30 and 2 m ca. The B-Scan has revealed anomalies at a depth of 0.80 m that would indicate the presence of the survived sectors of the walls that delimitate the two side tanks (fig. 3).

Fig. 3. a) longitudinal and b) transversal B-Scans of Grid 1

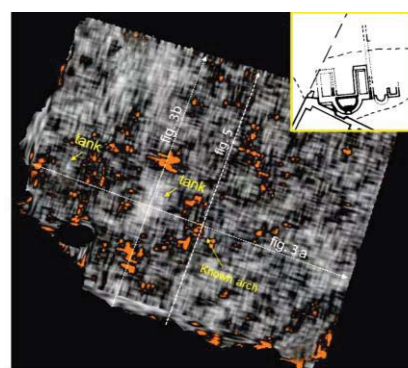


The issues related both to the dampness of the soil and to the nature of the backfill highlighted difficulties regarding the interpretation of the B-Scan, in particular in the easternmost corner of the grid area which is at a higher level.

Other anomalies located at a deeper level (1.60 m ca.) show a horizontal surface that would underline the presence of the flooring of the various tanks. According to the same B-Scan, beneath this surface (at a depth of 2.20 m ca.), another flooring seems to be visible. This latter floor must have hosted the *suspensurae* that allowed the circulation of hot air for heat up the different rooms of the thermal complex.

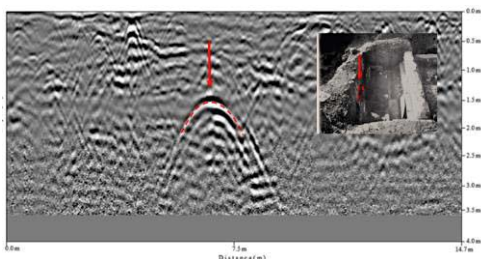
The presence of these two floors has conceded to recognize this space as the *calidarium* – the room provided with hot water - of the bath complex. In this case, the data coming from the GPR prospections have constituted an effective help in determining the historical function of this specific space.

Concerning the tomographic analysis (Fig. 4), it is possible to recognize the features already noticed in the B-Scans. It would seem detectable the rectangular right tank (most likely the walls and the flooring), part of the left and of the apse of the tank. In the middle of the latter one a tree had damaged the pavement thereby inhibiting further investigation of this sector.



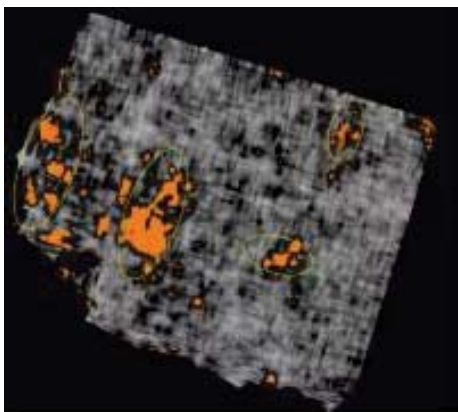
*Fig. 4. Tomography of Grid 1 at 1.5 m of depth, with highlighted the scan direction of the radargrams in Fig. 3*

Other structural elements clearly visible in the B-Scans are the arches in which the hot air went through from the furnaces placed in the praefurnia - structures made of bricks or stone - to the wall cavities made of tubuli and in the hypocaustum. This heating system is visible through the data analysis thanks to the strong reflections generated by the arches (fig. 3). From the data of the previous excavations only one arch was detected but its position was not registered. This survey allowed to established the exact position of the known vaulted passage (fig. 5).



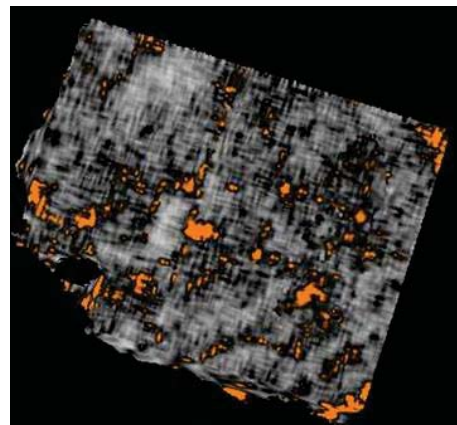
*Fig.5. Longitudinal B-Scan of Grid 1 with the anomaly of the known arch.*

In order to evaluate the presence of additional bath tanks over the inspected area, tomographic inspection between 1.5 m and 2.0 m of depth was conducted. This analysis, together with the evaluation of the relevant B-Scans, has permitted to recognise two further potential tanks in the right side of the area, which in turn allows to hypothesize further rooms just close to the excavated ones (fig. 6).



*Fig. 6. Tomography of Grid 1 at 1.8 m of depth, with highlighted the potential presence of further tanks in the right side of the area*

According to the above assumption, a further tomographic investigation was conducted to recognise the wall pattern across the area. Despite the depth of the reflections from the top of the walls turned out to be significantly variable throughout the area (fig. 7, e.g.).



*Fig. 7 Tomography of Grid 1 at 1.45 m of depth with revealed the wall pattern.*

These results seem to confirm the presence of further rooms in the top and right direction, with respect to the drawings from the excavations.

## V. CONCLUSIONS

This paper deals with a geophysical experimental activity carried out in Maxentius Complex, an archaeological site located in Rome, Italy.

The aim of the study is to focus on the possibilities of GPR to detect buried archaeological remains and in particular architectural features and to interpret the function of buried structures.

As a result, GPR allowed to confirm the literature-based information, i.e. to precisely locate the tanks of the thermal area which was known to be buried in the inspected area. In addition, the tomographic analysis highlighted the presence of two further tanks, thereby suggesting the possibility of further rooms to be located close to the excavated ones. This assumption was also confirmed by tomographic analysis, which stressed out a wall pattern that seems to suggest the presence of further rooms in the top-right side of the area.

In general terms, GPR demonstrated a great applicability to archaeological purposes, despite the reliability and productivity of the data interpretation are strongly influenced by the expertise of both the geophysicists and the archaeologists involved.

Further efforts should be paid on the development of algorithms for the automatic detection of hidden structures, in order to increase the productivity of the interpretation.

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