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Ground Penetrating Radar survey at the Basilica of San Paolo fuori le mura (Roma, Italy)

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***Abstract* – This paper shows the results of a new archaeogeophysics investigation at the Basilica of San Paolo fuori le mura (Roma) carried out thanks to a collaboration between Dartmouth College (USA), the Institute of History and Theory of Art and Architecture of the Università della Svizzera Italiana, the Institute of Heritage Sciences of the CNR of Rome and the Governatorato of Vatican City. The new research includes high-resolution Ground Penetrating Radar surveys and bibliographic and archival analyses, still in progress, concerning the history of the development of building and its liturgical furnishings from the fourth century through modern times. The main purpose of this new study is to understand the evolution of the Basilica's core, the area around the tomb of St. Paul, which across the centuries attracted attention from pilgrims, popes, and other potentates. The GPR profiles were processed with the aim to obtain a 2D time-slices images and 3D visualization (isosurface) of all reflections in the ground. The results obtained from the geophysical surveys were interpreted together with the archaeologists and historians to define the meaning of the individuated structures and to enhance the knowledge of this historical building.**

I. INTRODUCTION

The Basilica of San Paolo fuori le mura was one of Rome's oldest and most venerable churches, and, until a fateful fire in 1823, it had survived relatively intact as the principal resting place of the Apostle Paul. What had been lost in that fire was a building built at the end of the fourth century, the last imperial basilica built in Rome, the city's second largest church and, for the faithful, the unquestioned epicenter of Pauline veneration. Through the centuries, the building—like its namesake—had become a protagonist in the development of Christianity and its major institutions like the Catholic Church, the papacy, and monasticism. Even today, following the lengthy reconstruction begun in 1825 and completed only during the Fascist era, it stands as a UNESCO World Heritage Monument. Despite the reconstruction, the possibilities for study still appear enormous today [1][2].

The investigation presented here was financed by Dartmouth College's Neukom Institute and the Swiss National Science Foundation as part of research conducted for the 'The Churches of the City of Rome in the Middle Ages, 1050-1300' (Corpus Cosmatorum). The multi-volume project deals with the architecture and liturgical furnishing of the medieval churches of Rome from the 11th to the end of the 13th century. It was started in 2002 by Prof. Dr. Cornelius Claussen at the University of Zurich and continued as a cooperative project of the chairs for medieval Art History of the Istituto di storia e teoria dell'arte e dell'architettura (ISA) at the Accademia di Architettura (AAM), Università della Svizzera italiana (USI), Mendrisio (Prof. Dr. Daniela Mondini), and the Institute for Art History at the University of Zurich (KHIST UZH) (Prof. Dr. Carola Jäggi). The sixth volume is currently in progress and is planned to be completed as a manuscript ready for printing in Spring 2024. It is exclusively dedicated to the two important commemorative churches of St. Paul and St. Peter (S. Paolo fuori le mura and S. Pietro in Vaticano). For this volume Prof. Nicola Camerlenghi (Dartmouth College) and Prof. emer. Sible de Blaauw (Radboud University) contributed substantial essays.

In order to better understand the sequence of alterations in the transept of the Basilica of San Paolo fuori le mura during Late Antiquity, as well as the Early and High Middle Ages, we decided to apply a Ground Penetrating Radar (GPR) investigation carried out through the collaboration with the Institute of Heritage Sciences of CNR (Roma). The main questions we wanted to get an answer through this investigation were: (a) the sizes and the transformations to a sequence of presbyteries around the main altar and tomb of Paul; (b) the presence of tombs in the vicinity of that of Paul; (c) the possibility of the existence of a crypt in the transept or, analogous to the ring crypt of Old St. Peter's, along the curvature of the apse; (d) the remains of the Constantinian church, which pre-dated the fourth century basilica; (e) foundations of the transverse wall or "muro divisorio" built around

1130/1140. Many of these topics have been of interest to scholars for decades now [3][4].

The geophysical survey has the objective of investigations with high-resolution GPR methods aimed at understanding and conserving the structures buried beneath the current floor of the Basilica of San Paolo. The surveys are based on geophysical surveys with the high resolution Ground Penetrating Radar method (HR-GPR). These investigations were concentrated in the following internal areas: Transept, Apse and adjacent areas the Apostolic Altar, the Altar to the right of the Transept and two adjacent environments (known as the Oratorio di San Giuliano, now the ticket office to the cloister), and have as their objective the identification of the archaeological structures still buried, Fig. 1.

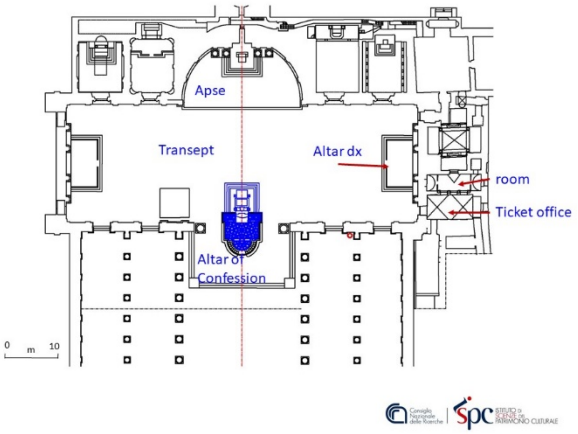

Fig.1 – San Paolo fuori le mura. Plan of the investigated areas

II. METHOD

GPR acquisitions were carried out on 22 and 28 September 2021 compatibly with the logistical availability of the basilica, concentrating the measurements in 7 sub-areas of different sizes that cover the surfaces between the Transept, the Apse and the Apostolic altar, Fig.1.

For the GPR measurements, data were collected, along parallel profiles, employing the SIR4000 (GSSI) system, equipped with a dual frequency antenna with 300/800 MHz with constant offset (Fig. 2) and a bistatic antenna with constant offset and frequency of 500 MHz (GSSI) [6]. The horizontal spacing between parallel profiles used was 0.5 m for all sectors of the square. The spacing was chosen based on the indications of archaeologists regarding the size and dimension of the hypothesized structures in the studied area [5]. After the usual preventive tests and considering both the geo-environmental situation and the type of assumed structures, the following instrumental configuration was adopted: with the 300/800 MHz antenna, depth intervals 3 m for the 800 MHz antenna and 5 m for 300 MHz antenna, 32-bit dynamic range; with the 500 MHz antenna: time scale 95 ns (nanoseconds) twt (two-way-time), dynamic range 16 bit, 512 samples per track and stack equal to 3.

The radar traces were acquired in line-scan mode, which consists in dragging/pushing the antenna along the pre-set direction in continuous recording. The investigations involved the entire seven sub-areas.

Fig.2 –. San Paolo fuori le mura. GPR SIR4000.

III. PROCESSING AND RESULTS

All the GPR profiles collected with this standard equipment were processed with GPR-slice v7.0 Ground Penetrating Radar imaging software [6]. For each profile, a vertical ground penetrating radar section was obtained in which, by means of a suitable chromatic scale, the values of the amplitudes of the reflected waves are reported, according to the chosen time (or depth) scale.

During the elaboration of the single ground penetrating radar profiles, the following electromagnetic signal analysis procedure was applied: (a) analysis of the radargram and application of a suitable gain function; (b) removal of DC drift (antenna/ground coupling effect); (c) resampling of radar traces along each single profile; (d) application of the bandpass filter on each single profile; (e) application of the background removal filter on each individual profile; (f) migration. With the aim of obtaining a planimetric vision of all possible anomalous bodies, the time-slice (2D planimetric image) representation was calculated using all processed profiles [6].

The results obtained in the current elaboration and interpretation phase are related to different levels of depth (surfaces) for an investigated subsoil thickness (depth) equal to 4.0 m.

The depths to which the calculated time-slices refer, for the areas investigated with the 300 MHz and 500 MHz antennas, are: 0.15 m, 0.25 m, 0.40 m, 0.60 m, 0.80 m, 1.10 m, 1.40 m, 1.60 m, 1.80 m, 2.00 m, 2.40 m, 2.80 m, 3.10 m, 3.40 m, 3.80 m, 4.00 m; these depths refer to the

walking surface of the investigated surfaces.
The anomalies identified have been included in the general plan of the basilica.
Fig. 3 shows the time-slices obtained at a depth of 0.60 m, on these images a part of the identified reflectors are indicated with the arrows. At this depth we can observe the following anomalies: T1: anomaly of strong intensity with dimensions equal to 3.0 x 2.7 m; T2: linear anomaly, inclined, with dimensions equal to 14.0 x 0.9 m. T3 and T4: two linear anomalies, parallel to each other, at a distance of 3.1 m, which in the area between them present a "white" area (very attenuated intensity of the reflected signal, probably due to the filling following the excavation carried out in this area). The dimensions of the two anomalies are equal to 20.0 x 0.9 m. T5: an anomaly with dimensions equal to 2.7 x 2.7 m is highlighted.
In the western part of the transept, in front of the left altar, two symmetrical anomalies stand out at a distance of 2.9 m from each other, with dimensions respectively equal to 3.6 x 0.9 m and 3.0 x 0.7 m.

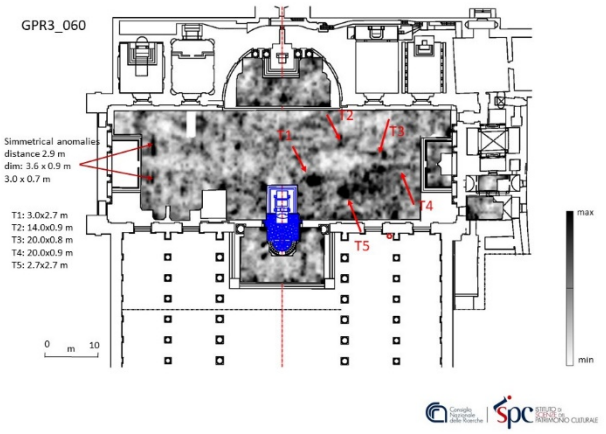

Fig. 3 – San Paolo fuori le mura. GPR time slices at the estimated depth of 0.60 m.

Fig. 4 shows the time-slices obtained at a depth of 1.40 m, on these images a part of the identified reflectors are indicated with the arrows. The two anomalies T1 and T5 seem to merge into a single anomaly with dimensions equal to 8.4 x 2.8 m. The T6 and T7 anomalies are reduced in size; the T8, aligned with the T5, has dimensions of 1.1 x 17.0 m. The T9 anomaly is present only in traces; T10 has dimensions equal to 0.8 x 4.1 m. The T11, of strong intensity, has dimensions equal to 4.8 x 2.8 m; T12 anomaly with dimensions equal to 9.4 x 1.4 m; T13: semicircular anomaly and T14 circular anomaly with a diameter equal to 5.0 m.

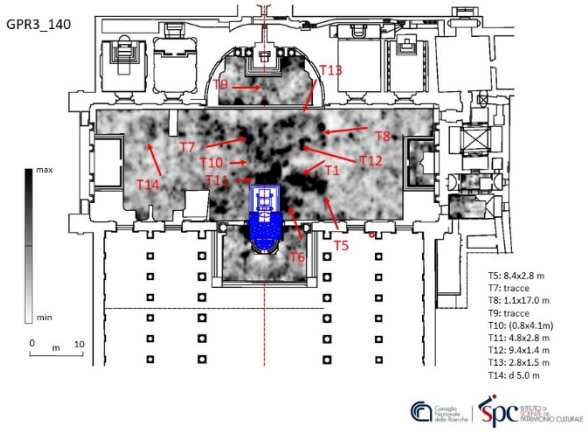

Fig. 4 – San Paolo fuori le mura. GPR time slices at the estimated depth of 1.40 m.

Fig. 5 shows the time-slices obtained at a depth of 1.80 m, on these images a part of the identified reflectors are indicated with the arrows. Also at this depth the anomalies already found are confirmed. The T5 decreases the dimensions which are equal to 8.4 x 2.8 m. T15 two linear anomalies, parallel to each other, at a distance of 3.1 m, which in the area between them present a "white" area (very attenuated intensity of the reflected signal, probably due to the filling following the excavation carried out in this area). The dimensions of the two anomalies are equal to 20.0 x 0.9 m. There are also anomalies that flank them with dimensions of 1.1 x 2.9 m and 1.4 x 5.5 m respectively.

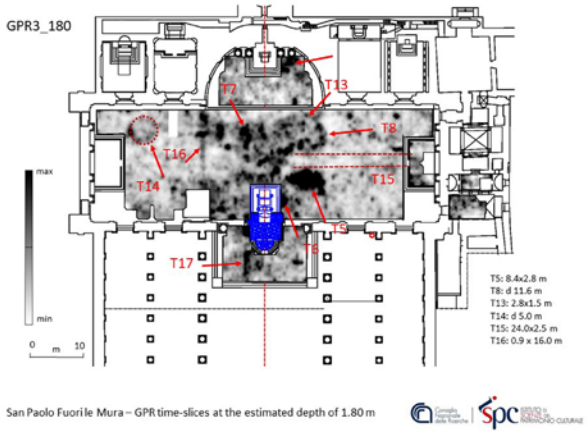

Fig. 5 – San Paolo fuori le mura. GPR time slices at the estimated depth of 1.80 m.

Fig. 6 shows the time-slices obtained at a depth of 2.40 m, on these images a part of the identified reflectors are indicated with the arrows. Also at this depth the anomalies already found are confirmed. The T5 decreases the dimensions which are equal to 5.9 x 3.3 m. T16 is always with strong intensity and dimensions equal to 1.1 x 15.8 m. In the apse there are two semicircular anomalies with a section of 1.1 m. There are also anomalies that flank them with dimensions of 1.1 x 2.9 m and 1.4 x 5.5 m respectively. The background of the image has a fairly uniform intensity, to suggest the presence of a paving level.

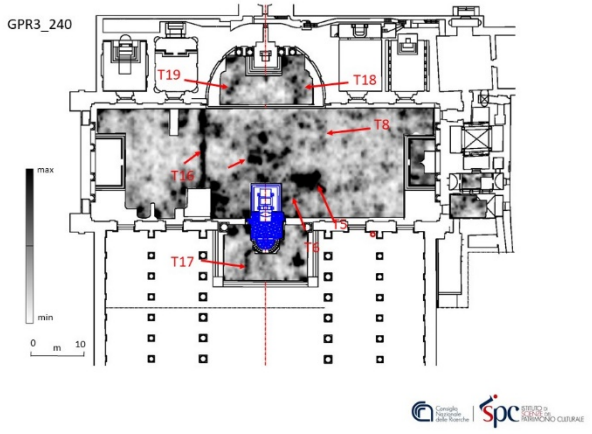

Fig. 6 – San Paolo fuori le mura. GPR time slices at the estimated depth of 2.40 m.

Fig. 7 shows the time-slices obtained at a depth of 2.80 m, on these images a part of the identified reflectors are indicated with the arrows. Also at this depth the anomalies already found are confirmed. The T5 decreases the dimensions which are equal to 5.9 x 3.3 m. T16 is always with strong intensity and dimensions equal to 1.1 x 15.8 m. In the apse there are two semicircular anomalies with a section of 1.1 m. There are also anomalies that flank them with dimensions of 1.1 x 2.9 m and 1.4 x 5.5 m respectively. The background of the image has a fairly uniform intensity, to suggest the presence of a paving level.

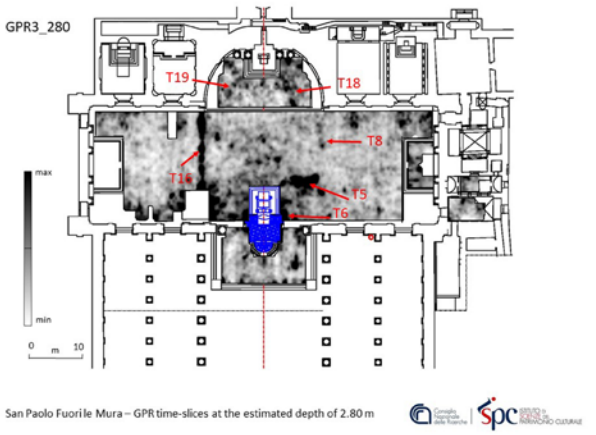

Fig. 7 – San Paolo fuori le mura. GPR time slices at the estimated depth of 2.80 m.

IV. CONCLUSIONS

The investigations carried out so far inside the basilica of San Paolo fuori le mura (Rome), using the GPR equipped with 300/800 MHz and 500 MHz antennas, according to a high resolution acquisition method (interdistance of the profiles equal to 0.5 m), designed taking into account the average dimensions of the possible buried structures, have allowed us to characterize the subsoil of the basilica down to a depth of 4.00 m in the case of the Transept, the Apse, the Apostolic Altar, the Altar to the right of the Transept and the two adjacent rooms.

The analysis of the depth-slices shown in the figures has allowed us to confirm, in terms of position and depth, some structures known from previous excavations [4], to calibrate the depths of the observed structures, to locate of structures in almost all the investigated areas and for the total thickness investigated.

The Transept area is particularly rich in evidence which partly correlates with information gathered from the literature [1] [2] and partly indicates new structures, characterized by geometric shapes and significant orientations, which stimulate historical-archaeological interpretation.

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