# Integrated Methodologies for the Survey and the Documentation of Two Byzantine Churches at the UNESCO Archaeological Site of Umm ar-Rasas (Jordan)

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**Abstract.** Since 2013, a multidisciplinary research project is in progress at the UNESCO archaeological site of Umm ar-Rasas in Jordan. Among a general study of the area, a special focus is dedicated to the survey and documentation of two Byzantine churches and their mosaic floors. Different investigation techniques, such as laser scanning, photogrammetry and GPR surveys, were reciprocally integrated, in an effort to create geometric models enabling the interpretation of data related to the masonry, the mosaic floors and the buried structures as well as to the documentation of the archaeological area. The results will be the starting point to plan and develop restoration projects for the protection and valorisation of the UNESCO site.

**Keywords:** World heritage site · UNESCO · Jordanian cultural heritage · Applied technologies · Survey

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 Moab's plateau (Fig. 1a). From 1986 to 2007, the archaeological researches were conducted by the Franciscan Archaeological Institute of Mount Nebo [1, 2] under the patronage of the Department of Antiquities of the Hashemite Kingdom of Jordan. In 2004, it was inscribed in UNESCO's World Heritage List. From 2013, the Institute for Technologies Applied to Cultural Heritage (now Institute of Heritage Sciences, CNR, Italy), 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 [3].

The remains consist of a huge area, fortified by a massive wall that measures 158 m × 140 m, on which numerous buildings are located and that once was a Roman Castrum (Fig. 1b). Towards the northern part of the archaeological site, housing and

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sacred structures have been identified, which can be dated from the Byzantine to the Early Islamic period, up to the IX century A.D. [2].

Towards north, a kilometre and a half from the residential zone, an exceptional example of Stylite Tower stands 15 m high at the centre of a courtyard protected on the northern side by a squared defensive tower nearby some water tanks dug in the rocky soil. The Stylite Tower does not have stairs; instead, it has just one room with windows in its highest portion, which is thought to be a place of meditation for a Stylite monk [4, 5].

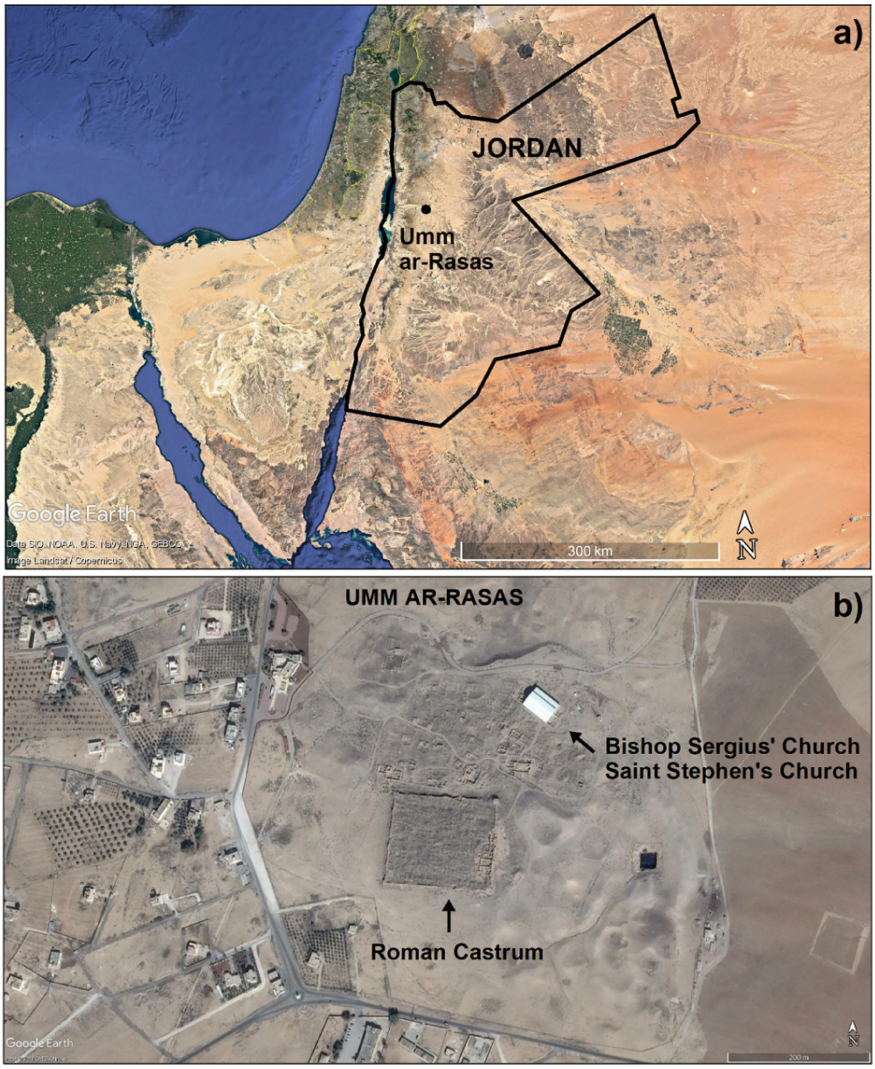



**Fig. 1.** Location of Umm ar-Rasas on a Google Earth™ satellite image of Jordan (a), detail of the site with indication of the roman castrum and the two Byzantine churches (b).

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 century A.D., formed by at least four communicating buildings: the Church of the Tabernacle that is the most ancient, Bishop Sergius' Church with its baptistery and the funerary chapel to the front, Saint Stephen's Church and the Church of the Courtyard, raised between the other three churches.

This paper has focused on the rich mosaic decoration of Bishop Sergius' and Saint Stephen's Churches (Fig. 2), both with three aisles and one apse and with the chancel rose by two steps. The two churches host some 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 a mosaic 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. The readability of the portions that represent figurative elements in fact was for the most part made uneasy to perform because of actions of censorship on the figurative images, realised taking off the *tesserae* one by one and then putting them again in position but without a precise scheme with the aim of filling the gaps in the floor. In Saint Stephen's Church also, built after Bishop Sergius' Church and dated around 717 A.D., the subjects portraying people and animals were disfigured. However, it has to be noticed that the intervention on the figures of the mosaic floor results, for its execution mode, as made by Christian workers. They cared scrupulously about the complete preservation of the floor, either for the beauty and the decorum assured to the cultic building and for its value as an offer by local community members, whose names were written together with the images in the mosaic representations.

The archaeological missions undertaken until now were mainly aimed at photogrammetric and laser scanning surveys to determine morphological anomalies of the mosaic floors. The project foresees as its ultimate goal the documentation and consecutive valorisation and accessibility of the site, though also the professional training of local technicians with the help of systems of distance learning. During the measurements' campaigns, the work proceeded in continuity with the activities realised in the previous years and the following activities are expected to be completed in the near future, representing only a small portion of actions, compared to the more general framework of issues affecting the entire archaeological site:

1. The survey of the outer walls of Saint Stephen's and Bishop Sergius' Churches, both by photogrammetric methods and by detailed and high-resolution laser scanning.
2. The documentation of the decaying state of the most relevant and at high risk structures through the use and integration of high resolution laser scanning and photogrammetric methods which will highlight the decay, even the type which is not perceivable by direct sight. These methodologies produce micro DEM of the floors useful for a correct interpretation of the structural solicitations of the building that,

if compared to the other parameters and measurements taken during the survey campaigns, will provide a punctual documentation useful to plan the following restoration and reinforcement actions on the mosaics. A further fundamental element for the documentation and conservation will be given by the high-resolution orthogonal pictures of the mosaic surface, arriving to a pixel dimension of a few tenth of square millimetres, allowing obtaining images with dimensions comparable to the real dimensions of the mosaic.

3. Non-invasive geophysical prospections of the areas of the main churches, which will allow detecting anomalies possibly indicating more ancient structures or graves.



**Fig. 2.** Details of the walls of two Byzantine churches (St. Stephen and Bishop Sergius).

## 1 Methodology

### 1.1 Photogrammetry

*T*he Structure from Motion technique was utilized in order to obtain complete documentation of the floor at high resolution in terms of chromatic definition of surfaces and photographic detail. During these years, photogrammetric images were acquired from the mosaic floors, with a 21 Mpixels' resolution for every single frame, standing by 1.5 m from the floor, with the camera perpendicular to it. The images, taken in RAW format, were calibrated in the RGB map with a predisposed chromatic table. This table has also the peculiar characteristic of being recognized automatically by a specific algorithm

allowing the definition of the chromatic scale. This operation was necessary to standardize the colors of the photographic takes depending on the different level of lighting to which the floor was subject to at different hours of the day and on the different spatial positions of the camera inside the church.

A test conducted on a small portion of the floor (the apse of Saint Stephen's Church) in the 2013 mission had evidenced the need to build a tool allowing the realisation of the photogrammetric images with the camera in an easy way at a fixed distance from the floor. The photogrammetric tool that was set up is made of a camera calibrated with a 20 MP Full Frame sensor and a 28 mm lens, mounted on a pole that can be put on the shoulder. The camera was constantly held to a height of 170 cm obtaining a very good compromise between the accuracy of the photogrammetric takes and a sufficient dimension of the area to be acquired (3m$^2$ for each take, GSD of 0,4 mm)[1]. The research group chose to operate using an experimental tool that allowed more freedom in movements, considering the extreme delicateness of the surface and that the main purpose of the work was documenting the decay and avoiding damage to the building. The choice has fallen on quick and light weighted tools, easy to move on the mosaic floor. Moreover, the presence of metal structures (boardwalks) *in situ* has in many cases created some difficulties on taking the pictures and has limited the action range of the group to lower heights (this brought the need to take frames at a higher frequency). In general a good quality of takes is the best guarantee of a final result in which the mapping of the model is at a good level.

For each floor approximately 2000 frames were taken, with the purpose of covering in full the surfaces of the two investigated churches (Saint Stephen: 242,26 sq.m; Bishop Sergius: 226,12 sq.m), also the use of a color-checker allowed the balancing of the color white made through the use of a raw-converter software. At every movement the operator, before taking the shot, had to assure the perfect stability of the camera, without oscillations; the movements had to allow an adequate overlapping, in order to guarantee, during the data processing phase, the assembling of the frames. It has to be noticed that, at each change of the light conditions, the color has been calibrated again with the help of the color-checker, to avoid chromatic differences between each stripe. The final point cloud is the result of the alignment of the various strips. The software application, based on the technique known as Structure from Motion [6], doesn't make the built model a metrical model; therefore it is necessary to determine a ratio based on the topographical data at hand. Hence, the photogrammetric survey was combined to the laser scanning survey [7].

### 1.2 Laser Scanning

To perform the survey through laser scanner on the structures subject to investigation a pneumatic pole has been used to raise the scanner up to 5 m high, allowing in this way to measure even the highest walls' crests [8] (see Fig. 3). This tool, designed and built specifically for this purpose, allowed performing 3D surveys from observation points that nowadays require the use of drones (that have sight from up above), without altering the geometric and metric accuracy which only laser instruments can offer. Another

[1] The processing of the photographic takes was done using the software *Agisoft Photoscan.*

advantage brought by this survey technique is that the laser scanners are tools mainly made to perform scans in the architectural and engineering field; therefore, their best application is mainly addressed at everything that stands high above the planking level (walls, ceilings and arches). It is instead less efficient to measure structures that are located on the horizontal level of the instrument (floors, mosaics, holes, depressions and digs).

The scans made were 70 in total and the survey was completed for the entire monumental structure of the two churches, Saint Stephen's and Bishop Sergius'. The scans were executed with a resolution at a half of the maximum of the instrument and acquiring the RGB component. At the moment the research group is finishing processing all the acquired scans by isolating single elements of every building (walls, apse and floor), and then we will proceed to the modelling of the structures that will help doing in the future a virtual anastylosis of the monument.

The scans were all performed through a phase-shift laser scanner Focus120 3D, produced by Faro, that gives high accuracy results, despite the scan timings. The instrument was set on the profile "Outdoor over 20 m" with a resolution to a half of the maximum and the acquisition of the RGB component. Approximately 10 to 12 scans were made each day since it took 30 min to take each scan due to the scanner configuration, considering the 8h of overall duration of the two batteries at hand and the timings of movement of the pneumatic pole and the instrument. The registration[2] of the scans was made using a double alignment process, the first based on the automatic identification of suitable 3D high reflectance white targets (spheres) provided by Faro, with a 20 cm. diameter and a magnet allowing their attachment to metal structures[3]; the second required the use of complex mathematical algorithms providing the refinement of the initial alignments (ICP) [9]. When surveying with this technique, one has to account for three factors to get a good automatic alignment: first, at least three spheres have to be visible in between two adjacent scans, secondly the scans must have a suitable spatial distribution and lastly the laser scanner has to find enough points on the scans to recognize them and then calculate precisely their center. Once it has aligned the scans through the help of the spheres, the software automatically proceeds to the identification of at least 2000 common points to refine the alignment, resulting with an average error in the range of a millimeter.

### 1.3 Ground Penetrating Radar Survey

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 the submerged bodies and the surface on which the research group was working (i.e. on the mosaics), the GPR has been preferred to other methods. An IDS RIS K2 Georadar, equipped with a multi frequency antenna TRMF (600–200 MHz), has been used for data acquisition. All radar reflections were recorded digitally in the field as 16 bit data and 512 samples per radar scan. The spacing between

[2] The software *Faro Scene* has been used for a first alignment with spherical targets, *JRC Reconstructor* for the following processes.

[3] The research group opted to locate the instrument on mobile tripods, in order to move freely the targets.

parallel profiles at the site was 0.5 m and they were collected alternatively in opposite directions with angles of 90° in the survey grids. Radar reflections on each line were recorded at 25 scan s-1 (1 scan approximately corresponds to 0.025 m).

Standard bi-dimensional radargrams relative to single transects were processed through the GPR-SLICE 7.0 software. Band pass filters, background removal and the Gain Control were applied 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 [10].

Thus, 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 a 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 in which the electromagnetic wave fulfils the path transmitter antenna-discontinuity-receiver antenna). Data were then gridded using a kriging routine and a radius of interpolation equal to 0.75 m.

## 2 Results and Discussion

The survey provided a precise metric and photorealistic determination of the complex structure resulting in a complete reconstruction of the architectural artefact. Each survey performed at Umm ar-Rasas has given us a better knowledge of the structures located on the archaeological site. It should be also noticed that all the technologies employed resulted in new issues to be solved in the future with further applications.

The work conducted until now was a useful experiment for the integration of laser scanning and photogrammetric surveys: in this way the results guarantee from one side the descriptive accuracy in the colors and in the details of the surveyed surface; from another point of view the use of the laser scanning methods allows the representation with great precision, in the range of a few millimeters, of the geometrical deformities of the mosaic floors. Figures 3 and 4 report 3D view of the two churches obtained by laser scanning procedures and an inclination map of walls (Fig. 4b). In Fig. 5, the resulting orthogonal picture of the whole Saint Stephen's mosaic floor obtained by photogrammetric techniques is shown (dimension: 1 GB, equivalent to 8000 × 60000 pixel).

By analyzing the floor of Bishop Sergius' Church it has been pointed out a lifting of the floor by 0,10 m in the central aisle towards the apse; instead it has been noted a depression in the zone near the entrance door, the presence of which is probably related to an underground water tank located on the north-western side of the building, where traces of a water channel are visible. In Saint Stephen's Church there are also liftings of the floor on the right side of the central aisle, while light slopes are visible on the rest of the floor, especially on the portion of floor that is nearer to Bishop Sergius' Church (Fig. 6). The causes of these deformities could be linked either to geological instability issues of the area and to further underground man-made structures (graves, mural structures, tanks). The following investigations are aimed at the secure interpretation of these deformities. In relation to this, the execution of high-resolution photogrammetric surveys could be

used as a starting point for any conservation and restoration project to be planned for the preservation of the mosaic floors.

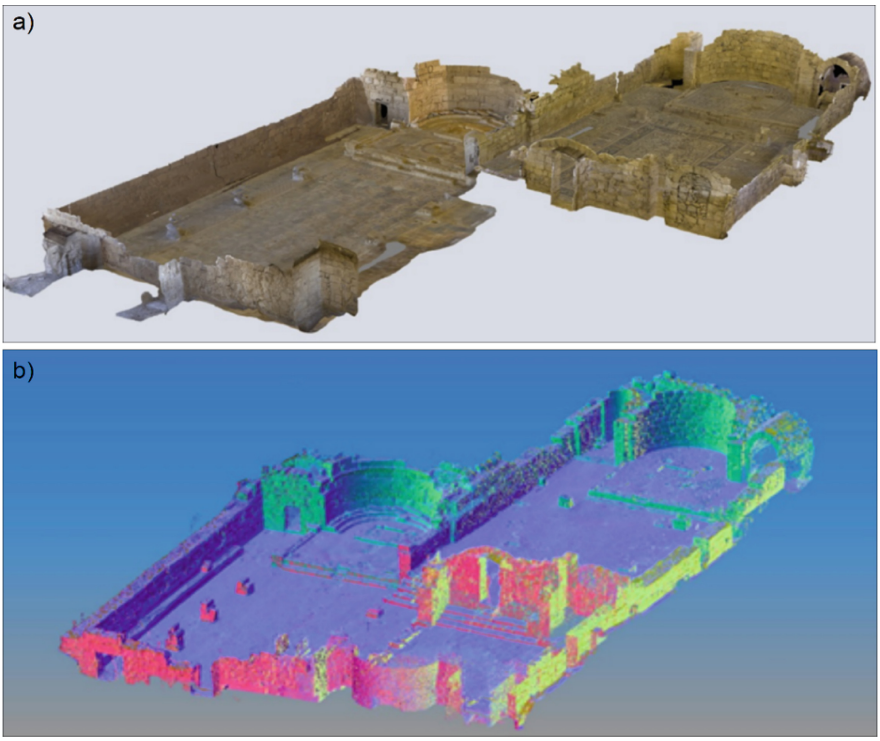



**Fig. 3.** 3D perspective view of the two churches obtained by laser scanning processing: 3D model of the two churches in their actual spatial arrangement (a); qualitative inclination map of walls where the colors indicate the direction of the surfaces (b).

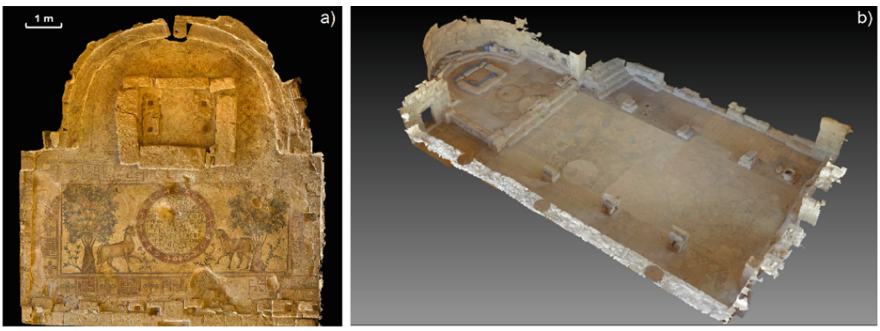



**Fig. 4.** Detail of the apse (a) and 3D perspective view of the model of the church of Bishop Sergius made by laser scanner (b).




**Fig. 5.** High-resolution orthographic view of Saint Stephen's mosaic floor obtained by integration of photogrammetric and laser scanning techniques.

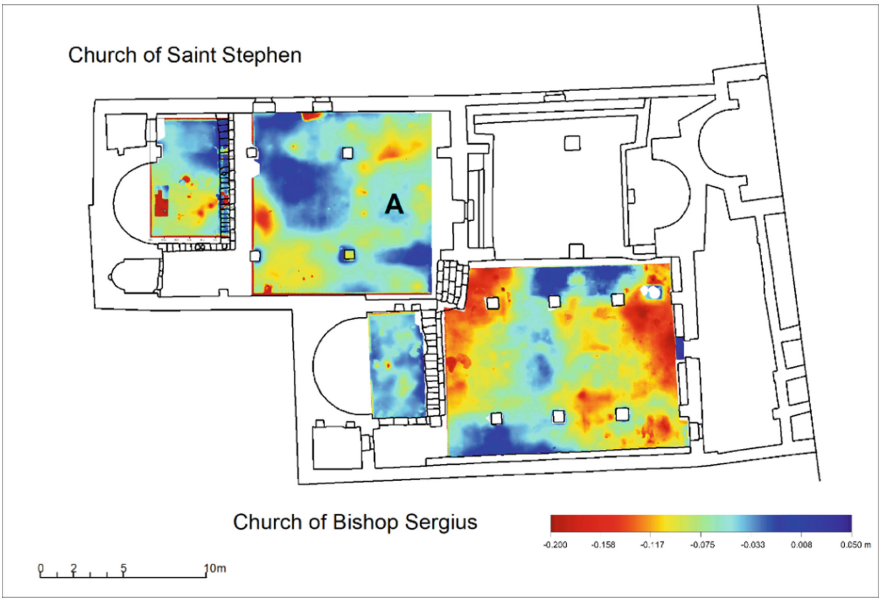



**Fig. 6.** Model of altitude variation of the floor of the churches.

Figure 7 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 center of the median body of the church and an anomaly in the space in front of the apse (at the right edge) are highlighted and they are indicated with pink arrows in Fig. 7. The presence of probable structures buried under the pavement, prior to the construction phase of the church, may have caused, in a phase of settling the materials, the deformation found by the laser scanner survey in particular in the point indicated with A. In the Church of Bishop Sergius, the prospection showed, at the entrance of the structure, 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 through integration of different geophysical methods such as electrical resistivity tomography, GPR and induced electromagnetic methods that generally produce a successful detection [11–14]. This application will be useful to promote archaeological excavations and project of valorization of the site.

All results are going to be stored in ad hoc geodatabase resulting from the partnership and debate between all the members of the research group made by archaeologists, art historians, geophysics and conservators [15]. The geodatabase is developing

in time following some steps: beginning with the development of a GIS platform to archive the acquired interdisciplinary data, to the development of analysis models for data management (Fig. 8). Therefore, the GIS technology offers both methodological and interpretative advantages: from one point of view, it allows the realization of an interdisciplinary dialogue between different research matters through the efficient data management and registration; from another point of view, it makes easy to interpret the information acquired from the spatial queries [16]. In addition, the geodatabase can be used as a monitoring device on the state of conservation of the mosaic, becoming a valid support for the planning of future restoration actions.

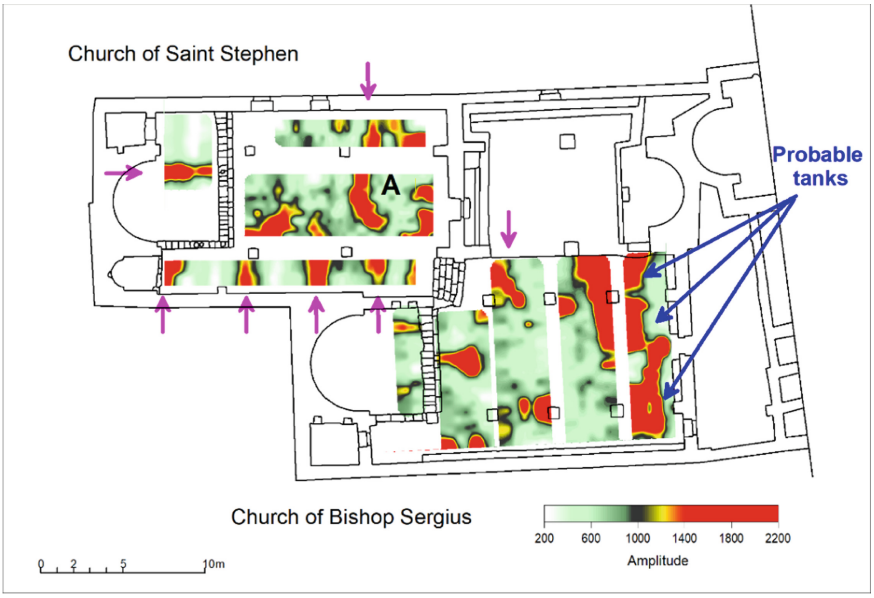



**Fig. 7.** Slices related to the depth window of 0.5–0.7 m overlapped on the map of the churches: the blue arrows indicate the location of probable tanks, while the pink arrows highlight probable buried archaeological structures. (Color figure online)

## 3 Future Outlook of the Project

The site of Umm ar-Rasas constitutes an extraordinary laboratory to study traditional masonry, either for the different use of materials in time and for the construction techniques' development. The settlement's long evolutionary history, that has its roots in the Roman castrum's implant, allows analyzing in a critical way the different typologies adopted for common houses and specialised building, such as the numerous medieval churches that have developed according to particular environmental conditions and materials' availability at the local level. The instability modes of the structures that have survived to time and earthquakes' action, typical destructive events that occur in this area,

are an aspect of great interest. This issue of the research can be studied beginning from the site currently under investigation and then be extended to a wider environmental context, with effects on the western world through a comparison with other construction traditions that are affected by the same issue. Therefore, this site offers a unique opportunity to understand the construction techniques' evolution putting the accent on anti-seismic actions. In particular, there are open questions about the static and seismic behavior of the arches and more generally of the pushing structures, considered among the most vulnerable structures but also some of the few that have survived to the general framework of instability. The study of the masonry through the mechanics of the arches constitutes the interpretation key that puts Umm ar-Rasas as a key site for the analysis of these events in an environment that keeps its original construction characteristics.

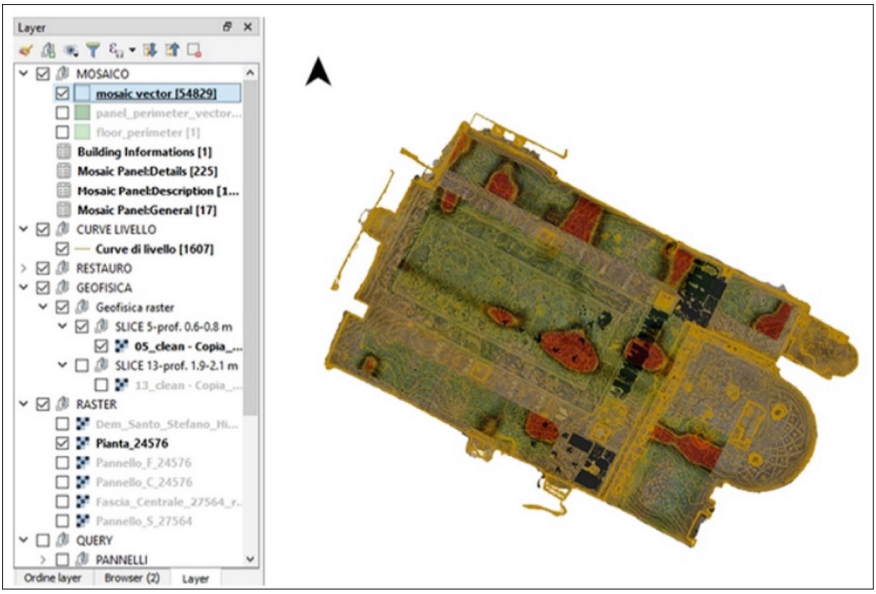



**Fig. 8.** Thematic map of the mosaic pavement of St. Stephen's church enriched in GIS application.

Analyses requiring superficial and underground observations of the soil and of the lithological and petrographical characteristics of the rocky subsoil have started on the area on which stands the so called Stylite Tower, this being among the most relevant structures of the archaeological complex. Moreover, the use of equipment such as georadar and geoelectric and seismic systems, both active and passive, will be implemented. Lastly, the identification of the structural mechanical characteristics and the decay, vulnerability and stability level caused by the atmospheric agents will be performed through the petrographical analysis and the direct topographical laser scanning survey. Another part will provide the realization and development of a tool for the valorisation and availability of the data by a wider range of users: the geodatabase of the mosaic floor in Saint Stephen's Church will allow the creation of a model for computerised management and interdisciplinary data analysis aimed at interpretation, conservation and valorization.

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