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Integrated Ground-penetrating Radar and Archaeological Surveys in the Ancient City of Hierapolis of Phrygia (Turkey)

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ABSTRACT Hierapolis of Phrygia (Turkey) was one of the most important Hellenistic, Roman and Byzantine city in Asia Minor. The Italian Archaeological Mission in more than 50 years of activity has brought to light and restored many monuments of the ancient city, helping to understand the urban layout in the various periods of its history. In 2011 ground-penetrating radar (GPR) prospection, with the aim of supporting the archaeological excavations and surveys, was performed in some important sample areas by a team of the Institute for Archaeological and Monumental Heritage of the National Research Council of Italy. The analysis of the GPR measurements revealed many anomalies that could be ascribed to archaeological structures, as well as other anomalies of presumable natural origin. The data collected were georeferenced in the digital archaeological map of Hierapolis using a RTK-GPS system. Copyright © 2013 John Wiley & Sons, Ltd.

Key words: Archaeology; GPR; GPS; Hierapolis; integrated analysis.

Introduction

Hierapolis of Phrygia is in southwestern Turkey, about 200 km east of Izmir and 15 km north of Denizli, near the modern village of Pamukkale (Figure 1). It was an important Hellenistic, Roman and Byzantine city and nowadays it is a UNESCO World Heritage Site thanks to its magnificent archaeological remains and the white travertine formations created by its peculiar geothermal setting. The ancient urban area stretches over a travertine shelf looking onto the valley of the Çürüksu River (ancient Lykos River), a tributary of the Meander River; along the western side of the shelf there is a sharp drop towards the plain below. The steep slope is covered by the travertine formations, which are produced by the calcareous waters from the springs located in the central area of the city, where the shelf is crossed by a seismic fault running along a NW–SE axis; along this structure there is surface evidence of a large geothermal field, giving rise to thermal water springs and poisonous gases. These thermal waters are rich in carbonates and have produced thick calcareous deposits. These deposits are particularly impressive along the escarpment towards the Lykos plain below, where the water flow has formed a step-like progression of white travertine pools. On the shelf, starting from the Middle Byzantine period, calcareous deposits have also covered archaeological remains of the central and western sectors of the ancient city.

Hierapolis was founded in the third century BC and was characterized by an orthogonal road network (D'Andria, 2003; D'Andria and Caggia, 2007; D'Andria *et al.*, 2008, 2012); the main sacred areas were the oracular Sanctuary of Apollo and the nearby *Ploutonion*, a monumentalized fracture in the ground along the seismic fault dedicated to Ade-Pluto and Kore (D'Andria, in press). In Roman times Hierapolis was an important Asian city characterized by many buildings in travertine and marble; during the Early Byzantine period the city became the *metropolis* of the *Phrygia Pacatiana secunda* and it was a very important

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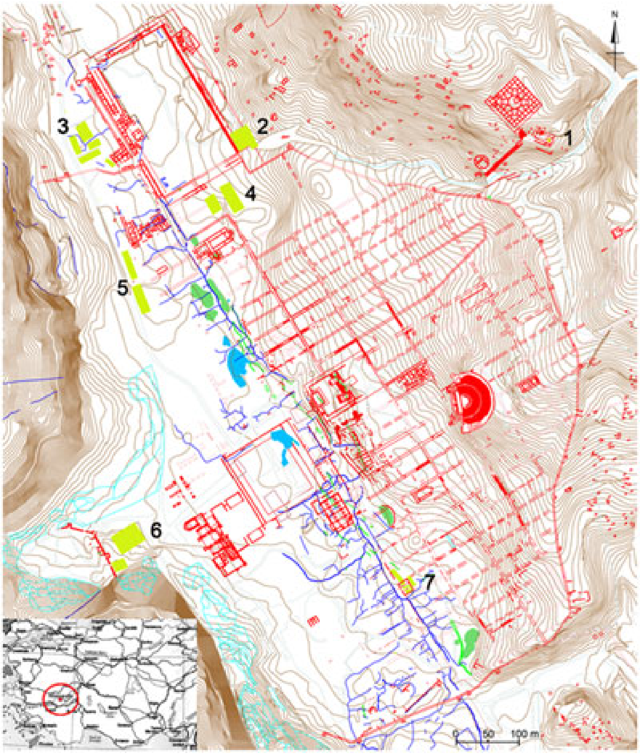

Figure 1. 2011 GPR surveyed areas (in yellow) in the archaeological site of Hierapolis in Phrygia (southwestern Turkey). This figure is available in colour online at wileyonlinelibrary.com/journal/arp

pilgrimage site due to the presence of the tomb of the Apostle St Philip. Hierapolis went into decline after a destructive earthquake in the middle of the seventh century AD; the regular urban layout was abandoned, and houses and small chapels were built on the ruins of the previous buildings and inside the ancient churches and roads. In the second half of the twelfth century AD or in the first half of the thirteenth century AD a small castle (the so-called Seljuk Fortress) was built on a promontory immediately on the west of the ancient urban area.

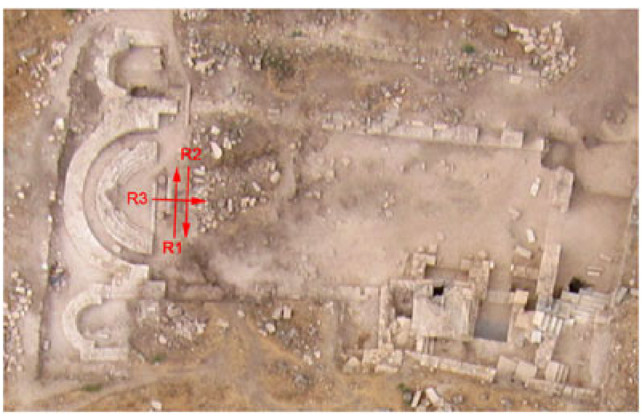

Figure 2. Area 1: location of GPR profiles in the area of the altar. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

Hierapolis survived until the thirteenth–fourteenth centuries, the period of the wars between the Byzantines and the Seljuk Turks for the control of the Anatolian peninsula. During subsequent centuries, some Ottoman houses and small farms were built in the ruins of the urban area and of the necropolises around the city, which were occupied only by shepherds.

The *Istituto per i Beni Archeologici e Monumentali* of the *Consiglio Nazionale delle Ricerche (IBAM-CNR)* (Institute for Archaeological and Monumental Heritage of the National Research Council of Italy) has from 2003 until 2012 performed archaeological research in Hierapolis, in cooperation with the University of Salento and the Italian Archaeological Mission, which from 1957 carried out excavation and restoration works in the urban area and surrounding necropolises. The final goal of the research of the *IBAM-CNR* (still in progress) is the reconstruction of the urban layout of Hierapolis and its transformation over the centuries, and will be based on the integration of different study methodologies and technologies: systematic archaeological and topographical surveys, geophysical prospecting, and processing, analysis and interpretation of aerial photographs and high-resolution satellite images (D'Andria *et al.*, 2008). In particular, geophysical surveys were performed in Hierapolis during the campaigns of 2001–2003, 2007–2008 and 2010–2011 in order to recover data concerning the sectors of the urban area covered by calcareous or alluvial and colluvial deposits (Leucci *et al.*, 2002, 2012; Negri and Leucci, 2006; Nuzzo *et al.*, 2009; Scardozzi, 2010; Scardozzi *et al.*, 2013).

In this paper some results of the 2011 archaeological and geophysical campaign in Hierapolis are presented; the research allowed the acquisition of many new data regarding the plan of buried buildings and large sectors of the urban area covered by thick calcareous and soil deposits. In particular, seven areas (Figure 1) were investigated using ground-penetrating radar (GPR): 1, the Church of St Philip; 2, the *Stoà-Basilica*; 3, the area north of the so-called Tomba Bella; 4, the area north of the Cathedral; 5, the area south of the so-called Great Building; 6, the area east of the so-called Seljuk Fortress; 7, the so-called *Bouleuterion*. The surveyed areas were chosen for variety reasons that are linked to the necessity of acquiring data about the urban layout in non-excavated sectors of the city and about the plan of non-excavated buildings (Scardozzi, 2010, 2012a); at the same time as the geophysical prospection, these areas were also studied by means of archaeological and topographical surveys, performed using a differential GPS in RTK mode. All the data collected were georeferenced in the digital map of Hierapolis, where they enriched the archaeological record.

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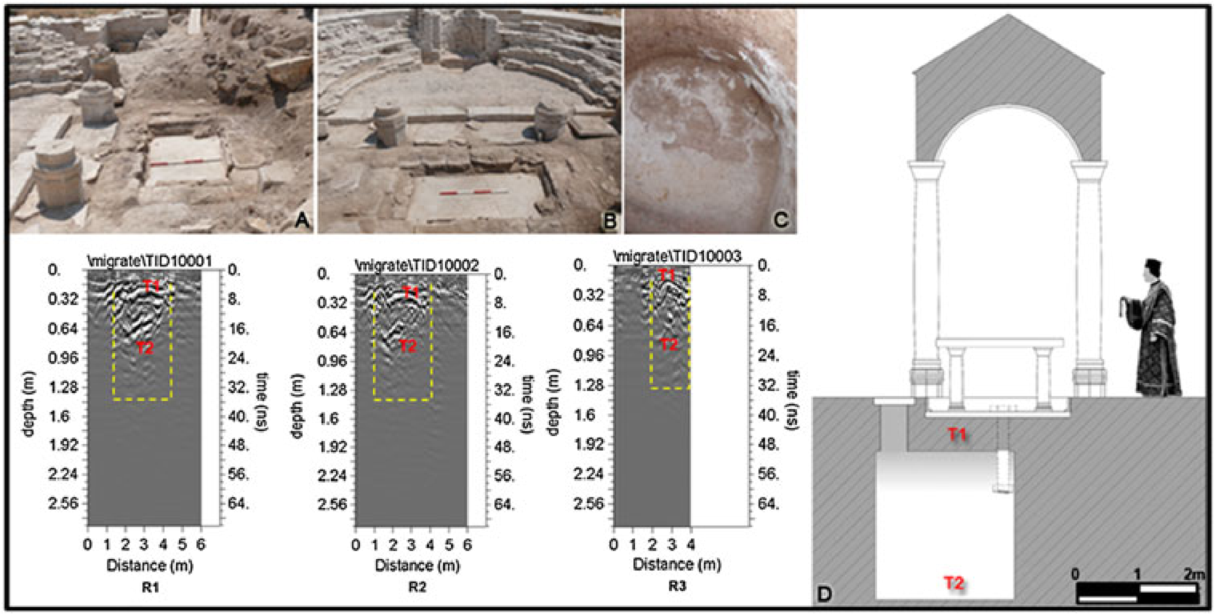

Figure 3. Area 1: the processed radar sections and the photographs taken after the excavation: (A and B) the base of the altar; (C) the chamber built under the altar; (D) reconstruction of the altar on the hypogeic chamber (from D'Andria, 2011–2012, figure 23). This figure is available in colour online at wileyonlinelibrary.com/journal/arp

GPR data acquisition and analysis

A wide range of geophysical methods are applied in archaeology for obtaining high-resolution images of the subsurface. The geophysical method used in this study is based on the detection of variations in the electromagnetic properties of the subsoil and the use of these data to identify artefacts and distinguish between these and natural variations in the soil.

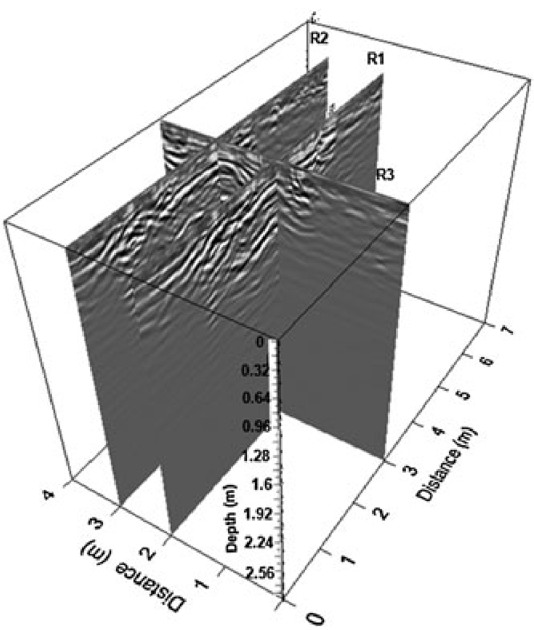

Figure 4. Area 1: the pseudo three-dimensional visualization of the two-dimensional processed radar sections.

The GPR prospecting was carried out with an IDS Hi Mod system with 200 and 600 MHz antennae, although only the results from the high-resolution 600 MHz survey are presented here. Data were acquired in continuous mode along 0.5-m-spaced survey lines, using 512 samples per trace, 80 ns time range and a manual time-varying gain function. The exception was in area 2 where GPR prospecting was carried out using the GSSI Sir 3000 system with a 400 MHz antenna. In this area data were acquired along 0.5-m-spaced survey lines, using 512 samples per trace, 120 ns time range and a manual time-varying gain function.

The data were subsequently processed using standard two-dimensional processing techniques by means of the GPR-Slice Version 7.0 software (Goodman, 2013). The processing flow-chart consists of the following steps: (i) header editing for inserting the geometrical information; (ii) frequency filtering; (iii) manual gain, to adjust the acquisition gain function and enhance the visibility of deeper anomalies; (iv) customized background removal to attenuate the horizontal banding in the deeper part of the sections (ringing), performed by subtracting in different time ranges a 'local' average noise trace estimated from suitably selected time–distance windows with low signal content (this local subtraction procedure was necessary to avoid artefacts created by the classic subtraction of a 'global' average trace estimated from the entire section, due to the presence of zones with a very strong signal);

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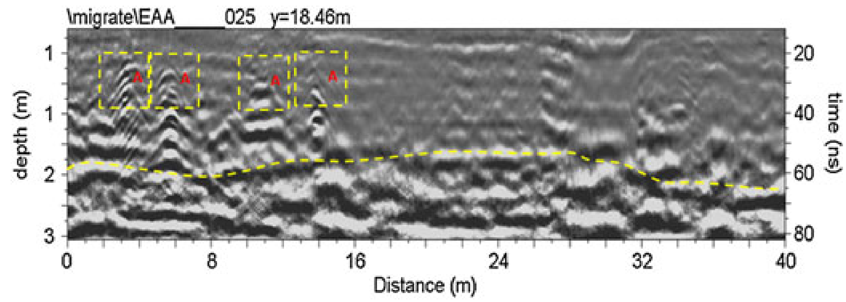

Figure 5. Area 2: the processed radar section related to profile R25. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

(v) estimation of the average electromagnetic wave velocity by hyperbola fitting; (vi) Kirchhoff migration, using a constant average velocity value of 0.07 m ns^{-1}. The migrated data were subsequently merged together into three-dimensional volumes and visualized in various ways in order to enhance the spatial correlations of anomalies of interest.

A way of obtaining visually useful maps for understanding the plan distribution of reflection amplitudes within specific time intervals is the creation of horizontal time slices. These are maps on which the reflection amplitudes have been projected at a specified time (or depth), with a selected time interval (Conyers, 2006). In a graphic method developed by Goodman *et al*. (2006), termed 'overlay analysis', the strongest and weakest reflectors at the depth of each slice are assigned specific colours. This technique allows the linkage of structures buried at different depths. This represents an improvement in imaging because subtle features that are indistinguishable on radargrams can be seen and interpreted in a more easyily. In the present work the time-slice technique has been used to display the amplitude variations within consecutive time windows of width $\Delta t = 5$ ns.

Moreover the highest amplitudes were rendered into an isosurface (Conyers and Goodman, 1997; Conyers, 2004, 2012; Conyers *et al*., 2013). Three-dimensional amplitude isosurface rendering displays amplitudes of equal value in the GPR study volume. Shading is usually used to illuminate these surfaces, giving the appearance of real archaeological structures. In this case the threshold calibration is a very delicate task in order to obtain useful results.

In order to define the depth of archaeological remains the electromagnetic (EM) wave velocity, using the characteristic hyperbolic shape of a reflection from a point source (diffraction hyperbola), was used.

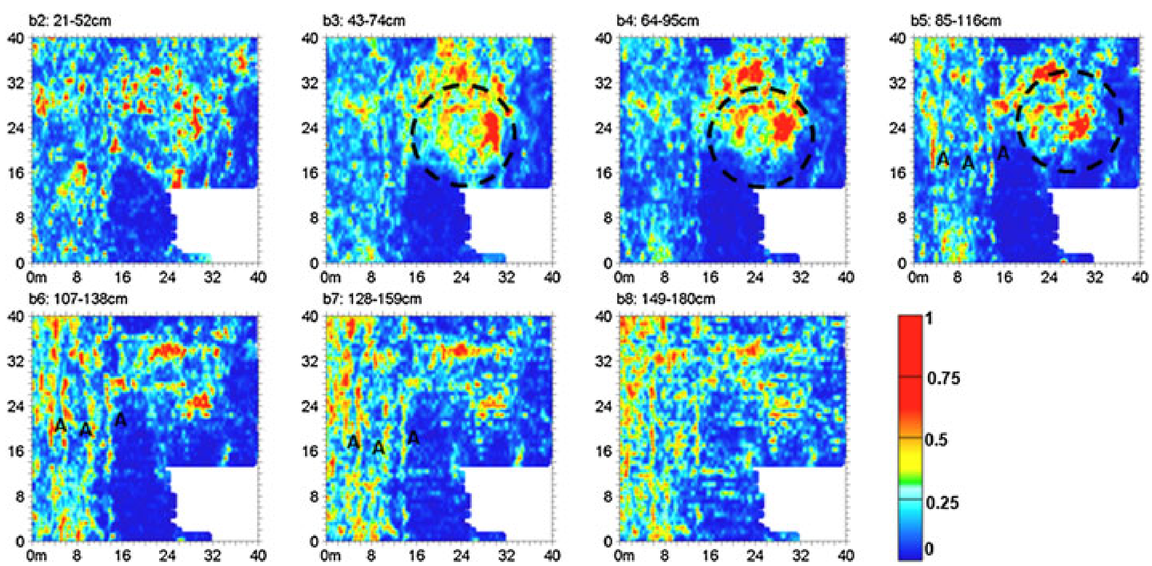

Figure 6. Area 2: time slices. In the slices ranging from 85 cm to 159 cm depth, relatively high-amplitude alignments (labelled A) are clearly visible. In the time slices ranging from 43 cm to 116 cm depth the dashed dark circle highlights a high-amplitude anomaly (labelled B); in the same area, the time slices ranging from 107 cm to 180 cm depth show other high-amplitude alignments (labelled C). Moreover, to the south of this area, the time slice ranging from 149 cm to 180 cm depth highlights relatively high-amplitude alignments with the same direction (labelled D). This figure is available in colour online at wileyonlinelibrary.com/journal/arp

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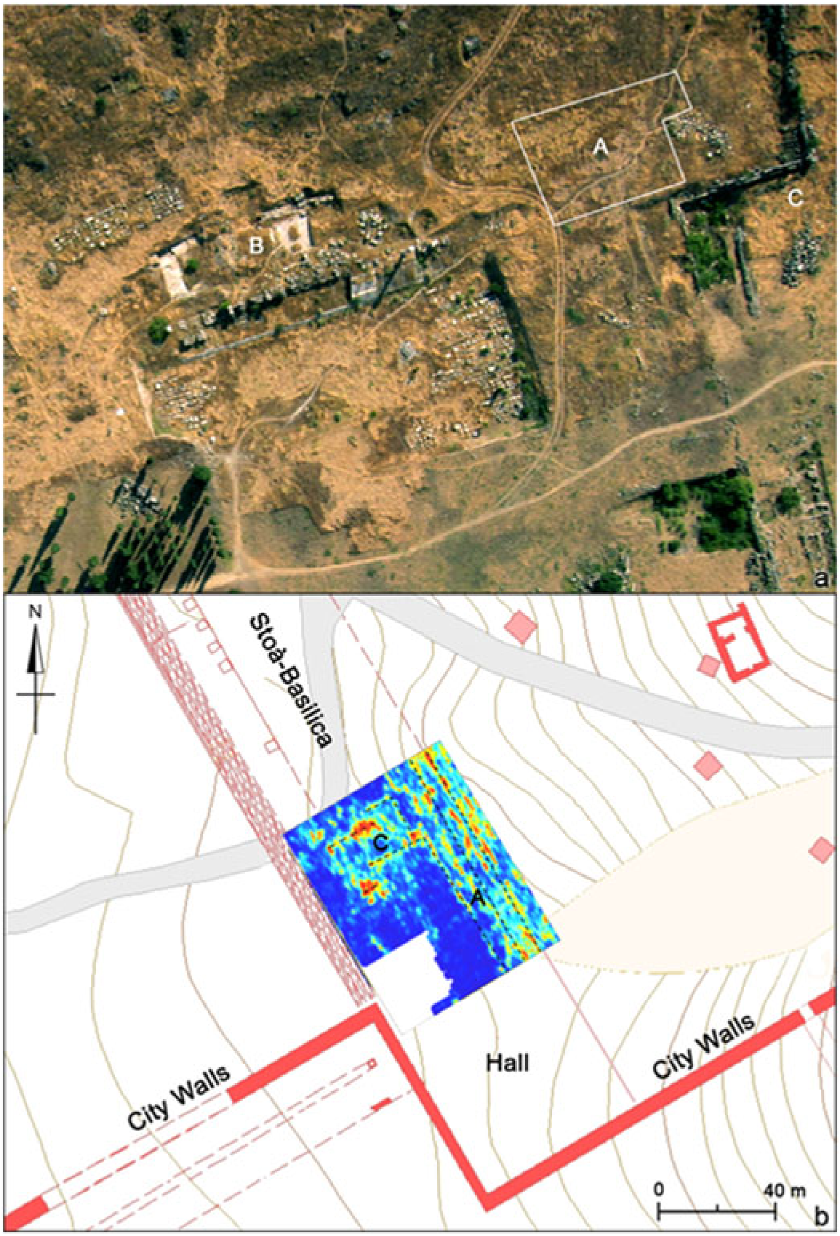

Figure 7. Area 2: (a) the surveyed area (A) between the excavated remains of the *Stoà-Basilica* (B) and the Early Byzantine city walls (C) in an aerial photograph taken from an hexacopter; (b) time slice at 1.07–1.38 m depth georeferenced in the archaeological map. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

Surveyed areas

Area 1: Basilica of St Philip

GPR data analysis

Due to the limited dimensions of the area (about 2 × 6 m) only three profiles were acquired (Figure 2). In this area an electromagnetic energy penetration depth of 30 ns was found. The GPR profiles that were measured in the area (Figure 3) show different reflectors with clear continuity along the three acquired profiles. A hyperbolic shaped reflection labelled T1 at the two-way travel time window between 4 and 8 ns is visible in radar sections. Its size is about 2.5 m and the depth of the top is between 0.16 and 0.32 m (with an average electromagnetic wave velocity of 0.08 m/ns). The hyperbolic-shaped reflection labelled T2 at two-way travel time window between 12 and 20 ns is visible in the radar section (with a size of 1.5 m and a depth between 0.48 and 0.8 m).

Unfortunately the acquisition of just three GPR profiles allows creation of only a pseudo-three-dimensional

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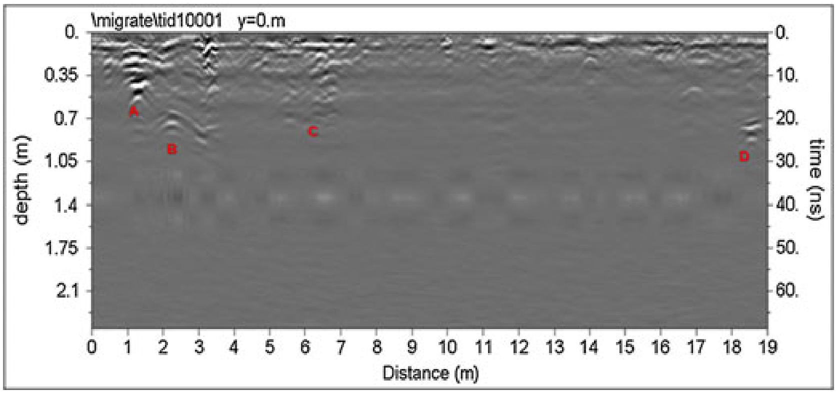

Figure 8. Area 3: subarea 1: the processed radar section related to profile R1.

visualization of the acquired data. In fact the data are displayed in a cube in which they appear in the position where they were acquired (Figure 4). This allows an understanding of the development in a three-dimensional way of the anomaly highlighted in the two-dimensional profiles.

Archaeological survey and interpretation of GPR data

The Church of St Philip (Area 1) is an Early Byzantine basilica with three naves that includes the Roman chamber tomb attributed to the Saint; it is located on a hill to the northeast of the city, where a pilgrimage Early Byzantine Sanctuary was identified and reconstructed thanks to the integration of systematic topographical surveys, satellite remote sensing and archaeological excavations. In particular, the chapel tomb attributed to St Philip was identified in 2009 during archaeological surveys (Scardozzi, 2012b, pp. 77–78), while in 2010–2012 the church that includes the tomb in the eastern nave was brought to light (D'Andria 2011–2012; D'Andria, 2012, pp. 483–484).

Archaeological excavations carried out in the surveyed area (Figure 3) confirmed the interpretation of GPR measurements. They revealed the presence of a vaulted chamber (about 1.80 × 1.25 m; height about 1.80 m) built under the altar; it probably contained the relics of the Apostle Philip that were transferred inside the chamber from the tomb. The GPR anomalies labelled T1 and T2 are respectively related to the top and bottom of this chamber; in fact the distance between T1 and T2 is about 2.4 m if the electromagnetic wave velocity is 0.3 m ns^{-1} (i.e. the electromagnetic wave velocity in empty space).

Area 2: Stoà-Basilica

GPR data analysis

Area 2 was a square of about 40×40 m^2. In this area an electromagnetic energy penetration depth of 70–80 ns was found. Figure 5 shows the processed radargram related to the 25th profile. It shows several hyperbolic shaped reflections labelled A at two-way travel time window between 25 and 35 ns. Its size is about 1.5 m

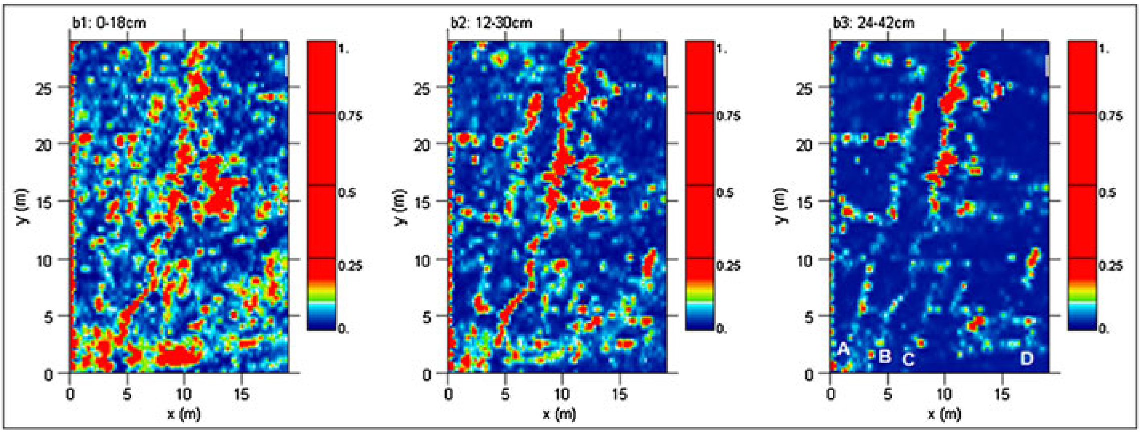

Figure 9. Area 3: subarea 1: time slices. In the slices ranging from 0 to 42 cm depth, relatively high-amplitude alignments (labelled A, B, C and D) are clearly visible. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

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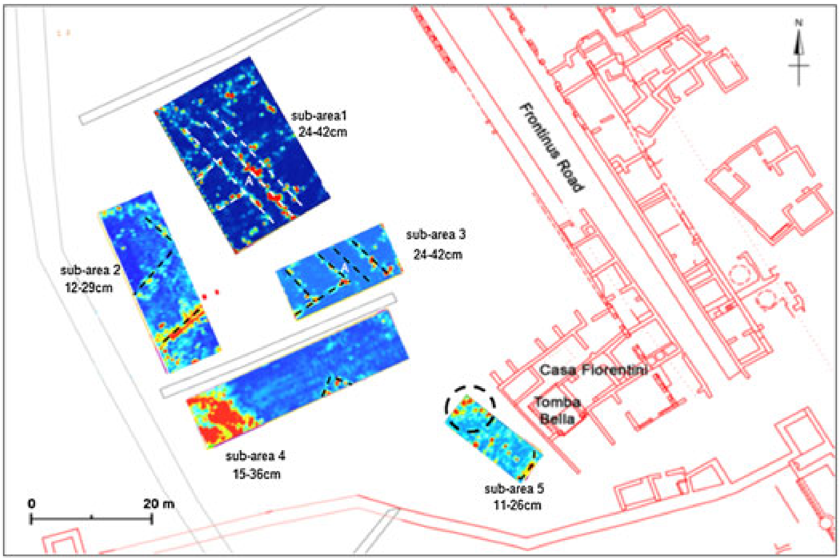

Figure 10. Area 3: time slices (11–42 cm of depth) georeferenced in the archaeological map: many anomalies are visible and they can be related to ancient structures and to a possible road (A). This figure is available in colour online at wileyonlinelibrary.com/journal/arp

and the depth is between 1.25 and 1.75 m (with an average electromagnetic wave velocity of 0.1 m ns^{-1}). On each of the GPR records the lowest (dashed yellow) continuous and slightly undulating reflector appears strong and irregular and reaches a maximum depth below the ground surface ranging from 1.75 to 2.11 m.

In order to identify the depth evolution of buried structures, including their size, shape and location, time slices using the overlay analysis (Goodman *et al*., 2006; Goodman and Piro, 2013) were built (Figure 6). The time slices show the normalized amplitude using a range defined by blue as zero and red as 1. In the slices ranging from 85 cm to 159 cm depth, relatively high-amplitude alignments (labelled A) are clearly visible. These correspond to the anomalies labelled A in the radargram (Figure 5). In the time slices (Figure 6) ranging from 43 cm to 116 cm depth the dashed dark circle highlights a high-amplitude anomaly (labelled B); in the same area, the time slices ranging from 107 cm to 180 cm depth show other high amplitude alignments (labelled C). Moreover, to the south of this area, the time slice ranging from 149 cm to 180 cm depth highlights relatively high-amplitude alignments with the same direction (labelled D).

Archaeological survey and interpretation of GPR data

Area 2 includes the southern sector of the *Stoà-Basilica*, the large portico that lies along the eastern side of the north *Agorà* (Figure 7); it was built in the second century AD and collapsed due to an earthquake (D'Andria *et al*.,

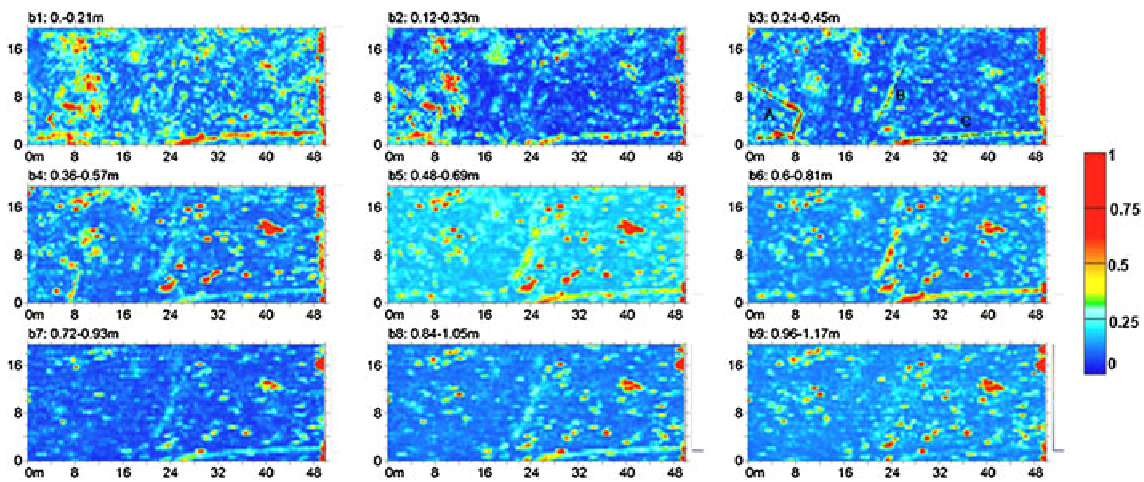

Figure 11. Area 4: subarea 1: time slices in which some alignments (A–C) are highlighted. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

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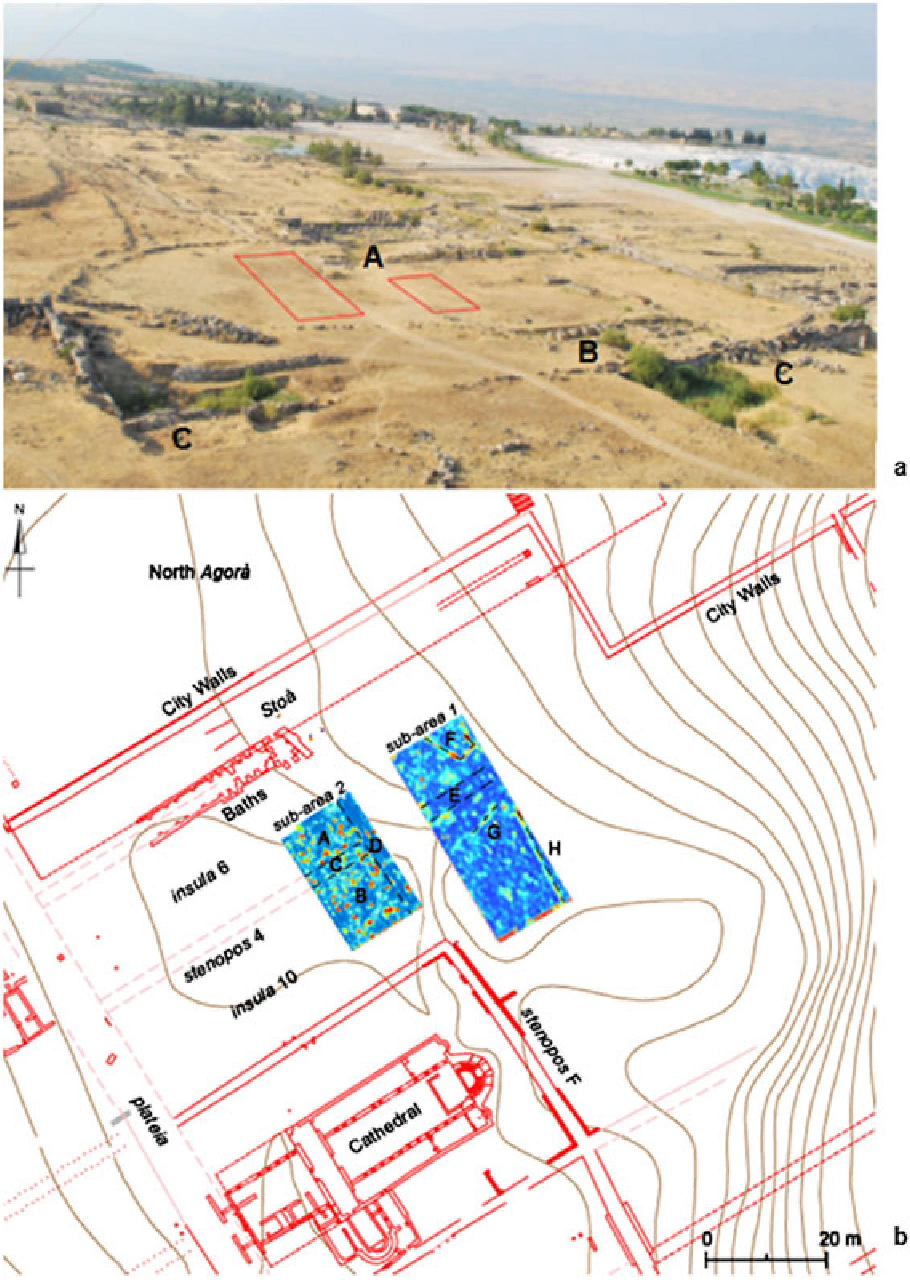

Figure 12. Area 4: (a) the surveyed subareas between some monuments of the Early Byzantine period: the cathedral (A), the baths (B) and the city walls (C); (b) time slices at 0.36–0.57 m depth georeferenced in the archaeological map. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

2008, p. 89). This sector of the monument was partially demolished in the second half of the fourth century AD and materials were reused in the nearby Early Byzantine city walls; colluvial and alluvial deposits covered the remains. In this case, the aim of the research was to understand the internal plain of the building, in particular, the presence of one or two naves and the link to the large hall at the southern end of the *Stoà-Basilica*.

The anomalies highlighted by GPR measurements (Figure 6) are probably related to structures inside the building. In particular, the anomalies labelled A (Figure 7b), with a NW–SE axis, can be related to the eastern end wall of the *Stoà-Basilica*, while the anomalies labelled C, with an orthogonal axis in comparison with the previous ones, are probably related to internal structures. Moreover, the anomalies labelled B, at a short

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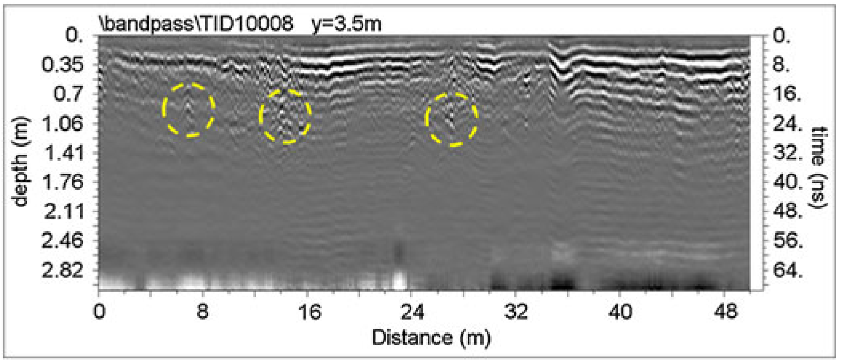

Figure 13. Area 5: subarea 1. The processed radar section related to profile R7. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

depth, can be linked to collapsed architectural materials in marble and travertine, while the few anomalies labelled D, with the same alignment of the C, could be related to the wall that divided the *Stoà-Basilica* from the hall immediately to the south. No clear evidence of the division between the two naves of the building is visible.

Area 3: Tomba Bella

GPR data analysis

Area 3 was divided in five subareas and a total area of about 1170 m^2 was surveyed. In particular, the results of subarea 1 are very interesting; it is a rectangular area of 20×28 m^2. In this area an electromagnetic energy penetration depth of 30 ns was found. The observed anomalies are confined within about 2 ns to about 30 ns (Figure 8); this is also the case in all the other profiles acquired in Area 3.

Figure 8 shows the processed radargram related to the first profile acquired in the subarea 1. It shows several hyperbolic shaped reflections (labelled A, B, C and D) at two-way travel time window between 10 and 25 ns. Its size is about 0.5 m and the depth is between 0.35 and 0.87 m (with an average electromagnetic wave velocity of 0.07 m ns^{-1}). Also in this case the time-slice maps were built (Figure 9). In the slices ranging from 0 to 66 cm depth, relatively high-amplitude alignments (labelled A, B, C and D) are clearly visible. These correspond to the anomalies labelled A, B, C and D in the radargram (Figure 8).

Archaeological survey and interpretation of GPR data

Area 3 is immediately to the north of the so-called Tomba Bella, a funerary monument of Julio-Claudian age, and to the west of the Frontinus Road, the main street of Hierapolis, that crosses the city along a NW–SE axis (Figure 10). This area was occupied by a necropolis from the Hellenistic age to the 60 AD, when an earthquake affected and damaged the city (D'Andria *et al.*, 2008, pp. 83–85). In the Flavian age the urban area was extended over this sector of the North Necropolis, with only the Tomba Bella (the main funerary monument) being preserved, and at the same time Frontinus Road was flanked by shops. During the Roman Imperial age a large *domus* ('Casa Fiorentini') was built to the east of the Tomba Bella, while in the Byzantine age some structures (houses and deposits) were built over this *domus*, the shops of the Frontinus Road and the street itself.

The target of the GPR surveys was to understand the topographic organization of the area, where scarce remains are visible on the surface; it is covered by soil deposits mixed with the calcareous formations. The GPR measurements highlighted anomalies, in particular at a shallow depth, and in subareas 1–3 these can be related to ancient structures linked to the scarce remains of walls preserved on the surface. According to their characteristics, they can be interpreted as houses and deposits flanking a road, which is along the alignment of the *stenopos* F (Figure 10), excavated a few metres to the south of the surveyed area; these structures are probably datable to the Byzantine period because of their short depth and irregular orientation, different from that of the previous periods. It is not evidence of the presence of the regular plan of the *insulae*, and of tombs of the Hellenistic and Early Roman Imperial times.

Area 4: cathedral

GPR data analysis

Area 4 has a total area of about 2000 m^2 and is divided into two subareas labelled 1 and 2. In this area an electromagnetic energy penetration depth of 30 ns was found. In the slice maps the observed anomalies

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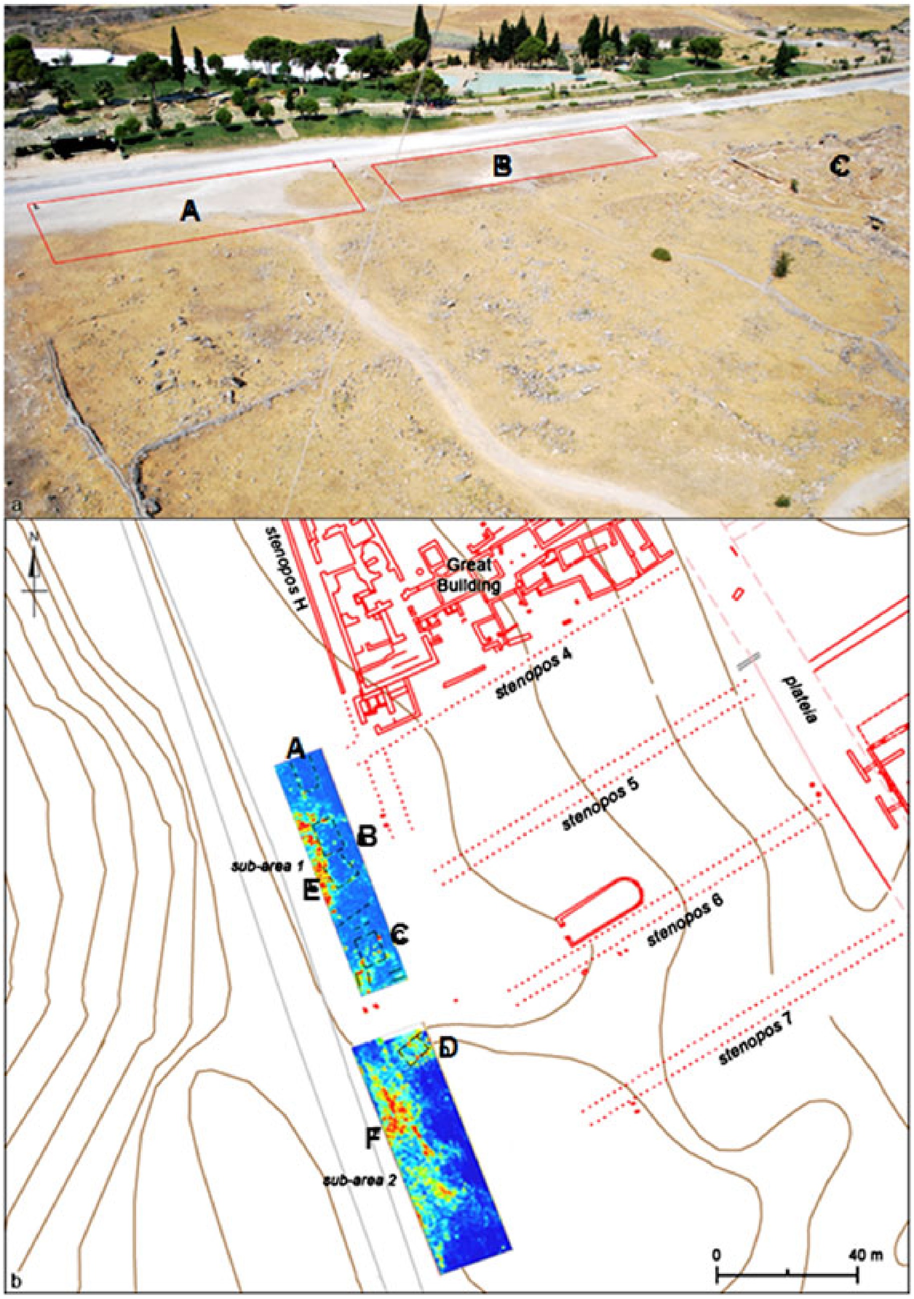

Figure 14. Area 5: (a) the surveyed subareas (A and B) to the south of the so-called Great Building (C) in an aerial photograph taken from a tethered balloon; (b) time slice at 0.92–1.14 m (subarea 1) and 0.61–0.83 m (subarea 2) depths, georeferenced in the archaeological map. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

are confined within about 0 m to about 1.05 m (Figure 11). Figure 12b show several alignments visible down to 1.05 m depth.

Archaeological survey and interpretation of GPR data

Area 4 concerns an unknown sector of the urban area sited to the east of the *plateia* and between the Early Byzantine cathedral and the baths of the same period (Figure 12); the latter was built near the remains of the *Stoà*, which in the Roman Imperial period delimited the southern side of the north *Agorà* (D'Andria *et al.*, 2008, pp. 90 and 101). In the EarlyByzantine period, the city walls were built on these remains. The investigated western subarea 2 involves the *insulae* 6 and 10 of the urban orthogonal plan of Hierapolis, planned in the Hellenistic period

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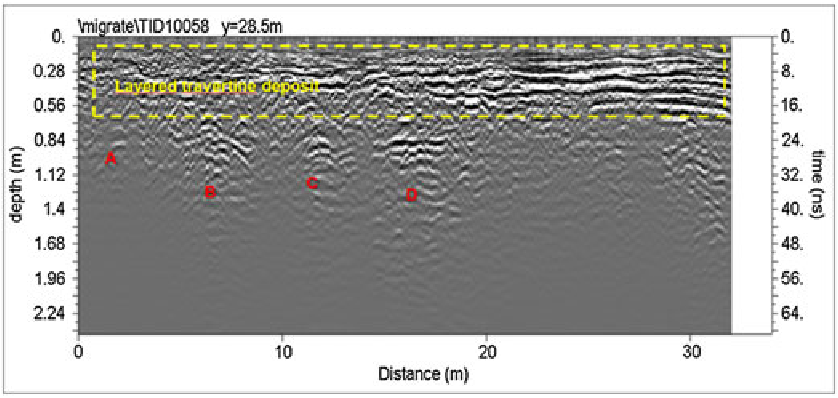

Figure 15. Area 6: subarea 1. The processed radar section related to profile R58. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

and used until Early Byzantine times; the *insulae* must be separated by a road, the *stenopos* 4, but remains of ancient structures are not visible on the surface. The investigated eastern subarea 1 is immediately to the east of the possible extension in the northwest direction of *stenopos* F, which was revealed immediately to the east of the cathedral; also in this second area no remains are visible on the surface and the geological investigations have highlighted the possible presence of a sinkhole due to the seismic fault. In both subareas colluvial deposits cover possible buried ancient structures.

The task of the GPR surveys in these two subareas was to examine the extension of the urbanization or the absence of ancient structures at the periphery of Hierapolis. The GPR measurements show anomalies, in particular to 1.05 m depth, which according to their characteristics could be related to ancient buried structures. In particular, in subarea 2 they seem to be related to structures (Figure 12b, A and B) with the same orientation of the city plan and located near the possible routes of *stenopoi* 4 and F (Figure 12b, C and D). In subarea 1 some anomalies that are probably linked to

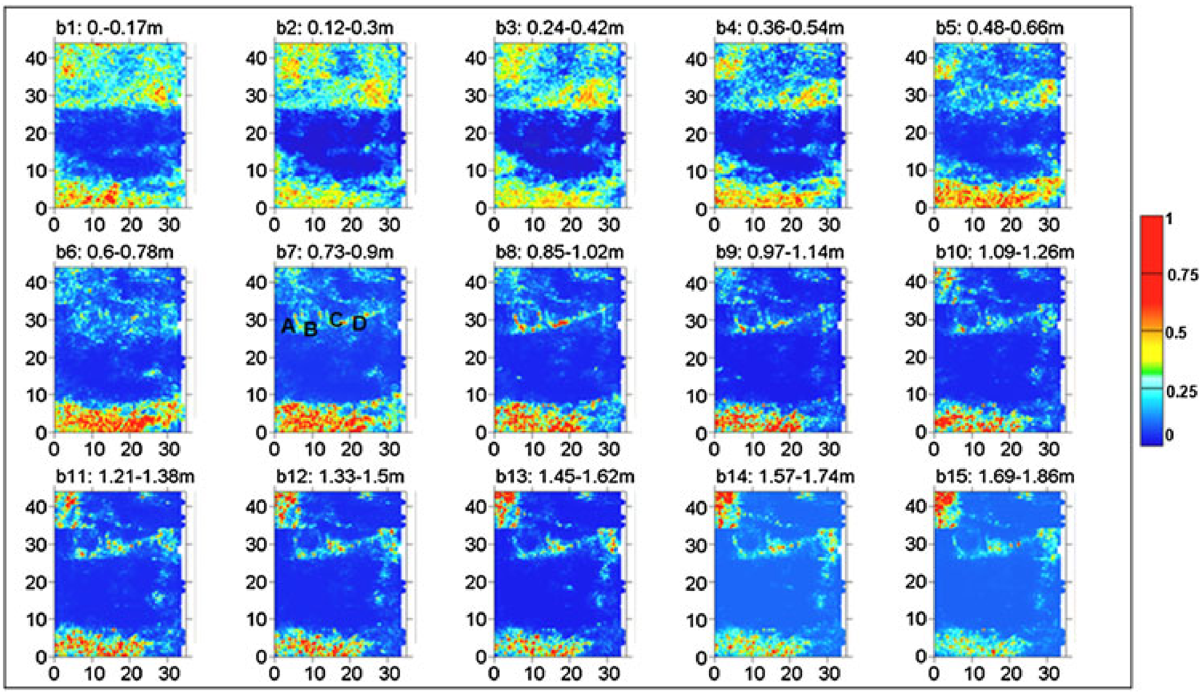

Figure 16. Area 6: subarea 1 time slices. Here there is evidence for several alignments. In particularl the alignments (slightly inclined) visible at a depth ranging from 0.73 to 1.99 m explain the different sizes of the anomalies labelled A, B, C and D. In fact, the single radar profile crosses this alignment in an oblique way. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

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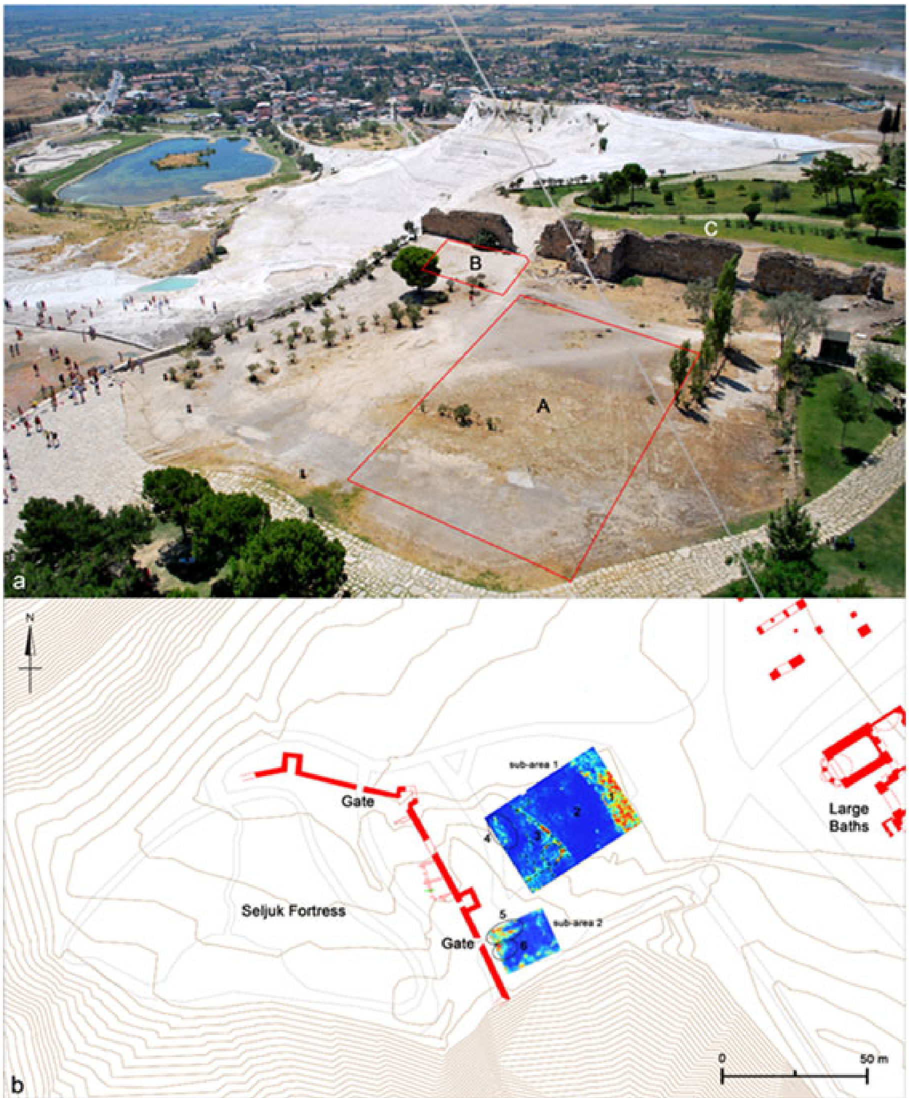

Figure 17. Area 6: (a) the surveyed subareas (A and B) to the east of the eastern wall of the so-called Seljuk Fortress (C) in an aerial photograph taken from a tethered balloon; (b) time slices at 0.85–1.02 m depth georeferenced in the archaeological map. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

ancient buildings (Figure 12b, F and G) are visible near the possible extension in the northeast direction of *stenopos* 4 (Figure 12b, E); they have a different orientation in comparison to the urban layout of Hierapolis. Moreover, in the southeastern sector of the investigated area a long anomaly that can be related to a wall is clearly visible (Figure 12b, H).

Area 5: Great Building

GPR data analysis

Area 5 has a total area of about 500 m^2. In this area an electromagnetic energy penetration depth of 30 ns was found. The observed anomalies are confined to the first 30 ns (Figure 13); this is also the case in all the other profiles acquired in area 5.

Figure 13 shows a processed radar section related to the seventh profile in subarea 1. It is possible to note in the first 15 ns (0.5 m in depth) some high horizontal electromagnetic energy reflections. They are probably related to the stratified travertine layer. The hyperbolic shaped reflections (dashed yellow circlesthe) are also visible at two-way travel time window between 14 and 24 ns. Its size is about 0.5 m and the depth is between 0.61 and 1.04 m (with an average electromagnetic wave velocity of 0.087 m ns^{-1}). Also in this case time-slice maps were built and they highlight several alignments.

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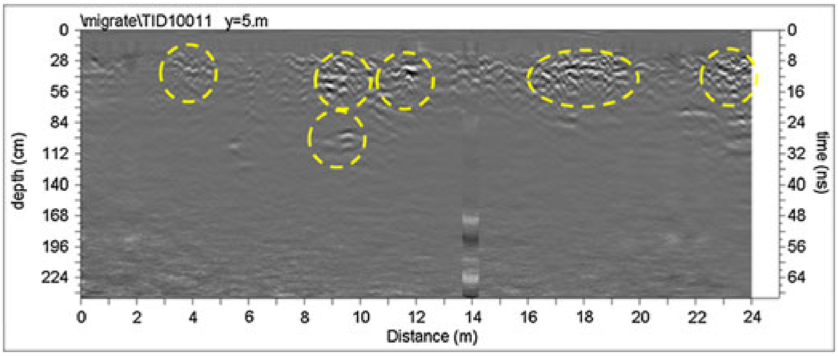

Figure 18. Area 7: subarea 1. The processed radar section related to profile R1. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

Archaeological survey and interpretation of GPR data

Area 5 is located south of the so-called Great Building, a thermal edifice of the Roman Imperial period on which houses and productive installations of the Byzantine times were built (D'Andria *et al*., 2008, p. 99). Only scarce ancient remains are visible on the surface of the two subareas (Figure 14a). The task of the GPR measurements was to examine the possible presence of buried structures and the existence of the extension in the west direction of *stenopoi* 4, 5, 6 and 7; in fact traces and remains of these roads are visible to the east of the two subareas investigated.

The GPR surveys have documented some anomalies at a depth of 0.61–1.29 m and linked to buried ancient structures of the Roman or Byzantine period in both the subareas; they have rectangular and square plans and were built particularly near the possible routes of *stenopos* 4, 5 and 6 (Figure 14b, A and D). In particular, a rectangular structure, characterized by a probable apse (Figure 14b, A), is on the path of the *stenopos* 4

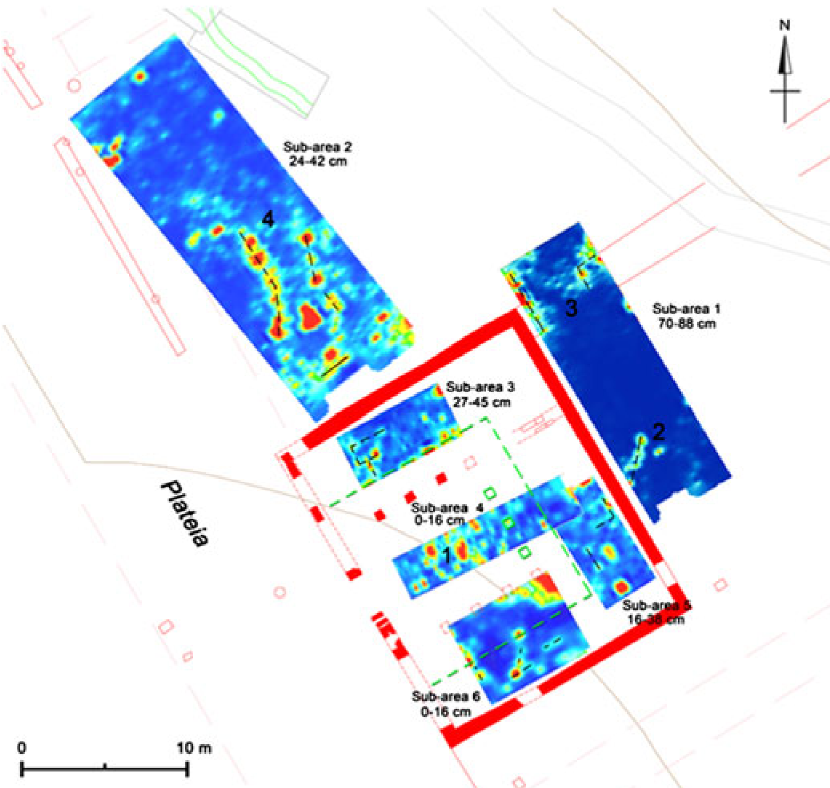

Figure 19. Area 7: time slices at different depths (between 0 and 88 cm) georeferenced in the archaeological map: dashed green line represents the hypothetical reconstruction of the central courtyard of the so-called *Bouleuterion*. This figure is available in colour online at wileyonlinelibrary.com/journal/arp

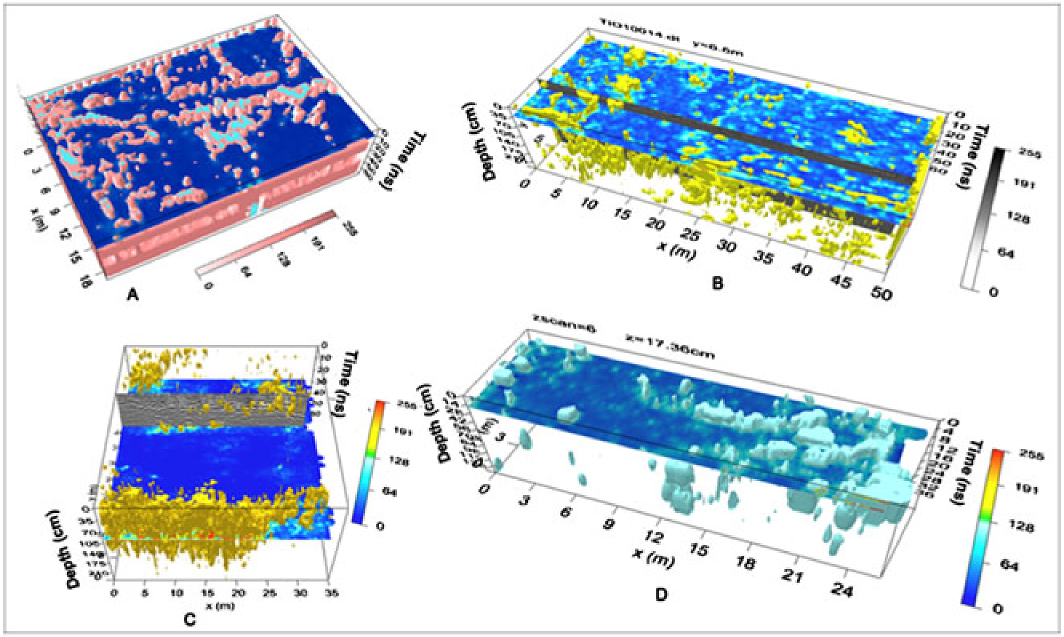

Figure 20. Examples of three-dimensional visualizations by means of iso-amplitude surfaces of the complex trace amplitude: (A) Area 3 (subarea 1); (B) Area 4 (subarea 1); (C) Area 6 (subarea 1); (D) Area 7 (subarea 2). This figure is available in colour online at wileyonlinelibrary.com/journal/arp

and therefore is datable to the Mid-Byzantine period, when the building along the roads was frequent. Another rectangular structure built on the path of a road is visible along the possible extension of *stenopos* 6 (Figure 14b, D). Again in this case, and also due to its shallow depth and its different orientation in comparison to the urban layout of the Hellenistic and Roman time, it is possibly a Mid-Byzantine structure. No paving traces of the ancient road are visible, but in general, according the orientation of some structures (e.g. Figure 14b, A–C), it seems that the urban orthogonal layout of Hierapolis extended to this area located near the western limit of the shelf, where probably the blocks could have a dimension of half *insula*. Moreover, the anomalies on the western side of the two subareas (Figure 14b, E and F) are probably due to the structures (compacted layers of earth and small stones, and underground services) of the nearby modern road.

Area 6: Seljuk Fortress

GPR survey data analysis

Area 6 has a total area of 1840 m^2 and was divided into two subareas. In all radar sections acquired in area 6 there are visible strong subhorizontal reflections confined to the first 20 ns. These reflections are related to the layered travertine deposit of modern origin (Figure 15). Other observed anomalies (labelled A, B, C and D) are confined within about 20 ns to about 35 ns (0.7–1.22 m in depth, with an average electromagnetic wave velocity of 0.07 m ns^{-1}). The size of the anomalies ranges from about 0.5 m to about 0.8 m.

In the slices shown in Figure 16 several alignments are evident. Particularly the alignments (slightly inclined) visible at a depth ranging from 0.73 to 1.99 m explain the different sizes of the anomalies labelled A, B, C and D. In fact, the single radar profile crosses this alignment in an oblique way.

Archaeological survey and interpretation of GPR data

Area 6 is to the east of the so-called Seljuk Fortress, a small castle that in the twelfth century AD was built on the promontory over the Lykos valley from the central western part of the terrace of Hierapolis (D'Andria *et al.*, 2008, p. 111). The fortress was built with reused architectural elements of Roman times and was abandoned in the late fourteenth century AD. Only the eastern and northeast walls of the fortress are preserved (up to about 4.50 m height): the first stretch is about 78 m long and the second about 52 m. In the corner linking the two stretches a pentagonal tower was built; moreover each stretch has a square tower and a gate. The fortress was probably defended to the east by a ditch, now filled; steep escarpments protected the other sides.

The investigated areas are located outside of the fortress, in the large area located east of the walls (Figure 17); this area, covered by soil and calcareous

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deposits, was chosen for investigation in order to understand its ancient topography in relation both to Seljuk Fortress and to the Roman urban layout. The internal area of the fortress, now used as a garden, was not surveyed because it was occupied from the 1960s to the 1990s by a hotel, the building of which destroyed the archaeological remains. Moreover, thick calcareous deposits cover the area.

The GPR measurements in the area to the east of the fortress showed the presence of some ancient structures; according their shallow depth (between 0.85–1.02 ns) and orientation (different in comparison to the urban layout of the Roman period) they could be dated to Byzantine times (probably Mid-Byzantine). In the eastern sector of subarea 1 the travertine basement is visible (Figure 17b, 1); to the west of this evidence, a large depression is documented (Figure 17b, 2). Further west are some anomalies linked to different structures (Figure 17b, 3) that are difficult to understand: some of them could be fortifications of uncertain chronology. Other structures (Figure 17b, 4), connected to two jambs of a door visible on the surface, could be a house, maybe on the extension of a road from the east. Moreover, in subarea 2 anomalies possibly linked to a path (Figure 17b, 5) that went out the western gate of the fortress (maybe defended by a structure immediately to the south; Figure 17b, 6) are also visible.

Area 7: Bouleuterion

GPR data analysis

Area 7 has a total area of 450 m^2 and was divided into six subareas (four inside the so-called *Bouleuterion* and two outside, in areas free from collapsed materials). The observed anomalies are confined in the first 30 ns (Figure 18). The size of the anomalies are about 0.5 m and their depths range from about 8 ns to about 24 ns (0.28–0.84 m in depth with an average electromagnetic wave velocity of 0.07 m ns^{-1}). The time-slice maps show alignments visible in particular from 0 to 0.66 m.

Archaeological survey and interpretation of GPR data

Area 7 concerns the so-called *Bouleuterion*, a quadrangular building (18 × 22 m) with a perimeter wall in squared travertine blocks (Figure 19). Its function and chronology are still uncertain, because it was never excavated (D'Andria *et al*., 2008, p. 135); it was not a *bouleuterion* and the visible remains (maybe of the Late Roman or Early Byzantine period) are characterized by reused marble elements, including an inscribed base for a statue dedicated to an *archigallos* in the third century AD (Ritti, 2006, pp. 130–133).

The aim of the investigations was to reconstruct the internal plan of the building and the ancient topography of the surrounding area. The GPR measurements show several anomalies that could be interpreted as features of archaeological interest (internal walls and pillars, and also nearby structures and roads). The integration of geophysical and topographical surveys allowed a hypothetical reconstruction of the internal plan of the building, characterized by a central courtyard (about 7.5 × 8.5 m) with pillars in a local polychrome *breccia* with a reddish matrix and white marble clasts.

In particular, in the inner surface of the building, the anomalies observed in subarea 4 (Figure 19, 1) could be related to the collapse of walls and pillars; in the surveyed subareas (3, 5 and 6) around the courtyard, some anomalies linked to partition walls of rooms are visible. Moreover, other anomalies that can be related to buried ancient structures are clearly visible in subareas 1 and 2, surrounding the building (Figure 19, 2–4).

Conclusions

The 2011 GPR surveys in Hierapolis allowed the acquisition of much new data about the internal plan of buildings and the ancient topography of large sectors of the city. These investigations allowed the identification of buried walls and roads, which were georeferenced in the digital archaeological map of Hierapolis. The research clarified many problems in the understanding of the shape of buildings and of the urban layout and its transformation over the centuries. Particularly important for the GPR data interpretation was integration with the data previously acquired, thanks to the georeferencing of the results in the digital archaeological map of the city. Very important also was the integration of geophysical prospecting with archaeological and topographical surveys, with the aim of better planning measurements and correct interpretations of results. In one case (Area 1: Church of St Philip), archaeological excavations were conducted according to the results of the GPR survey and have confirmed the interpretation of the measurements. In two cases (Area 2: *Stoà-Basilica*; Area 7: *Bouleuterion*) the GPR survey allowed the reconstruction of the internal plan of buildings. In the four other cases (Areas 3, 4, 5 and 6) the GPR measurements reveal many buried structures in sectors of the urban area where there are no remains on the ground; in the latter case (Area 6: Seljuk Fortress), geophysical surveys also allowed acquiring data about the shape of the saddle that linked the promontory of the castle to the terrace of Hierapolis.

In some cases the archaeological interpretation of GPR measurements was favoured by displaying the acquired data set acquired with iso-amplitude surfaces, using 60% of the maximum complex trace amplitude threshold value (Figure 20). Obviously, lowering the threshold value increases the visibility of the main anomaly and smaller objects, but also the heterogeneity noise. Relatively strong continuous reflections are visible on the threshold volumes. This visualization technique portrayed better the evidence of the anomalies found in the surveyed areas. In this work an integration of archaeological information with the GPR data results was necessary first of all to understand the context and continuity of the structures found. It demonstrates that geophysical analysis can be very useful in order to place archaeological structures into a three-dimensional framework. Archaeological and topographical information merged with GPR mapping of the buried units leads directly to an ancient landscape reconstruction.

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