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Insights into the Buried Archaeological Remains at the Duomo of Lecce (Italy) Using Ground-penetrating Radar Surveys†

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ABSTRACT The town of Lecce located in the southern part of the Apulia region of Italy, contains the remains of an ancient settlement in the city centre. One of the most important buildings in the town is the Duomo and its crypt. The crypt is found beneath the Duomo and was used as a burial place from the first century AD until the nineteenth century. The area around the crypt is highly urbanized today, but was the locus of social and political life over the centuries for people of different cultures who inhabited the area, starting from the eighth century BC. Therefore this area contains stratigraphically complex layers of buildings and other remains, which can help us understand the usage of this area of the town over many centuries. A ground-penetrating radar survey was performed at the crypt, the data of which were visualized in three-dimensions using a standard amplitude slice technique as well the construction of isosurface images of amplitudes. These images reveal the position of architectural features whose shape, size and burial depth suggest they are Roman and earlier in age. The features mapped are superimposed tombs, which indicates that this area was used for the same purpose over many centuries and demonstrates a long continuity of similar burial practices at this sacred place. Copyright © 2012 John Wiley & Sons, Ltd.

Key words: GPR survey; archaeological stratigraphy; crypt of Duomo of Lecce

Introduction

In autumn 2008 a multidisciplinary research team began a ground-penetrating radar (GPR) survey at the Duomo of Lecce (southern Italy) and its crypt, which is beneath the Duomo. Part of the survey was aimed at outlining the presence, distribution, burial depth and age of possible archaeological remains buried under the surface crypt. The presently exposed crypt or *Soccorpo* of the Duomo of Lecce was built in AD 1114 on a pre-existing structure containing tombs of Christian martyrs or other witnesses of the faith (De Giorgi, 1907; D'Andria *et al.*, 1980). Also, according to ancient legend the body of the Saint Oronzo, protector of the town, was buried under the crypt after his martyrdom, probably in the first half of the first century AD. More recently, and until the nineteenth century, members of noble lineages were also buried under the floor and in the walls of the crypt, as shown by the inscriptions on tombstones (Figure 1).

The use of this site over the centuries makes it challenging to understand the distribution of various features in space and time because the remains of different ages are located at different levels and superimposed on each other. Also, the study area, as well as the largest part of the ancient town of Lecce, is highly urbanized today with many nearby buildings from the nineteenth century making the area fairly 'noisy' for the purposes of most geophysical data acquisition methods.

Numerous studies have described efficient geophysical methods for archaeological application. Carrozzo *et al.* (2003) studied the archaeological site of Pisa with the main purpose to test the value of radar in respect of penetration depth and, therefore, to reconstruct the archaeological stratigraphy given the general not too favourable site conditions.

Microgravimetric techniques have been useful in archaeological contexts (Butler, 1984; Cuss and Styles, 1999; Pasteka *et al.*, 2007; Panisova and Pasteka, 2009).

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†GPR data were acquired, processed and interpreted by Dr Giovanni Leucci; historical data were collected by Dr Rosella Cataldo and Delia D'agostino.

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Tomb	Name	Year
1	Unknown	Unknown
2	Michael Mincuzzi	1988
3	Marasco-Specchia	1838
4	Fam. Bernardini	unknown
5	Martirano	1858
6	Raffaele Perulli	1858

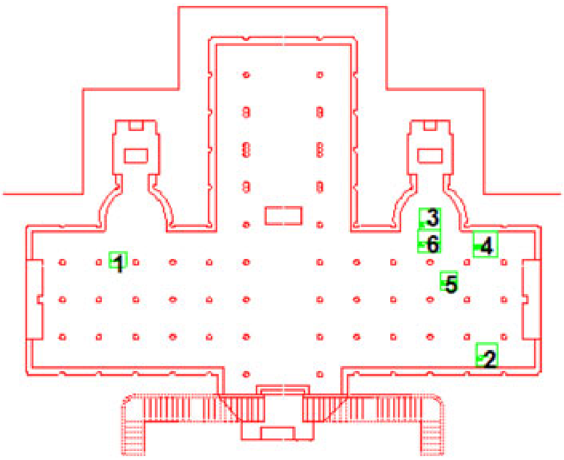

Figure 1. The surveyed area with the location known tombs (1–6).

The applicability of seismic methods for detecting archaeological features has been evaluated by several authors (Woelz and Rabbel, 2005; Leucci *et al*., 2007, Forte and Pipan, 2008).

Magnetic prospection can be successful used on archaeological sites (Ciminale and Loddo, 2001; Crew, 2002; Linford, 2004). Electrical resistivity tomography (ERT) imaging can be used to delineate archaeological features and to locate shallow cavities directly, particularly when cavities are filled with high resistivity contrast material such as voids and more conductive materials (Senos Matias, 2003; Leucci, 2006; Leucci *et al*., 2007). In the case studied microgravimetry was very difficult to use because of the many buildings and severe ground vibration due to the heavy traffic. The severe man-made noise made it impossible to use the seismic method. The underground telephone, electricity and water supply networks made it impossible to use magnetic methods. The high resistivity contact values make it very difficult to use the ERT method. Therefore GPR was used, which can produce images in three-dimensions without being affected by surface obstructions or other features.

The GPR results show that the surveyed area was used as a burial area over a long period of time, at least since the second part of the fourth century BC, in the Messapic age, with other burial features dating from the Roman age (since third century BC) into the twentieth century. Three specific burial periods were discovered at this site using the three-dimensional imaging capabilities of GPR.

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Historical framework

Lecce (Figure 2a) is an urban Mediterranean centre in the Apulia region (southern Italy). Its history is as old as 24 centuries and it is characterized by various urban and social changes by people with different cultures who inhabited the town (Giardino, 2002). While the first settlements date to the eigthth century BC, it is only in the second part of the fourth century BC, in the Messapic age, that Lecce assumed the form of an urban centre. At this time the nearby towns of Cavallino, Rudiae and Lecce were included into the territory of Lecce (D'Andria *et al.*, 1980; Giardino, 2002). Historic documents indicate that many tombs have been discovered since 1860 at various depths between 1.50 and 2.50 m, with a few at only 0.40 m depth below the present surface (D'Andria *et al.*, 1980; Giardino, 2002). The typology and sizes of the tombs recovered in Lecce are quite variable (Giardino, 1994). The burials can be classified in three main types:

(i) « *Ipogei* » (*hypogeum* type: dimensions of the order of 3 m × 1.5 m × 1.5 m).
(ii) « *Tombe a fossa* » (*grave pit* type: average dimensions of 1.8 m × 0.5 m × 0.5 m; some of which covered by stone slabs).
(iii) « *Urne cinerarie* » and « *urne a cassetta in pietra* » or « *ciste litiche* » (*cinerary urn* and *stone chest* types: dimensions of the order of or smaller than 0.5 m × 0.5 m × 0.5 m).

In the second century BBC, during the Roman age, a crucial change occurred in this area with the construction of buildings that usually characterize a Roman town such as a theatre, amphitheatre and perhaps an area with a 'forum'. All were probably built near the surveyed area (Giardino, 2002). Only the theatre and the amphitheatre (T and A in Figure 3) are clearly visible on the surface today. Historians and archaeologists suspect the possible location in the same area of other buildings, such as the 'forum', the 'Capitolium' and the thermal baths (Giardino, 2002). The amphitheatre was discovered in 1906 by De Giorgi, and the ruins of the theatre were identified in May 1929, at a depth of about 5 m. Other ruins that are all of Roman age were found at different depths. An example of the archaeological section of the area near the amphitheatre is shown in Figure 4 showing the complexity of architecture in this general area.

Acquisition of GPR data and processing methods

The GPR survey was carried out inside the crypt of the Duomo with a GSSI SIR-3000 using the 270 MHz (centre frequency) antennae. The frequency was chosen to optimize both the penetration depth and resolution, considering that the targets of the survey were supposedly located between 0.5 and 6–7 m below floor level. Survey profiles were spaced at 1 m in both parallel and perpendicular transects (Figure 5).

Each reflection profile was processed by standard two-dimensional processing techniques and transformed into pseudo-three-dimensional amplitude maps using using ReflexW software (Sandmeier, 2008). The following data processing was performed: (i) amplitude normalization, consisting of the declipping of saturated (and thus clipped) traces by means of a polynomial interpolation procedure (Sandmeier, 2008); (ii) background removal, whereby the filter is a simple arithmetic process that sums

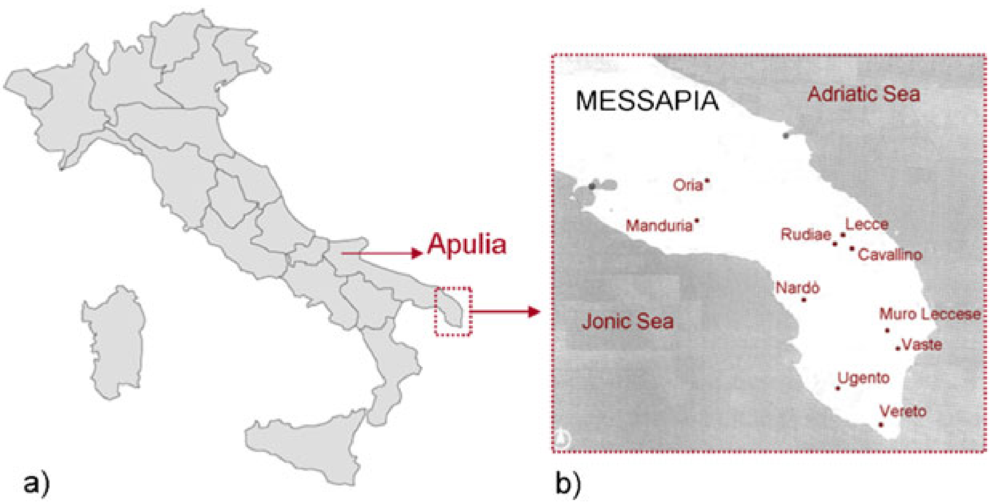

Figure 2. a) Map of Italy with localization of Apulia region. (b) Map of Messapia.

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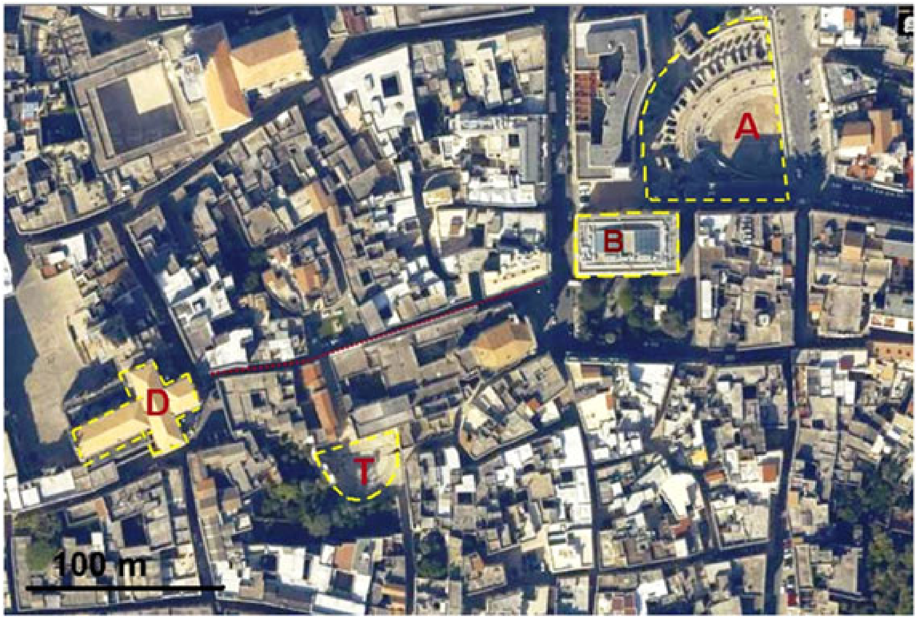

Figure 3. Aerial photograph of Lecce (modified from www.visual.paginegialle.it): D, the Duomo; A, the Amphitheatre; T, the Theatre; B, the Bank of Italy; the red dotted line indicates via degli Ammmirati. This figure is available in colour online at wileyonlinelibrary.com/journal/arp.

all the amplitudes of reflections that were recorded at the same time along a profile and divides by the number of traces summed – the resulting composite digital wave, which is an average of all background noise, is then subtracted from the data set; (iii) Kirchhoff two-dimensional velocity migration (Yilmaz, 1987),which is a time migration of a two-dimensional profile on the basis of a two-dimensional velocity distribution, is performed. The goal of the migration is to trace back the reflection and diffraction energy to their 'source'. The Kirchhoff two-dimensional velocity migration is done in the x–t range, this means that a weighted summation for each point of the profile over a calculated hyperbola of pre-set bandwidth is performed. The bandwidth means the number of traces (parameter summation width) over which summation takes place.

Each profile was gained manually, and background was removed. This was performed in different time

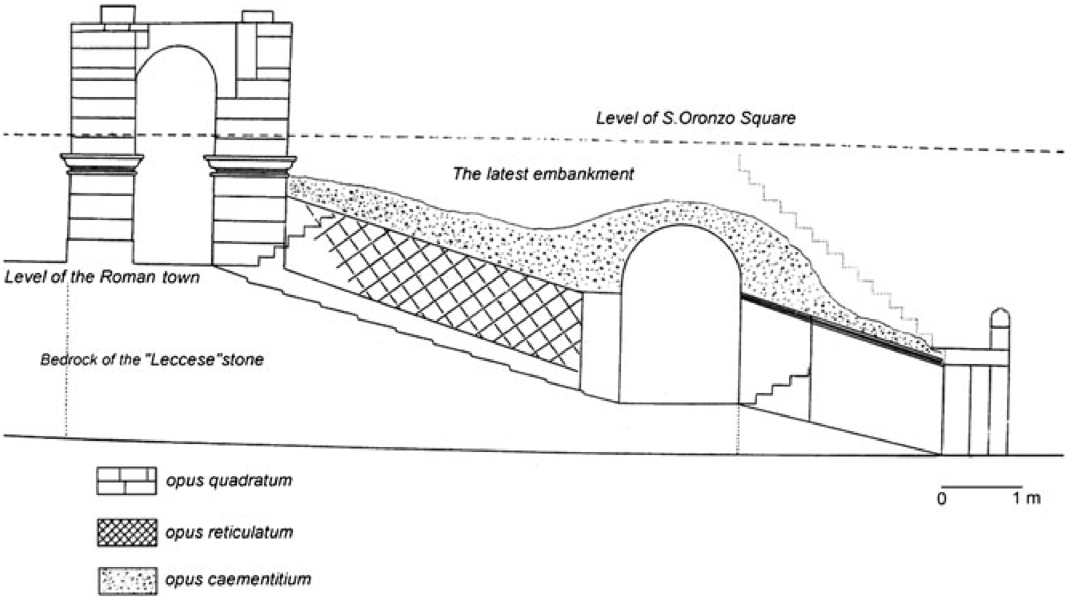

Figure 4. Cross-section of the Roman Amphitheatre. (From De Giorgi C., *Lecce sotterranea. Relazione su gli scavi archeologici eseguiti in Lecce dal MCM al MCMVI*, LECCE.)

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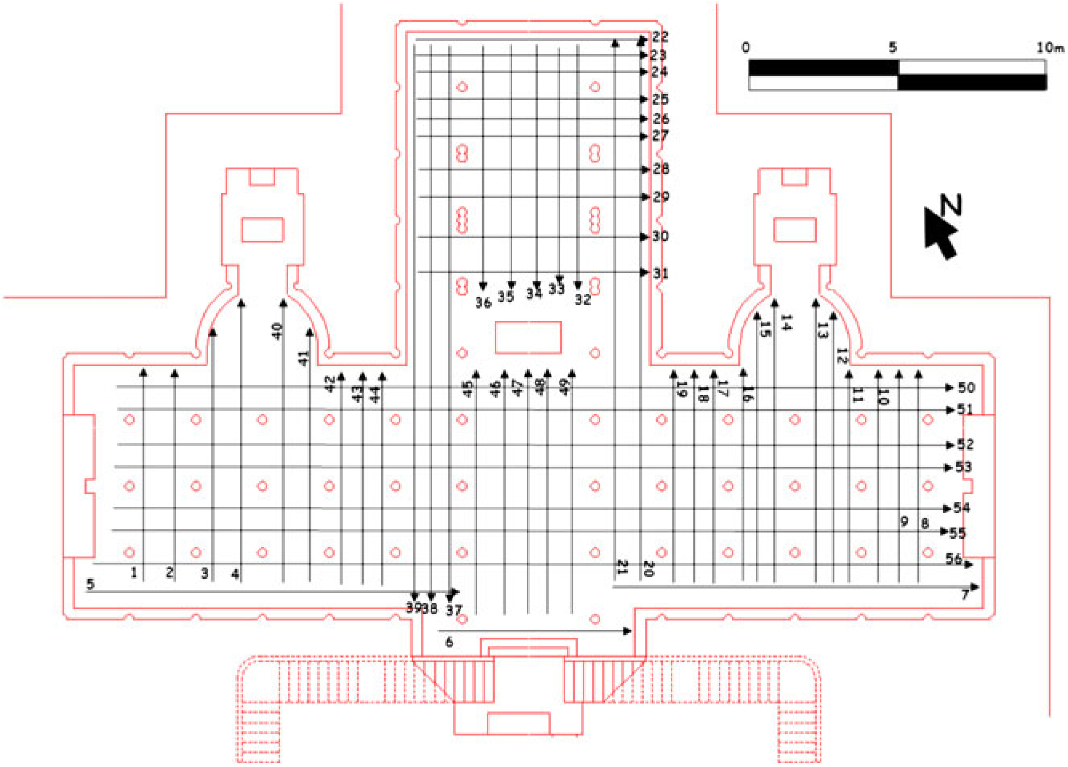

Figure 5. The surveyed area with ground-penetrating radar profile locations.

ranges by subtracting a 'local' average noise trace, which is estimated from suitably selected time–distance windows with low signal content. This local-subtraction procedure was necessary to avoid artefacts created by the usual subtraction of a 'global' average trace estimated from the entire section, which is due to the presence of zones with very high amplitude reflections. An estimation of electromagnetic wave velocity was undertaken by hyperbola fitting (resulting in an average velocity of 0.11 m ns^{-1}) and reflections were migrated utilizing the Kirchhoff method using this value. Migrated reflections were also visualized as a pseudo-three-dimensional volume in isosurfaces, also using ReflexW software.

Results and interpretation

The GPR profiles show good reflections to 130 ns, which corresponds to about 7 m in depth. The reflections show areas of vertical fill layers, which are probably units placed into tombs after burial. Also there are extensive horizontal reflections that are probably the tops of bases of crypts. Jumbled areas with many point-source reflections are probably areas where homogenized sediment was used to fill in vertical shafts and level the surface after burial. Distinct vertical truncation surfaces are visible in many profiles, such as R56 (Figure 6), where vertical shafts were incised into the surrounding material.

A distinctive pattern of very high amplitude reflection features is visible at several depths in the R1, R35 and R56 reflection profiles. At the end of profile R56 (between 26–28 m), a shallow high-amplitude reflection is clearly visible at between 8–30 ns (0.44–1.65 m in depth) (Figure 6). This is the top of a known tomb clearly visible in Figure 1 and labelled 2. Below it a high-amplitude reflection (labelled W) is also visible. Its depth, ranging from 3 m to 5 m, and dimension, ranging from 0.8 m to 1.2 m, suggests the presences of a wall. A zone labelled 'disturbed zone' in profile R56 in Figure 6 suggests the presence of homogenized sediment that was used to fill in vertical shafts and level the surface after burial. The R1 reflection profile shows a shallow high-amplitude reflection (T) related to the tomb labelled 1 in Figure 1. Below it a high-amplitude reflection (labelled T1) is also visible. Its depth, ranging from 3.5 m to 4.5 m, and dimension, same as the known tomb labelled T, suggests the presence of a tomb.

Profile R1 in Figure 6 also shows a high-amplitude horizontal reflection that is slightly undulating reflection (B). This reflection was generated from bedrock, as confirmed by archaeological excavations performed

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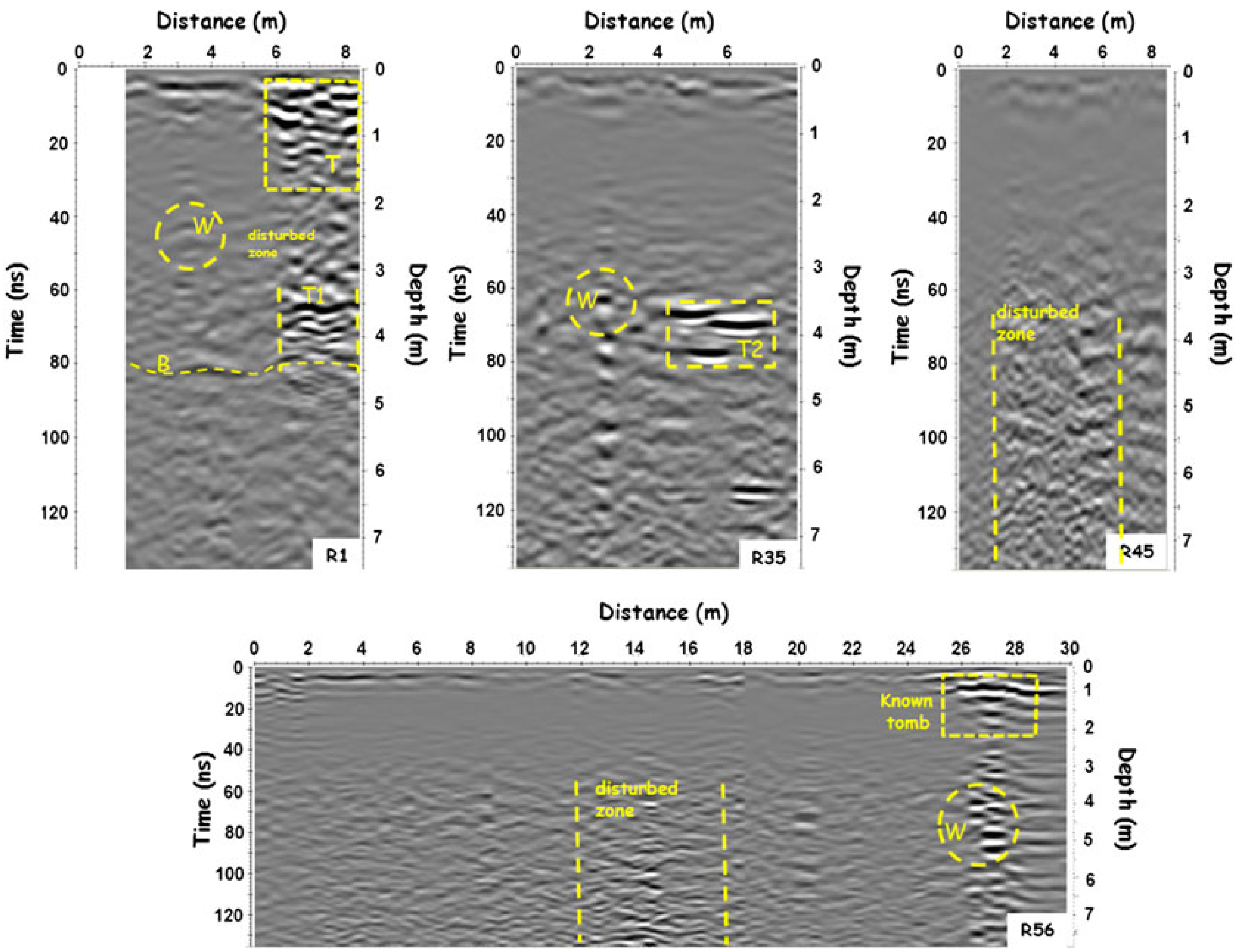

Figure 6. Processed ground-penetrating radar reflection profiles named R1, R35, R45, and R56. Profiles R1 and R45 run in the SW–NE direction, R35 runs in the NE-SW direction, and R56 runs in the NW–SE direction. T1, tomb, visible in the two-way time range 65–75 ns (3.57–4.12 m in depth); T2, tomb, visible in the two-way time range 62–80 ns (3.41–4.40 m in depth); W, feature of probable archaeological interest visible in the two-way time range 60–90 ns (3.30–4.95 m in depth); disturbed zone is visible in the two-way time range 60–130 ns (3.30–7.15 m in depth); B, bedrock , located in the two-way time range 80–85 ns (4.40–4.67 m in depth).

near the surveyed area, which encountered this horizon at about 8.5 m in depth (from the present-day surface, which corresponds to 4.5 m in depth on the R1 profile. In those excavations the bedrock is a fractured calcarenite ('pietra leccese') according to geological map of Italy. This bedrock level also corresponds to the depth of the ancient Roman living surface shown in Figure 4 about 200 m away.

Other features (labelled W) are visible in the R1 and R35 profiles (Figure 6), and their shape and dimensions (about 0.6 m) could indicate archaeological interest. A depth ranging from 2 to 4 m from the surveyed surface and an excavation performed near the surveyed area suggest that W could be related to the presence of a Roman walls. In the R35 profile a high-amplitude horizontal reflection (labelled T2) is visible. The shape of the reflection suggests that it is probably a covering stone over a tomb.

The spatial relationships between reflections can be visualized in the pseudo-three-dimensional isosurfaces produced from the two-dimensional profiles (Figure 7). These were produced after Kirchhoff migration and the application of the Hilbert transform, which created a positive-valued envelope of the amplitude of radar reflections (Figure 7). As asserted in Nuzzo *et al.* (2002), the selection of a proper amplitude threshold is crucial in the iso-surface method because lowering the threshold value increases the visibility of the main anomaly and smaller objects, but also heterogeneity noise.

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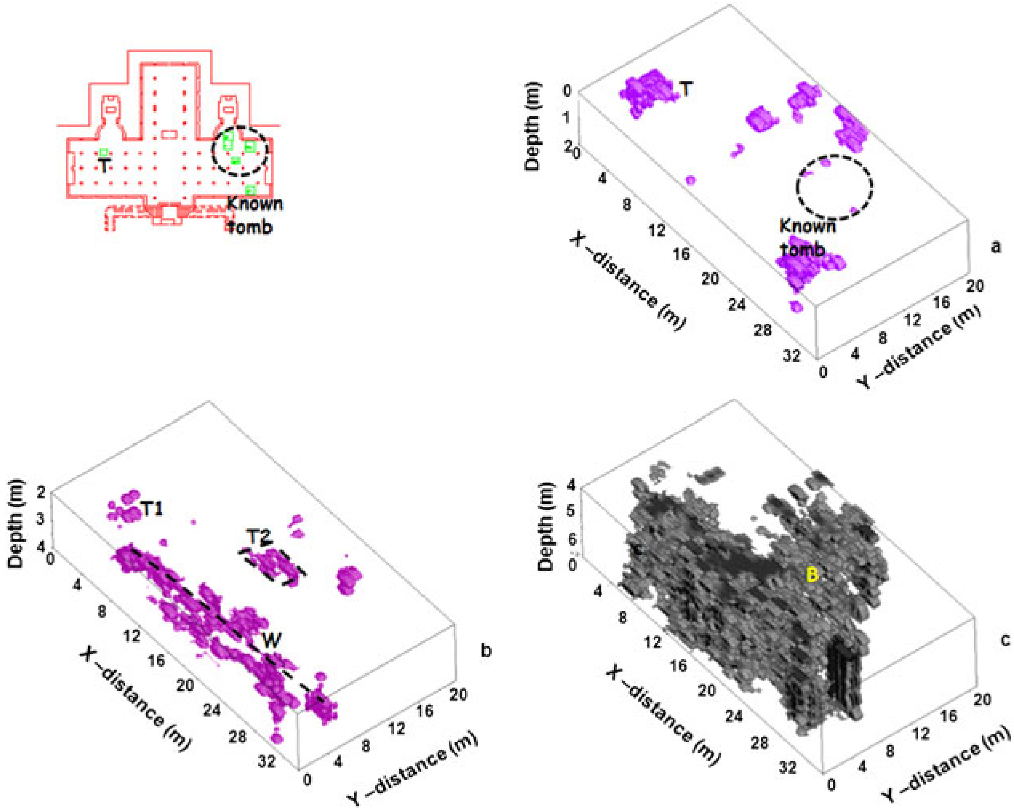

Figure 7. Isosurface visualization of the envelope of the processed data, showing (a) shallow, (b) medium and (c) deep ground-penetrating radar anomalies related to the buried remains.

Isosurface renders are displays of surfaces of equal amplitude in three-dimensional volume. It is possible to display any surface between 0 and 100% of maximum amplitudes in the volume. The 100% surface represents the strongest surface in the volume and 0% isosurface represents the weakest reflector. As the amplitude of the reflections that could be related with features of archaeological interest assumed different values, in order to visualize the maximum amplitude events, three isoamplitude volumes were created. Thus the shallow (0–2 m in depth) (Figure 7a), the medium (2–4 m in depth) (Figure 7b) and the deeper (4–7 m in depth) (Figure 7b) isosurface three-dimensional volumes were displayed. This subdivision allows visualization of the strongest amplitude reflections.

The shallow reflection features labelled T (Figure 7a) were created from the visible tomb on the survey surface within the first metre. They are found directly below visible surface inscriptions that denote tombs and are probably 0.4 m depth. In the isosurface images representation, the different width and depth of the anomaly labelled W in Figure 7b was probably created by a Roman wall as explained in the description of two-dimensional GPR reflection profiles. The anomaly labelled T2 (described in the two-dimensional GPR reflection profile interpretation) located between 2 and 3 m depth in Figure 7b, is rectangular in shape and its dimension ($2 \times 1\,m^2$) suggests that it is associated with a tomb. In the deeper isosurface from 4 to 6 m depth (Figure 7c), the semi-continuous and slightly undulating reflection (labelled B in Figure 6), is interpreted as bedrock.

The GPR reflections were also visualized in horizontal amplitude maps. These were constructed by taking an average of the amplitudes over the 10 ns two-way time window, which was squared to produce positive values. The slices shown in Figure 8 are visualizations of the more significant subsurface features between 0 and 0.55 m (Figure 8a) and 2.75–3.30 m (Figure 8b). In the uppermost slice (Figure 8a) there is a strong correspondence between the location of the tombs visible at the surface (Figure 1) and the subsurface high-amplitude reflections visible in the 2D GPR reflection profiles. Also near the surface are other high-amplitude reflections (labelled '?' in Figure 8a), which are tombs not documented from surface information. In the deeper slice (Figure 8b) the black

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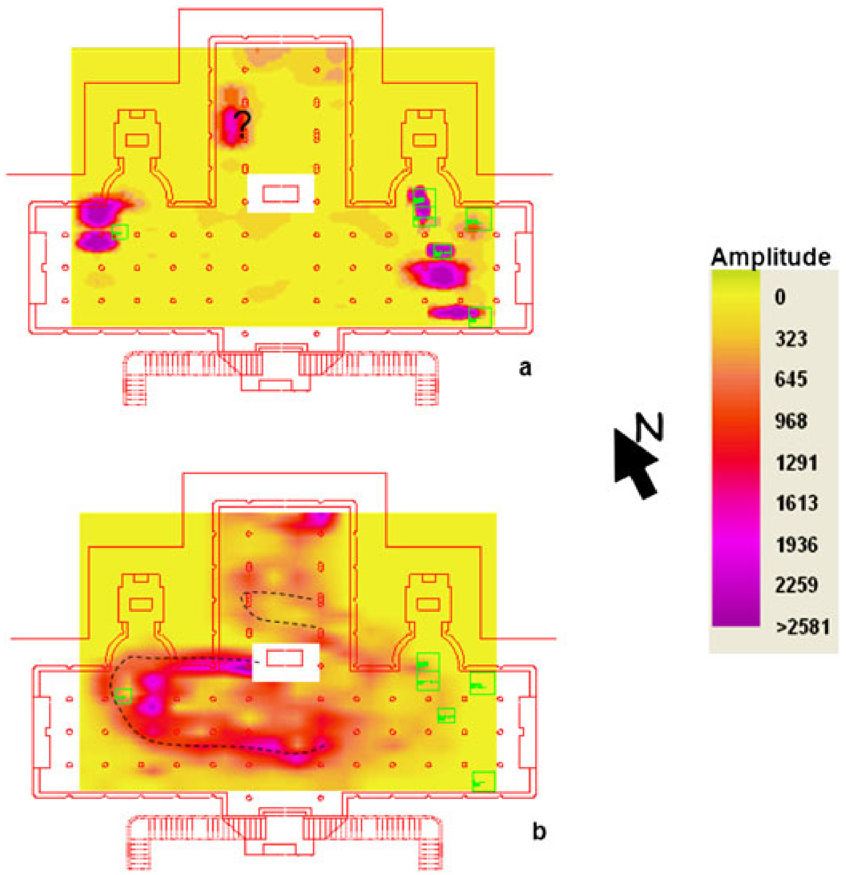

Figure 8. Depth-slice maps with visualization of the amplitude variations within consecutive time windows of width $\Delta t = 10$ ns. The selected two-way time interval corresponds to a soil layer of approximately 0.55 m thick. (a) Time-slice at the interval 0–0.55 m; (b) time-slice at the interval 2.75–3.30 m. This figure is available in colour online at wileyonlinelibrary.com/journal/arp.

dashed line denotes an alignment of high-amplitude reflections. These reflections (W) are visible in the two-dimensional profile labelled R45 in Figure 6.

Conclusions

The GPR images below the crypt of the Duomo of Lecce show the presence and distribution of features with shapes, sizes and burial depths that suggest they are of Roman and possibly earlier age. Most of them are interpreted as tombs. A variety of three-dimensional visualization tools were used to establish a connection between the information of the GPR data obtained in the Crypt and the archaeological features, in order to find relationships and possible interpretations. High- to moderate-amplitude GPR anomalies were identified as tombs in the shallow subsurface, placed just under the floor of the Crypt, while in the deeper subsoil anomalies of regular shape were found. These could be interpreted as other possible archaeological structures, probably from the Roman period, while the geometrical shape of a deeper and regular anomaly could be related to another older tomb. The other strong anomalies are probably related to embedded heterogeneities, found at what was ground level in Roman times. The scarcity of historical information on the site and on its former purpose, apart from being a burial area, prevents a full understanding of the meaning of the geophysical anomalies with respect to the people that built, used and modified the place.

These results show that the surveyed area was used as a burial location by people of different cultures who inhabited the town over a long period, at least since the second part of the fourth century BC, in the Messapic age, through the Roman age. Burials probably continued all the way into the twentieth century as shown by the known tombs present in the crypt. A few metres in the northeast direction from the area surveyed De Giorgi (1907) found a wall of Roman age that could constitute a boundary between the arena of the amphitheatre and the zone of the necropolis, which was surveyed here. He also discovered many funeral tombstones with Latin inscriptions belonging to a

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necropolis of Roman age. Our findings in the area of the crypt confirm the same orientation of De Giorgi's findings, which trend from northeast to southwest in the area surveyed. This shows cultural continuity of the area as a sacred place over the time.

The Italian, and in general the worldwide, archaeological history exhibits a great richness of sacred places. In the literature such places have been widely studied and characterized and many of their aspects have been emphasized. In particular many scientists underline that even if the quality of a sacred space depends upon the human context that has been shaped by it, all its aspects are, however ,governed by rules of action that maintain continuity over a long span of time. Our findings seem to confirm such continuity, as a place that symbolically represents the world and unifies different cultures.

Very intriguingly, we think is also important to consider that the structures revealed by GPR could belong to the Roman 'forum' area (not yet documented or located), in agreement with the hypothesis of many archaeologists who suggested it was probably situated in the area of the actual Duomo. This area has probably been a religious destination from the Norman age (12th century). This area was originally a market place but became a place for politics, public and private business, surrounded with temples and public buildings. While documentation is poor, only in the Episcopio gardens of the Duomo Square were two columns of 'opus incertum' covered by a red plaster found, which could have belonged either to a civil building or to a small temple.

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References

Butler DK. 1984. Microgravimetric and gravity gradient techniques for detection of subsurface cavities. *Geophysics* **49**(7): 1084–1096.

Carrozzo MT, Leucci G, Negri S, Nuzzo L. 2003. GPR survey to understand the stratigraphy of the Roman Ships Archaeological Site (Pisa, Italy). *Archaeological Prospection* **10**: 57–72.

Ciminale M, Loddo M. 2001. Aspects of magnetic data processing. *Archaeological Prospection* **8**: 239–246.

Crew P. 2002. Magnetic mapping and dating of prehistoric and medieval iron-working sites in northwest Wales. *Archaeological Prospection* **9**: 163–182.

Cuss RJ, Styles P. 1999. The application of microgravity in industrial archaeology: an example from the Williamson tunnels, Edge Hill, Liverpool. Geoarchaeology: exploration, environments, resources. *Geological Society, London, Special Publications* **165**: 41–59.

D'Andria F, Pagliara C, Siciliano F. 1980. 'La pianta di Lecce Antica. *Studi di antichità* **2**: 103–115.

De Giorgi C. 1907. Lecce sotterranea. Relazione su gli scavi archeologici eseguiti in Lecce dal MCM al MCMVI.

Forte E, Pipan M. 2008. Integrated seismic tomography and ground-penetrating radar (GPR) for the high-resolution study of burial mounds (tumuli). *Journal of Archaeological Science* **35**(9): 2614–2623.

Giardino L. 1994. Per una definizione delle trasformazioni urbanistiche di un centro antico attraverso lo studio delle necropoli: il caso di Lupiae, *Studi di Antichità* **7** (Congedo Editore): 137–203.

Giardino L. 2002. *La città sotto la città: archeologia nei centri a continuità di vita tra conoscenza e valorizzazione*. Novamusa Arcal: Reggio Calabria.

Leucci G. 2006. Contribution of ground penetrating radar and electrical resistivity tomography to identify the cavity and fractures under the main church in Botrugno (Lecce, Italy). *Journal of Archaeological Science* **33**: 1194–1204.

Leucci G, Greco F, De Giorgi L, Mauceri R. 2007. 3D seismic refraction tomography and electrical resistivity tomography survey in the castle of occhiolà (sicily, italy). *Journal of Archaeological Science* **34**: 233–242.

Linford NT. 2004. Magnetic ghosts: mineral magnetic measurements on Roman and Anglo-Saxon graves. *Archaeological Prospection* **11**: 167–180.

Nuzzo L, Leucci G, Negri S, Carrozzo MT, Quarta T. 2002. Application of 3D visualization techniques in the analysis of GPR data for archaeology. *Annals of Geophysics* **45**: 321–337.

Panisova M, Pasteka R. 2009. The use of microgravity technique in archaeology: A case study from the St. Nicolas Church in Pukanec, Slovakia. *Contributions to Geophysics and Geodesy* **39**(3): 237–254.

Pasteka R, Terray M, Hajach M, Pasiakova M. 2007. Microgravity measurements and GPR technique in the search for medieval crypts: a case study from the St. Nicholas church in Trnava, SW Slovakia. *Proceedings of the Archaeological Prospection 7th Conference*, *Nitra. Studijne zvesti* **41**: 222–224.

Sandmeier KJ. 2008. Reflexw 5.0 Manual. Sandmeier Software: Karlsruhe, Germany.

Senos Matias MJ. 2003. Electrical methods in archaeological exploration. *Bollettino di Geofisica Teorica ed Applicata* **44**: 193–207.

Woelz S, Rabbel W. 2005. Seismic prospecting in archaeology: a 3D shear-wave study of the ancient harbour of Miletus (Turkey). *Near surface Geophysics* **3**(4): 245–257.

Yilmaz O. 1987. *Seismic Data Processing*. Society of Exploration Geophysicists: Tulsa, OK.