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Geophysical investigations to search for the remains of sister Chiara Isabella D'Amato

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ABSTRACT

This paper reports the results of the integrated geophysical surveys performed inside the Monastery of St Chiara in Nardó in southern Italy. Ground-penetrating radar (GPR) and electrical resistivity tomography (ERT) investigations were carried out to find the tomb of Sister Chiara D'Amato, whose location has been lost over the centuries. Sister Chiara Isabella D'Amato was a charismatic and holy figure. She died in 1693. She was buried inside the monastery but her body has never been found. The data acquisition was performed along with a series of closely spaced lines for GPR and using a non-standard array for ERT. Data were processed and visualised as two-dimensional vertical sections and depth slices or three-dimensional volumes (GPR and ERT) to allow an integrated interpretation of the geophysical results. The analysis of the geophysical data sets revealed a series of anomalies that could be ascribed possible archaeological structures, probably related to the earliest ages of the sacred building as well as other anomalies (bedrock, fractures) of presumable natural origin. In particular, one geophysical anomaly was suspected of being connected to burial and consequently further investigated with the use of a video endoscope. The results reveal the presence of a void but it has not yet been clarified whether it is the burial of Sister Chiara or not as it is awaiting the excavation.

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Introduction

The non-invasive nature of geophysical prospecting makes their use an increasingly common complement to invasive archaeological investigations. Among them, ground-penetrating radar (GPR) plays a special role because in favourable conditions, i.e. resistive non-magnetic environments, it can provide subsurface information with a resolution far greater than that obtained by other geophysical methods (Conyers 2004; Leucci 2019). After appropriate data processing, various three-dimensional visualisation techniques (time slices, three-dimensional iso-surfaces) are currently used to display the GPR data conveniently for understanding the spatial relationships between the anomalous zones and improving their archaeological interpretation (Leucci 2019; Leucci 2020; Giannino and Leucci 2021). Due to the complexity of most archaeological environments, the integration of different methods can help to overcome the limitations inherent in the GPR method, such as its limited penetration depth in moderately conductive environments, low reflection amplitude in the case of scarce dielectric contrast between archaeological structures and hosting materials or a high level of clutter in strongly heterogeneous terrains. A multi-methodological approach, involving GPR and electrical resistivity tomography (ERT), generally reduces the uncertainty in the interpretation of the results, helping to define better the boundaries of individual archaeological buildings or the extent and layout of large settlements (Cammarano, Mauriello, and Piro 1997; Piro, Mauriello, and Cammarano 2000, 2003; Gaffney et al. 2004; Seren et al. 2004; Rizzo, Chianese, and Lapenna 2005; Cardarelli, Fischanger, and Piro 2008). A good spatial overlap of anomalous zones in different geophysical datasets is generally a powerful indication of the presence of underground bodies with physical properties strongly different from the embedding soil, such as tombs. The use of non-destructive geophysical methods is of paramount importance in cases where direct investigations (coring and archaeological excavations) are impossible, such as inside standing monuments or a partially preserved historical building. In the studied case GPR and non-invasive ERT techniques were used for indoor investigations. Aims of geophysical investigations were to find the remains of Sister Chiara D'amato inside the Monastery of St Chiara in Nardó (south Italy) (Figure 1). Isabella D'Amato was ordained nun on 11 April 1628 (De Angelis 2016) in the Monastery of St. Chiara di Assisi and she took the name of Sister Chiara.

She led his life in prayers, penitential vigils, self-flagellations and ecstasy. She died in Nardò on 6 July 1693 and was honoured by crowds of devotees. The body, kept in a wooden coffin, was buried in the cemetery inside the Monastery. Eight days later it was taken

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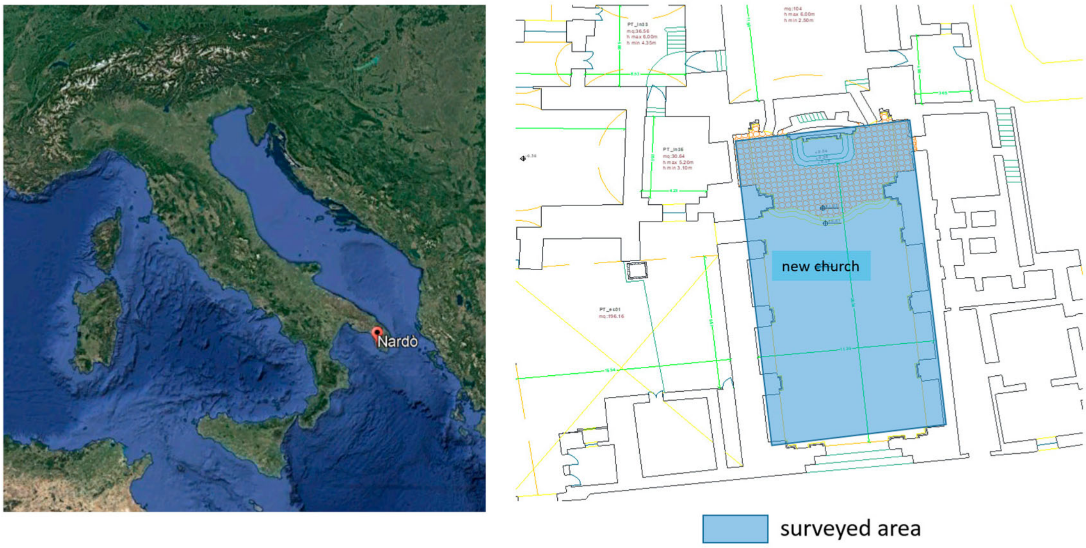


Figure 1. The surveyed areas.

out from the tomb and did not present the post-mortem rigidity (Figure 2). On 4 February 1700, the second exhumation was performed, finding the body miraculously uncorrupted. A few months later, on June 19, the beatification process was started, unfortunately never completed because the body has never been found. Successively in the analysed historical documents, especially all the depositions collected for starting the canonisation process, a clue was found stating that after the exhumation the nun was buried in the new Church built next to the old and consecrated in 1698 (De Angelis 2016; De Pascalis 2008; Mazzarella 1999; Tamblè 1999). Therefore the geophysical investigations were concentrated into the new church. The surveyed site is located in the historical centre of Nardó according to the geological map (Figure 3), the top layer of soil is made up of poorly cemented, yellowish clayey sands (Arthur, Sansò, and Vitale 2005). The water table is located at an average depth of about 4 m from the ground level.

The analysis of the geophysical data sets revealed a series of anomalies that could be ascribed possible archaeological structures, probably related to the earliest ages of the sacred building as well as other anomalies (bedrock, fractures) of presumable natural origin. One geophysical anomaly was suspected of being connected to a burial. It was inserted in a virtual excavation to have the exact spatial position and further investigated with the use of a video endoscope. Is this the tomb of Sister Chiara?

Figure 2. Portrait of Sister Chiara (oil on canvas, XVIII sec.).

Geophysical data acquisition and analysis

ERT and GPR surveys were conducted in the new church (Figure 1). GPR surveys were carried out using the ids hi mod system with the dual-band antenna 200–600 MHz since the analysis of the data acquired with the 200 MHz antenna does not give more information than the data acquired with the 600 MHz antenna, only the results from the high-resolution 600 MHZ antenna are presented here. Data were acquired in continuous mode along 0.1 m spaced survey lines in x and y-direction.

512 samples per trace, 80 ns two-way time window for 600 MHz antenna, manual time-varying gain function were used. A 24-channel georesistivity metre Syscal kid (Iris Instrument) was used to acquired ERT data. The dipole–dipole configuration was chosen to enhance lateral electrical resistivity variations (Loke 2001) possibly related to burials. The data were collected in a pseudo-three-dimensional mode along 0.5 m spaced in a snake mode parallel lines (Figure 4). The roll along the method (Loke 2001) with electrodes spaced 0.2 m was used.

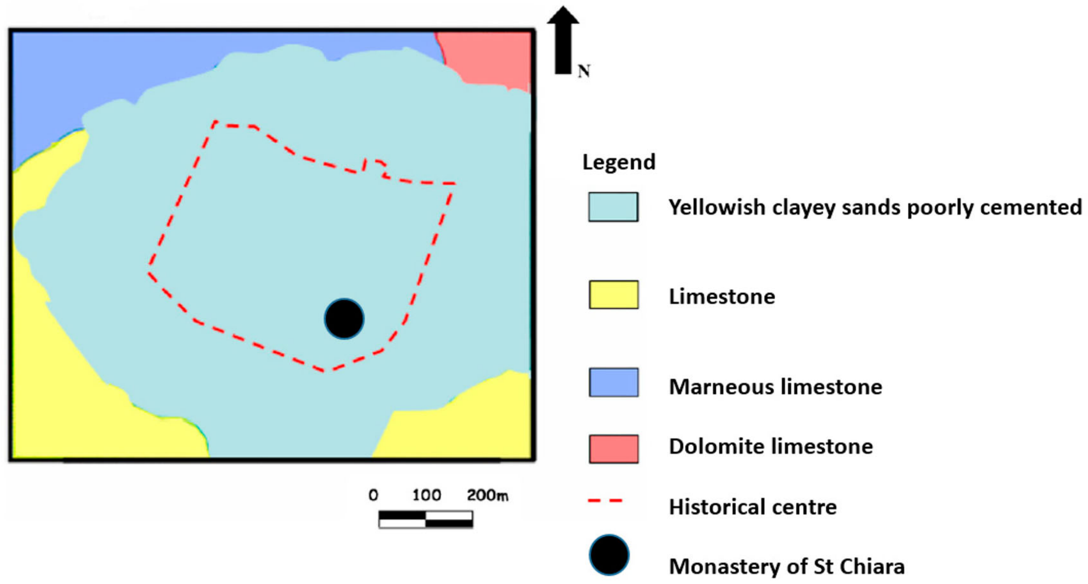


Figure 3. Geological map of the historical centre of Nardó (Vitale et al. 2007).

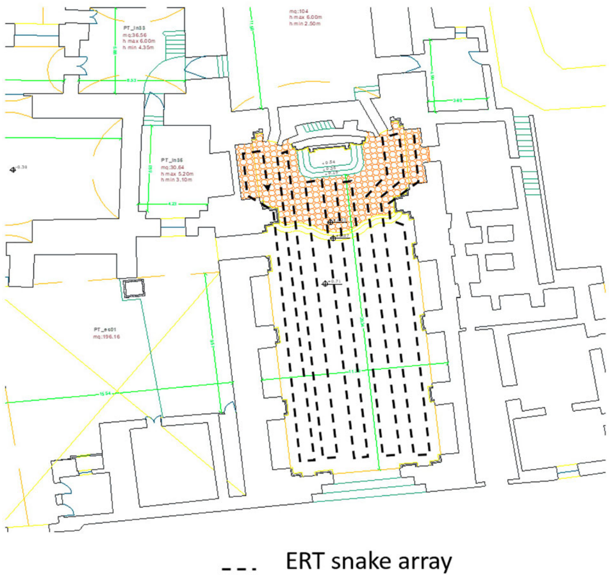


Figure 4. ERT array.

GPR data analysis

The GPR data were subsequently processed using standard two-dimensional processing techniques using the GPR-Slice Version 7.0 software (Goodman 2013).

The processing flow-chart consists of the following steps: (i) frequency filtering; (ii) manual gain, to adjust the acquisition gain function and enhance the visibility of deeper anomalies; (iii) customised 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); (iv) estimation of the 2D electromagnetic wave velocity. EM wave velocity was determined from the reflection profiles acquired in continuous mode, using the characteristic hyperbolic shape of reflection from a point source (FRUHWIRTH, SCHMOLLER, AND OBERAIGNER 1996). This is a very common method of velocity estimation and it is based on the phenomenon that a small object reflects EM waves in almost every direction; (v) 2D Kirchhoff migration; (vi) depth axis conversion using a constant average velocity value of 0.075 m/ns. The migrated data were subsequently merged into three-dimensional volumes and visualised in various ways to enhance the spatial correlations of anomalies of interest.

On the altar, the GPR, 600 MHz, processed profile (Figure 5) show a reflection event labelled "T". The size is about 1 m in width and the depth of the top is between 1.35 and 1.40 m (with an average electromagnetic wave velocity of 0.075 m/ns). This reflection event is also visible in the processed section and shows a length of about 1.8–2.0 m.

At this point a series of consideration that could be helpful in interpreting this reflection event should be done:

(1) the new church is built on a raised floor of about 2 m concerning the floor of the monastery. Below is a backfill of compacted debris;
(2) the documents show that Sister Chiara was buried inside a wooden coffin and the burial is covered by a stone plaque;
(3) the reflection event T shows a polarity change of the electromagnetic (EM) wave
(4) the shape of the anomaly T are rectangular, the dimensions are 1 m width × 2 m length.

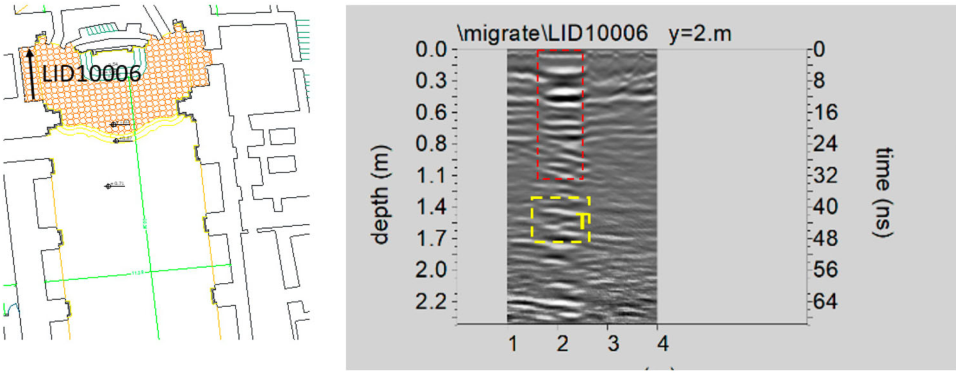


Figure 5. GPR processed radar section (acquired on the altar).

Starting from these considerations an interpretation could be made.

First, one the change in polarity of EM wave could be related to a strong contrast of EM properties such as the presence of empty space (Conyers 2012; Conyers 2013; Conyers 2015a; Conyers 2015b; Leucci et al. 2016; Leucci 2019; Leucci 2020).

Second, the reflection event related to the anomaly T seem to be flat and from the surface to the depth where the anomaly T is reported there are a series of reflected events (dashed red rectangular) that could suggest an excavation and a subsequent filling (Leucci 2020). Therefore this reflection event was interpreted as probably due to a void space and therefore to a probable burial.

Furthermore to confirm the polarity change into the reflection of EM wave in the presence of strong EM contrast such as a buried empty space a GPR profile was acquired in a known crypt near the altar.

The crypt is located inside the monastery and represents the old cemetery where the nuns were buried. It is hollowed out within the layer of yellowish clayey sands poorly cemented and is lined with bricks (Figure 6).

Figure 6. The photo of the Crypt.

Figure 7 shows hyperbolic shaped reflection events labelled "crypt". The size is about 6 m and the depth of the top ranges between 0.5 and 0.6 m (with an average electromagnetic wave velocity of 0.1 m/ns). The change in EM wave polarity is probably related to an empty space.

In the church, the results (Figure 8) include two reflection events labelled 1 and 2. The size is approximately 1 m and the depth of the top is between 1.3 and 1.35 m (with an average electromagnetic wave velocity of 0.075 m/ns). Reflection event "2" show a polarity change of the reflected EM wave. It is visible in some other processed radar profiles and has a length of about 1.2 m. The amplitude of this anomaly is smaller than the anomaly T therefore it could be due to a burial filled with other materials. Reflection event "1" show a normal polarity in EM wave reflection. It is visible in some other processed radar profiles and has a length of about 3.0 m. This is probably due to the presence of a buried wall. Reflection event "3" show a normal polarity in EM wave reflection. It is quite small (have a length of about 0.5 m). This is probably due to the presence of a buried little stone served as a filling material to raise the pavement of the church.

Useful maps (time slices) for understanding the plan distribution of reflection amplitudes within specific time intervals were made (Conyers 2006). The "overlay analysis" was used (Goodman et al. 2006), This technique allows the linkage of structures buried at different depths. 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 2013). Three-dimensional amplitude isosurface rendering displays amplitudes of equal value in the GPR study volume. Shading is usually used

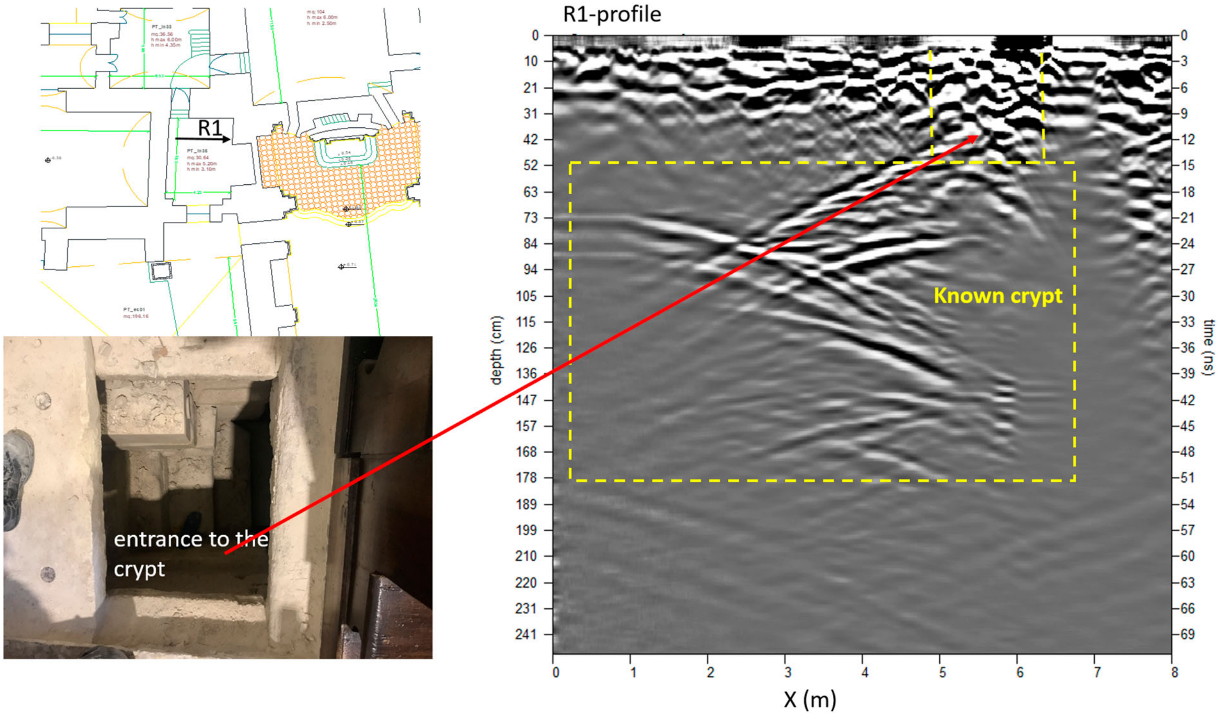


Figure 7. GPR processed radar section (acquired on the known crypt).

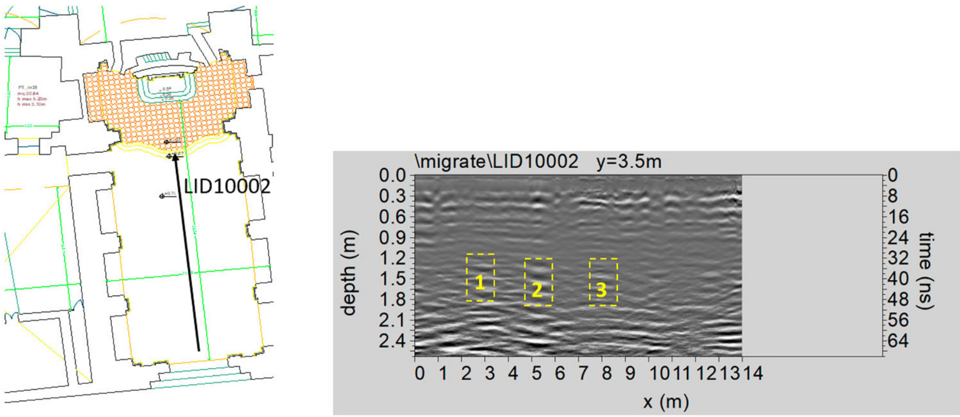


Figure 8. GPR processed radar section (acquired in the Church).

to illuminate these surfaces, giving the appearance of real archaeological structures. The threshold calibration is a very delicate task to obtain useful results.

In Figure 9 the more significant time slices related to the GPR data acquired on the altar are shown.

In the slices ranging from 1.1 to 1.5 m depth, relatively high-amplitude alignments (labelled T) are visible. These correspond to the anomalies labelled T in the radargram (Figure 5).

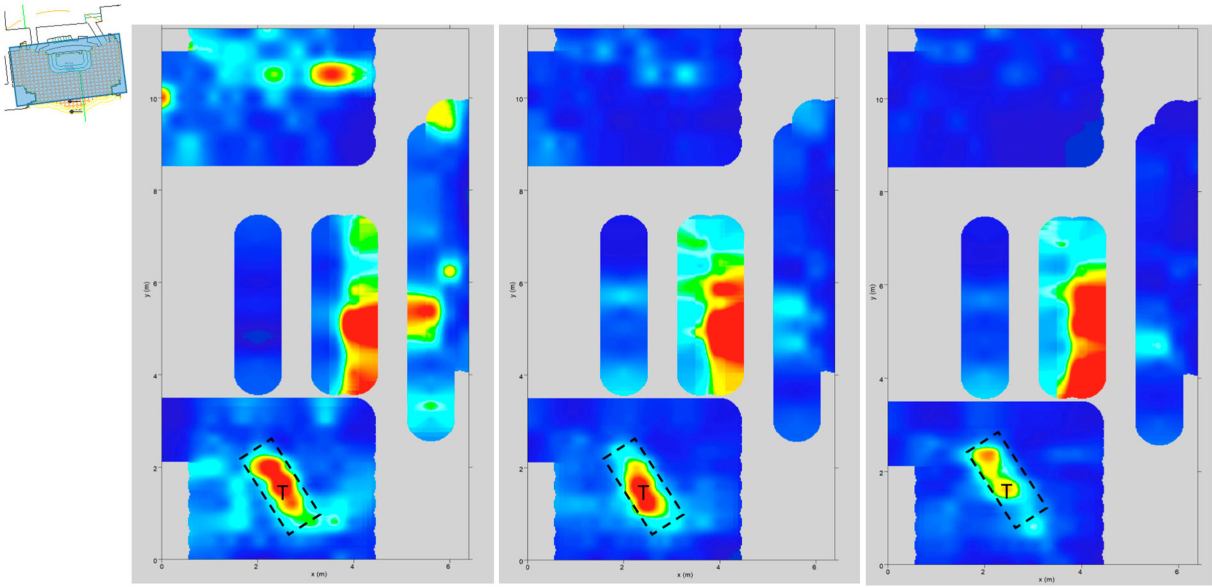
Figure 10 shows the more significant time slices related to the GPR data acquired in the Church.

In the slices ranging from 1.1 to 1.4 m depth, relatively high-amplitude alignments (labelled 1, 2 and 3) are visible. These correspond to the anomalies labelled 1, 2 and 3 in the radargram (Figure 8).

In Figure 11 the GPR data set is displayed with iso-amplitude surfaces using 60% threshold values of the maximum complex trace amplitude.

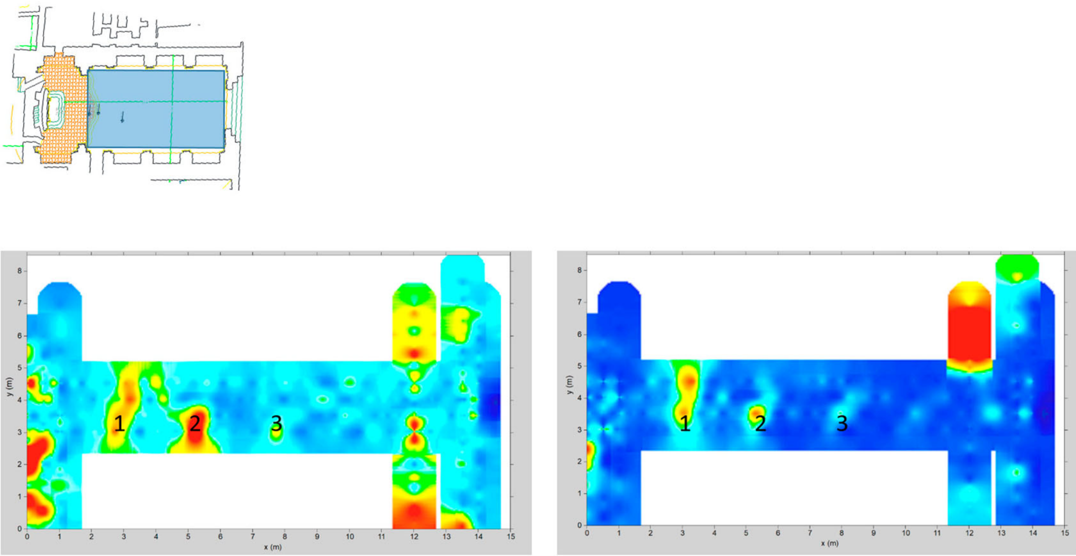
Relatively strong continuous reflections are visible on the threshold volumes. In this case, the shape and dimensions of the anomalies labelled T (Figure 11(a)) and 1, 2 and 3 (Figure 11(b)) are evidenced.

An important aspect of the research carried out was to identify those methodologies that could well illustrate the results of geophysical surveys. The aid of Computer Graphics has been needful to realise synthesis images calculated starting from three-dimensional environments. The first step was to create three-dimensional models from the georadar iso-surfaces volumes file (Figure 11): the meshes were then correctly oriented and scaled concerning the size of the investigated area. The polygonal surfaces have been mapped using a gradient texture that matches the altimetric map, on the axis of height, with a range of colours that form the most superficial areas (red colour), go with the different shades to indicate the different dimensions



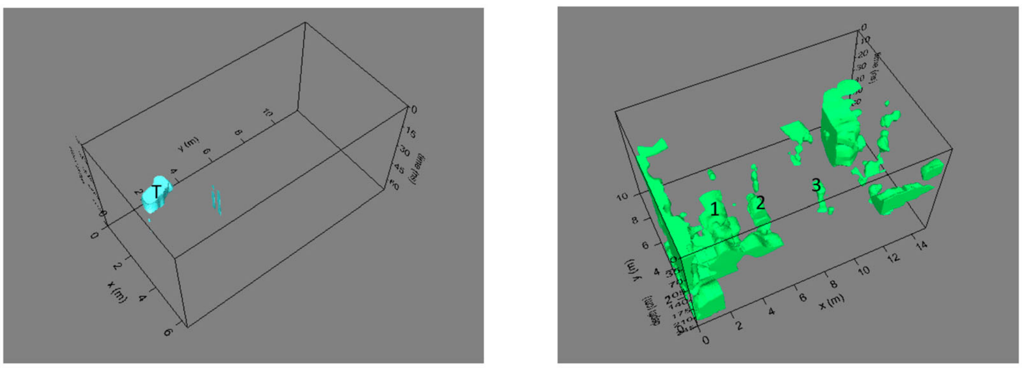
1.1-1.3 m depth 1.2-1.4 m depth 1.3-1.5 m depth

Figure 9. GPR time slices related to the altar.



1.1-1.3 m depth 1.2-1.4 m depth

Figure 10. GPR time slices related to the church.



a b

Figure 11. GPR iso-surfaces: (a) the altar; (b) the church.

Figure 12. 3D reproduction of the anomalies under the altar inserted in a digital photo.

up to that deeper (green colour). In this way, three-dimensional simulations have been carried out on the perspective views of the individual area explored, making immediately comprehensible the data obtained, both as in the whole and the specific levels. This is useful to offer further elements in the planning of the next archaeological excavation (Figure 12). Figure 12 shows the exact spatial position of the anomaly T.

ERT data analysis

The data were processed using a three-dimensional inversion algorithm using the ErtLab software (http://www.geostudiastier.it). In this method, the subsurface is divided into a number of rectangular cells of constant resistivity. The resistivity of each cell is then evaluated by minimising the difference between observed and calculated data in an iterative manner. It uses the Finite Elements algorithm. The true resistivity model computed has an investigation depth of 5 m. At first, it is possible to note the presence of a heterogeneous subsurface with resistivity values ranging from 1100 to 5000 ohm m (Figure 13). Afterwards, it is possible to note the presence of the high resistivity anomaly (3800–4000 ohm m) labelled "T" at a depth ranging from 1.3 to 1.5 m. This resistivity anomaly corresponds to the same anomaly evidenced in the GPR time slices (Figure 9).

The 3D images of resistivity can easily be visualised by 3D contouring of iso-resistivity volumes (Figure 13). In this representation, the transparency function is defined by two threshold values of the resistivity, $\rho 1$ and $\rho 2$ ($\rho 1 < \rho 2$). In the intervals $\rho < \rho 1$ and $\rho > \rho 2$, data are rendered as transparent, therefore only the data in the interval $\rho 1 < \rho < \rho 2$ are visualised. The threshold calibration is a very delicate task. In fact, by lowering the threshold value, not only the visibility of the main anomaly is raised, but also that of the smaller objects and noise increases. In Figure 14, the resistivity data set is displayed with iso-resistivity volumes using a threshold value ranging from 3500 to 4000 ohm m. The continuous high resistivity area (labelled T) are more visible.

The video endoscope survey

For the video endoscope investigation an Olympus Iplex Ultralite endoscope was used. The survey was performed by making one hole of 2 cm diameter and 1.2 m depth properly "cleaned" in the central part of the hypothetical anomaly T. Into the hole was introduced the endoscope. The analysis reveals the presence of a possible cavity at 1.2 m depth (Figure 15). In this way was possible to convince the archaeological superintendency to plan an excavation.

Conclusions

The results of the geophysical investigations inside the new church into the Monastery of St Chiara, revealed the effectiveness of the integrated approach to identifying a series of anomalies that could be ascribed

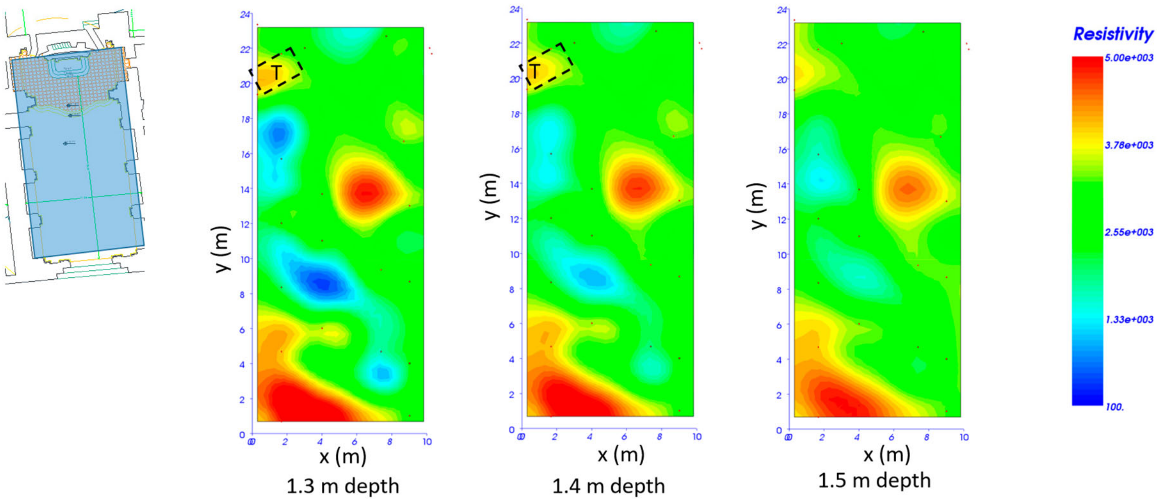


Figure 13. ERT depth slices.

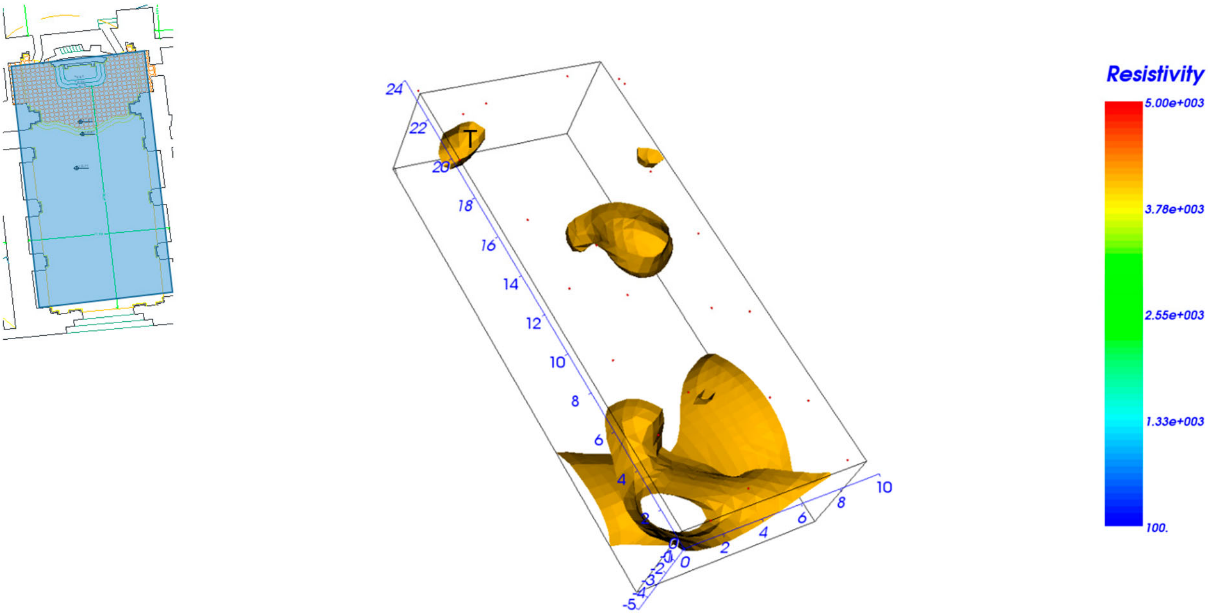


Figure 14. ERT iso-resistivity volume.

Figure 15. The videoendoscopic results.

to anthropogenic features and distinguish them from natural variations in the subsoil. High amplitude GPR anomalies with an inversion of polarity were interpreted as due to empty space. Different three-dimensional visualisation tools were useful to present the information of GPR data cubes in an efficient way for extracting the geometrical information of possible features and facilitate their interpretation. The immediacy in revealing the spatial positioning of highly reflecting bodies, such as voids inside a virtual excavation makes these techniques very attractive in archaeological applications. However, low-amplitude anomalies can be missed. The depth-slice technique allowed us a precise plan localisation of the GPR anomalies at progressive depths and facilitated their correlation to the ERT anomalies. The ERT method proved to be a good method for detecting features that could be related to empty spaces and to identify lithostratigraphical changes. The anomaly T was well correlated with a high resistivity anomaly in the same position of the altar.

Furthermore, a video endoscopic investigation confirms the presence of the empty space.

It should be stressed that these anomalies have been interpreted solely based on the geophysical results, geometrical considerations, and simple video endoscopic investigations but their true significance is still waiting for archaeological validation from ongoing investigations.

The suspicion that the anomaly detected by geophysics and confirmed by the videoendoscopic investigation is linked to the presence of Sister Chiara's burial is linked to the fact that it is located in an important part of the church, the altar. In the past, the burials therefore had to take place ad *sanctos et apud aecclesiam* (near the saints and near the churches). The closer the burial was to the relics, the more it was valued. A figure close to sanctity deserved a burial in an important place such as the altar of the church adjacent to the convent. Excavations are awaited.

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

Arthur, P., P. Sansò, and A. Vitale. 2005. Analisi geomorfologia del paesaggio archeologico di Nardò (Provincia di Lecce) Convegno sul tema La geoarcheologia: metodi ed applicazioni (Verona, 7–8 July).

Cammarano, F., P. Mauriello, and S. Piro. 1997. High-resolution geophysical prospecting with integrated methods. The ancient Acropolis of veio (Rome, Italy). *Archaeological Prospection* 4: 157–64.

Cardarelli, E., F. Fischanger, and S. Piro. 2008. Integrated geophysical survey to detect buried structures for archaeological prospecting. A case-history at Sabine Necropolis (Rome, Italy). *Near Surface Geophysics* 6: 15–20.

Conyers, L.B. 2004. *Ground-penetrating radar for archaeology*. Walnut Creek, CA: Altamira Press.

Conyers, L.B. 2006. Innovative ground-penetrating radar methods for archaeological mapping. *Archaeological Prospection* 13, no. 2: 139–41.

Conyers, L.B., and D. Goodman. 1997. *Ground-Penetrating radar: An Introduction for archaeologists*. Walnut Creek, CA: AltaMira.

Conyers, L.B. 2012. *Interpreting ground-penetrating radar for archaeology*. Walnut Creek, CA: Left Coast Press.

Conyers, L.B. 2013. *Ground-penetrating radar for archaeology*. 3rd ed. Walnut Creek, CA: Alta Mira Press, 258 pp.

Conyers, L.B. 2015a. Analysis and interpretation of GPR datasets for integrated archaeological mapping. *Near Surface Geophysics* 13: 645–51.

Conyers, L.B. 2015b. *Ground-penetrating radar data analysis for more complete archaeological interpretations*. Proceedings of the 11th International Conference on Archaeological Prospection, 15–19 September, Warsaw, Poland. Archaeologia Polona 53: 202–5.

De Angelis, C.S. 2016. *Serva di Dio. Suor Chiara di Gesù Clarissa*. Isabella D'Amato dei duchi di Seclì, Editrice Velar 2016, ISBN 9788866712954.

De Pascalis, G. 2008. *Il Monastero delle Clarisse e la Chiesa di S*. Chiara di Nardò, Saggio storico e illustrativo in occasione della XVI giornata Fai di Primavera, Nardò (Le).

Fruhwirth, R.K., R. Schmoller, and E.R. Oberaigner. 1996. *Some aspects of the estimation of electromagnetic wave velocities*. Proceedings of the 6th International Conference on Ground Penetrating Radar, tohoku university, Sendai, Japan, 135–8.

Gaffney, V., H. Patterson, S. Piro, D. Goodman, and Y. Nishimura. 2004. Multimethodological approach to study and characterize Forum Novum (Vescovio, central Italy). *Archaeological Prospection* 11: 201–12.

Giannino, F., and G. Leucci. *Electromagnetic methods in geophysics: applications in GeoRadar, FDEM, TDEM, and AEM*. New York: Wiley, 352 pp.

Goodman, D. 2013. GPR Slice Version 7.0 Manual. http://www.gpr-survey.com (accessed June 2013).

Goodman, D., J. Steinberg, B. Damiata, Y. Nishimure, K. Schneider, H. Hiromichi, and N. Hisashi. 2006. *GPR overlay analysis for archaeological prospection*. Proceedings of the 11th International Conference on Ground Penetrating radar, Columbus, Ohio; CD-rom.

Leucci, G. 2020. *Advances in geophysical methods applied to forensic investigations: New developments in acquisition and data analysis methodologies*. Springer editore, pp 200, ISBN 978-3-030-46241-3.

Leucci, G. 2019. *Nondestructive testing for Archaeology and Cultural heritage: A practical guide and new perspective*. Springer, 217, ISBN 978-3-030-01898-6.

Leucci, G., M. Parise, M. Sammarco, and G. Scardozzi. 2016. The use of geophysical prospections to map ancient hydraulic works: The triglio underground aqueduct (apulia, southern Italy). *Archaeological Prospection* 23: 195–211.

Loke, M.H. 2001. Tutorial: 2-D and 3-D Electrical Imaging Surveys. Copyright (1996–2001). Lecture notes available from http://www.geoelectrical. com/downloads.php.

Mazzarella, E. 1999. *Nardò sacra, a cura di M. Gaballo*. Galatina, pp. 110–28, ISBN 8880862758.

Piro, S., P. Mauriello, and F. Cammarano. 2000. Quantitative integration of geophysical methods for archaeological prospection. *Archaeological Prospection* 7: 203–13.

Piro, S., D. Goodman, and Y. Nishimura. 2003. The study and characterization of Emperor Traiano's Villa (Altopiani di Arcinazzo, Roma) using high-resolution integrated geophysical surveys. *Archaeological Prospection* 10: 1–25.

Rizzo, E., D. Chianese, and V. Lapenna. 2005. Magnetic, GPR and geoelectrical measurements for studying the archaeological site of 'Masseria Nigro' (Viggiano, southern Italy). *Near Surface Geophysics* 3: 13–19.

Seren, S., A. Eder-Hinterleitner, W. Neubauer, and S. Groh. 2004. Combined high-resolution magnetics and GPR surveys of the roman town of Flavia Solva. *Near Surface Geophysics* 2: 63–8.

Tamblè, M.R. 1999. Il Monastero di Santa Chiara di Nardò tra memoria ecclesiastica e identità storica (secc. XIV-XVIII). Pietro Polidori e la rivisitazione settecentesca del Medioevo neritino, in Il Monastero di Santa Chiara in Nardò. Miscellanea di studi nell'VIII Centenario della nascita di Santa Chiara d'Assisi, a cura di S. Bove Balestra e M. Gaballo, Galatina 1999, 37–124, ISBN 8880862693.

Vitale, A., G. Leucci, P. Sansò, and P. Giannaccari. 2007. I crolli nel centro storico del commune di Nardò (Lecce) Geol. *Ambientale* 2: 25–36.