NRIAG Journal of Astronomy and Geophysics (2012) 1, 1–11

National Research Institute of Astronomy and Geophysics

NRIAG Journal of Astronomy and Geophysics

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FULL LENGTH ARTICLE

The implementation of multi-task geophysical survey to locate Cleopatra Tomb at Tap-Osiris Magna, Borg El-Arab, Alexandria, Egypt "Phase II"

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Received 14 October 2012; accepted 19 November 2012
Available online 20 December 2012

KEYWORDS
Archaeology;
Tap-Osiris Magna;
Cleopatra Tomb;
VLF-EM;
ERT

Abstract According to some new discoveries at Tap-Osiris Magna temple (West of Alexandria), there is potentiality to uncover a remarkable archeological finding at this site. Three years ago many significant archeological evidences have been discovered sustaining the idea that the tomb of Cleopatra and Anthony may be found in the Osiris temple inside Tap-Osiris Magna temple at a depth from 20 to 30 m. To confirm this idea, **PHASE I** was conducted in by joint application of Ground Penetrating Radar "GPR", Electrical Resistivity Tomography "ERT" and Magnetometry. The results obtained from **PHASE I** could not confirm the existence of major tombs at this site. However, small possible cavities were strongly indicated which encouraged us to proceed in investigation of this site by using another geophysical approach including Very Low Frequency Electro Magnetic (VLF-EM) technique.

VLF-EM data were collected along parallel lines covering the investigated site with a line-to-line spacing of 1 m. The point-to-point distance of 1 m along the same line was employed. The data were qualitatively interpreted by Fraser filtering process and quantitatively by 2-D VLF inversion of tipper data and forward modeling. Results obtained from VLF-EM interpretation are correlated with 2-D resistivity imaging and drilling information. Findings showed a highly resistive zone at a depth extended from about 25–45 m buried beneath Osiris temple, which could be indicated as the tomb of Cleopatra and Anthony. This result is supported by Fraser filtering and forward modeling results. The depth of archeological findings as indicated from the geophysical survey is correlated

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Peer review under responsibility of National Research Institute of Astronomy and Geophysics.

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http://dx.doi.org/10.1016/j.nrjag.2012.11.001

well with the depth expected by archeologists, as well as, the depth of discovered tombs outside Tap-Osiris Magna temple. This depth level has not been reached by drilling in this site. We hope that the site can be excavated in the future based on these geophysical results.

Introduction

Ptolemaic Egypt began when Ptolemy I Soter declared himself Pharaoh of Egypt in 305 BC and ended with the death of queen Cleopatra of Egypt and the Roman conquest in 30 BC. During Ptolemaic period Alexandria became the capital city and a center of Greek culture and trade. To gain recognition by the native Egyptian populace, they named themselves as the successors to the Pharaohs. The later Ptolemies took on Egyptian traditions, had themselves portrayed on public monuments in Egyptian style and dress, and participated in Egyptian religious life. Unfortunately, no tombs from the Ptolemaic period have been revealed yet.

Tap-Osiris magna is located about 50 km west of Alexandria (Fig. 1). Excavations began 3 years ago. In the temples of Osiris and Isis inside the Tap-Osiris Magna, archeologists found 22 coins bearing Cleopatra's name and likeness, the mask of Mark Anthony, and a head of Cleopatra. Outside the temple, 500 m to the east, they discovered one of the largest Greek–Roman cemeteries. It contains a series of 40–45 tombs cut into the bedrock 35 m deep, with tunnels and passageway (Fig. 2). Inside the tombs, 200 skeletons were found, and 10 mummies, two of them are gilded with gold. Another cemetery zone to the west of the Tap-Osiris magna has been discovered (Zahi and Kathleen, 2009).

The large number of tombs around the temple suggests that there should be important persons inside the temple. The un-mummified skeletons indicate the remains may be Greeks; 2000 years old, but for the mummified skeleton, they are so well preserved, which indicates that they belonged to the class of nobles, with the resources to make this type of procedure possible (Zahi and Kathleen, 2009).

The geophysical survey was conducted to provide information to support or deny the suggestion that a tomb, probably of Cleopatra and Mark Anthony lie beneath the Temples of Osiris and Isis inside the Tap-Osiris Magna complex. The tomb is supposed to lie between 20 and 30 m below the surface, and accessed by either a vertical shaft or an inclined tunnel from the surface, possibly originating outside the complex. The local bed rock was limestone/sandstone of poor quality (many small holes and inclusions) for the first 10 m, grading to better quality limestone below that depth (Vickers and Abbass, 2009).

There are many case studies concerned with the application of different geophysical methods for discovering hidden archeological structures in different geographic locations. Bozzo

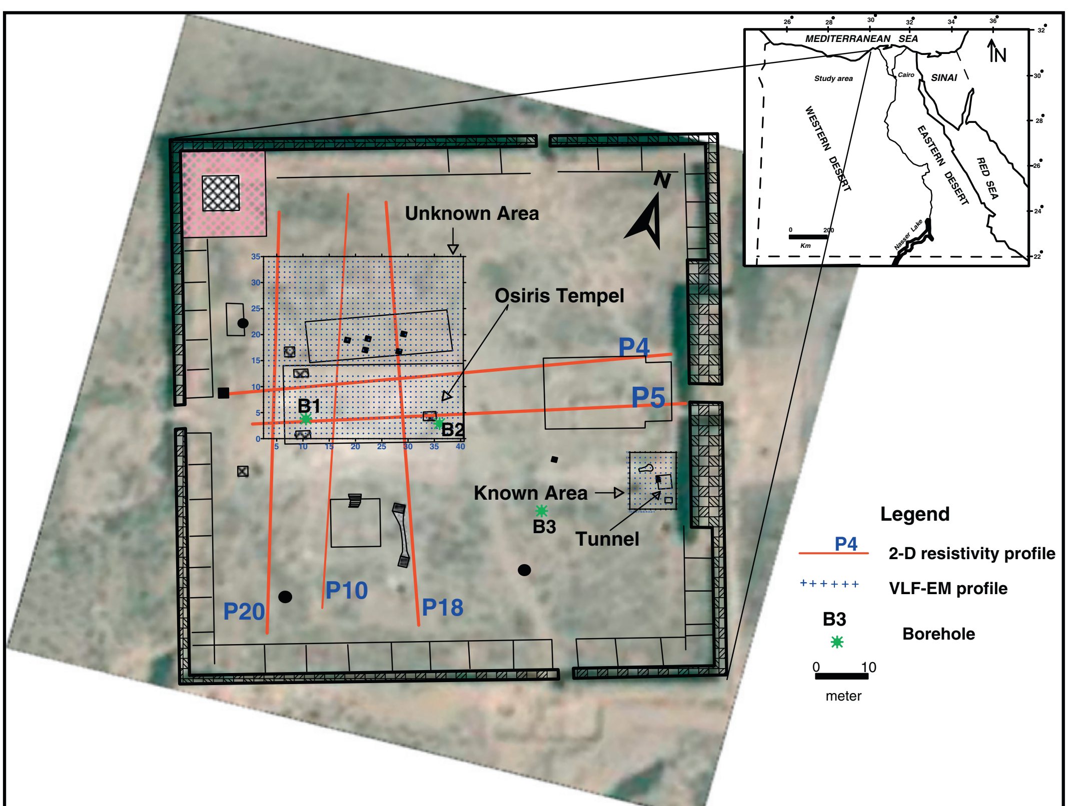


Fig. 1 Location map of Tap-Osiris Magna complex and geophysical survey.

Fig. 2 An example of the recently discovered tombs and mummies around the Tap-Osiris Magna complex (after Zahi and Kathleen, 2009).

et al. (1999) used VLF-EM to highlight some archeological structures characterized by different conductivities at depths shallower than 4–5 m in the eastern hill of Selinunte archeological site, on the south coast of Sicily. Mahmut (2006) used an integrated geophysical investigation, including magnetic, 2-D resistivity, VLF-R and seismic methods to determine the buried archaeological structures under the very thick soil in the upper part of Sardis archaeological site, Turkey. Papadopoulos et al. (2007) implemented a simple modification of a standard resistance-meter geophysical instrument, in order to collect parallel two-dimensional sections along the X-, Y- or XY-direction in a relatively short time, employing a pole–pole array in archeological sites. Abdallatif et al. (2009) discovered some of the outbuildings of the causeway and mortuary temple of the pyramid of Amenemhat II using near surface magnetic gradiometer. They successfully detected four main structures in the area east of the pyramid; the causeway that connected the mortuary temple with the valley temple during the Middle Kingdom of the 12th Dynasty, the mortuary temple and its associated rooms, ruins of an ancient working area and an Egyptian-style tomb structure called a Mastaba. Khalil et al. (2010) used VLF-EM and resistivity to outline the rooms, galleries, and courtyards of the hidden Labyrinth mortuary temple complex, south of the Hawara pyramid. The spatial distribution of the anomalies significantly matches the historical description of Herodotus.

Geophysical data acquisition

Two geophysical methods are employed in this study, very low frequency electromagnetic (VLF-EM) and 2-D resistivity imaging. VLF-EM data is collected on a known case and unknown case study. 2-D resistivity cross sections are measured in two directions crossing the temple of Osiris. Inside the Tap-Osiris magna complex, a known tunnel-about 5 m depth-is selected for VLF survey in order to compare with the unknown case, temple of Osiris, the proposed place of the tomb of Anthony and Cleopatra. Twelve VLF-EM profiles were measured, extending from East to West direction passing through the known tunnel. Test VLF measurements were made at a frequency of 26.600 kHz. The distance among the VLF profiles and stations is 1 m. The data were collected with a WADI (ABEM) device, which measures in-phase and out of phase components. In the unknown area (temple of Osiris), 35 VLF-EM profiles were measured, extending roughly from East to West. The frequency was 21.700 kHz for the measured profiles. Every profile contains 42 stations; the distance among the VLF profiles and stations is 1 m. Five 2-D resistivity profiles were conducted using SYSCAL R2 system from IRIS company. The system was combined by the multi-node part to apply the tomography through the automatic switching between the operated arrangements of electrodes. The acquisition was handled utilizing Wenner electrode configuration with equal-offset-distance between electrodes 2.5 or 3 m depending on the maximum available horizontal distance. Two 2-D resistivity profiles (P4 and P5) are extending roughly from East to West, more or less parallel to VLF-EM profiles. The other three resistivity profiles (P20, P10, and P18) are extending roughly from North to South. In addition there are three exploratory 2.5 inch boreholes were drilled in the area as shown in Fig. 1).

Data processing and interpretation

The theoretical basics of VLF-EM, in addition to its geological and hydrogeological applications can be found in literature, e.g. McNeill and Labson (1991). A primary low frequency electromagnetic field is sent out from many radio transmitters distributed in different parts of the world, designed for military communications and navigation. The transmitted frequency is usually between 15 and 30 kHz. This primary electromagnetic field of a radio transmitter (vertical electric dipole), possesses a vertical electric field component (EPz) and a horizontal magnetic field component (HPy) perpendicular to the propagation direction x (Fig. 3). At a distance greater than several free wavelengths from the transmitter, the primary EM field components can be assumed to be horizontally traveling waves. HPy penetrates into the ground and induces a secondary horizontal electric component (ESx) in buried conductive structures with an associated magnetic field (HS). The secondary magnetic field has horizontal and vertical components. This secondary EM field has parts oscillating in-phase and out-of-phase with the primary field. The intensity of the secondary EM field depends on the conductivity of the ground. The two common methods of using these fields are (1) Very low frequency-resistivity (VLF-R) method, which measures the local horizontal resultant magnetic field component (HRy) with an induction coil and the secondary horizontal electric field component (ESx) by means of a voltage drop between two electrodes placed in the ground. (2) Very low frequency-electromagnetic (VLF-EM) method, which is used in the present study. It measures the resultant local horizontal and vertical magnetic field component with two orthogonal induction coils. As a consequence, no ground contact is necessary, which allows a higher speed of survey. The local resultant magnetic field HR is the superposition of the primary field HP and secondary field HS, where HP » HS. HS and therefore HR depend on space, time and frequency (Bosch and Müller, 2001). Because of the far field conditions, HP is space independent (dependencies will not always be written explicitly in the following):

$$H_R = H_P + H_S \tag{1}$$

$$H_R = |H_P|e^{i\omega t} + |H_s|e^{i(\omega t-\varphi)} \tag{2}$$

with transmitter frequency $f = (\omega/2\pi)$ and phase shift φ between primary and secondary magnetic field component. The magnetic field vectors have the following components:

$$\begin{pmatrix} 0 \\ H_{\mathrm{Ry}} \\ H_{\mathrm{RZ}} \end{pmatrix} = \begin{pmatrix} 0 \\ H_{\mathrm{Py}} \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ H_{\mathrm{Sy}} \\ H_{\mathrm{SZ}} \end{pmatrix} \tag{3}$$

Results of the VLF-EM method are the in-phase and out-of phase (quadrature) parts of the ratio (HRz/HRy) and reflect changes in the resistivity distribution of the ground.

Qualitative interpretation

The twelve measured VLF-EM profiles are crossing a known limestone cave or tunnel extending north–south. The target is to study the capability of VLF-EM data processing and interpretation to outline the borders of this cave. The known case will be used to see how much we can depend on VLF-EM in tracing the caves or tunnels – if exist – in the unknown case.

Fraser filter (Fraser, 1969) is widely used for qualitative interpretation of VLF-EM data. Fraser (1969) filter is applied to the tilt angle of the magnetic polarization ellipse (real component). It calculates horizontal gradients and smoothes the data to give maximum values over conductors that can then be contoured. Consequently, the plotted Fraser filter function becomes,

$$F2,3 = (M3 + M4) - (M1 + M2), \tag{4}$$

Which is plotted midway between the $M2$ and $M3$, tilt angle stations (Fraser, 1969).

Accordingly, the Fraser filter: (1) completely removes DC bias and greatly attenuates long wavelength signals; (2) completely removes Nyquist frequency related noise; (3) phase shifts all frequencies by 90°, and (4) has the band pass centered at a wave length of five times the station spacing. Fraser filtering converts somewhat noisy, non-contourable, In-phase components to less noisy, contourable data, which ensures greatly the utility of VLF-EM survey. VLF-EM contour maps form a meaningful complement to magnetic maps (Sundararajan et al., 2006). The Fraser filter transforms the zero-crossing points into peaks enhancing the signals of the conductive structures. The center of the anomalous structure may fall directly under the peak of the Fraser filtered data.

The 12 VLF-EM profiles obtained from the application of the Fraser filter are plotted in a map to show the spatial distribution of the conductive and resistive zones (Fig. 4). From the map, the zero contour line separates between the positive Fra-

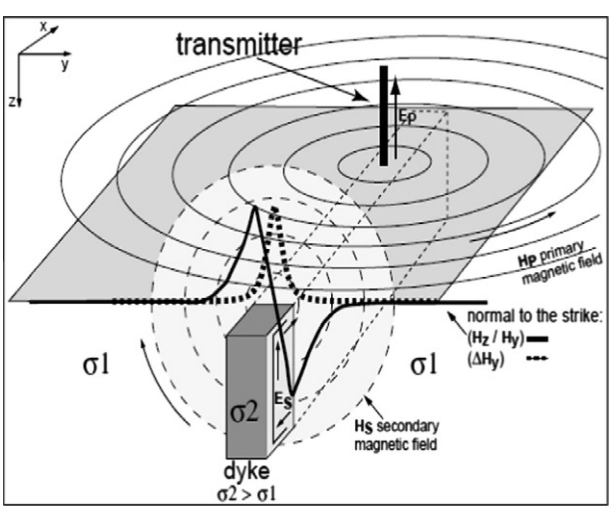


Fig. 3 EM field distribution for the VLF method in E-polarization with theoretical signals over a vertical conductive dike (after Bosch and Müller, 2001).

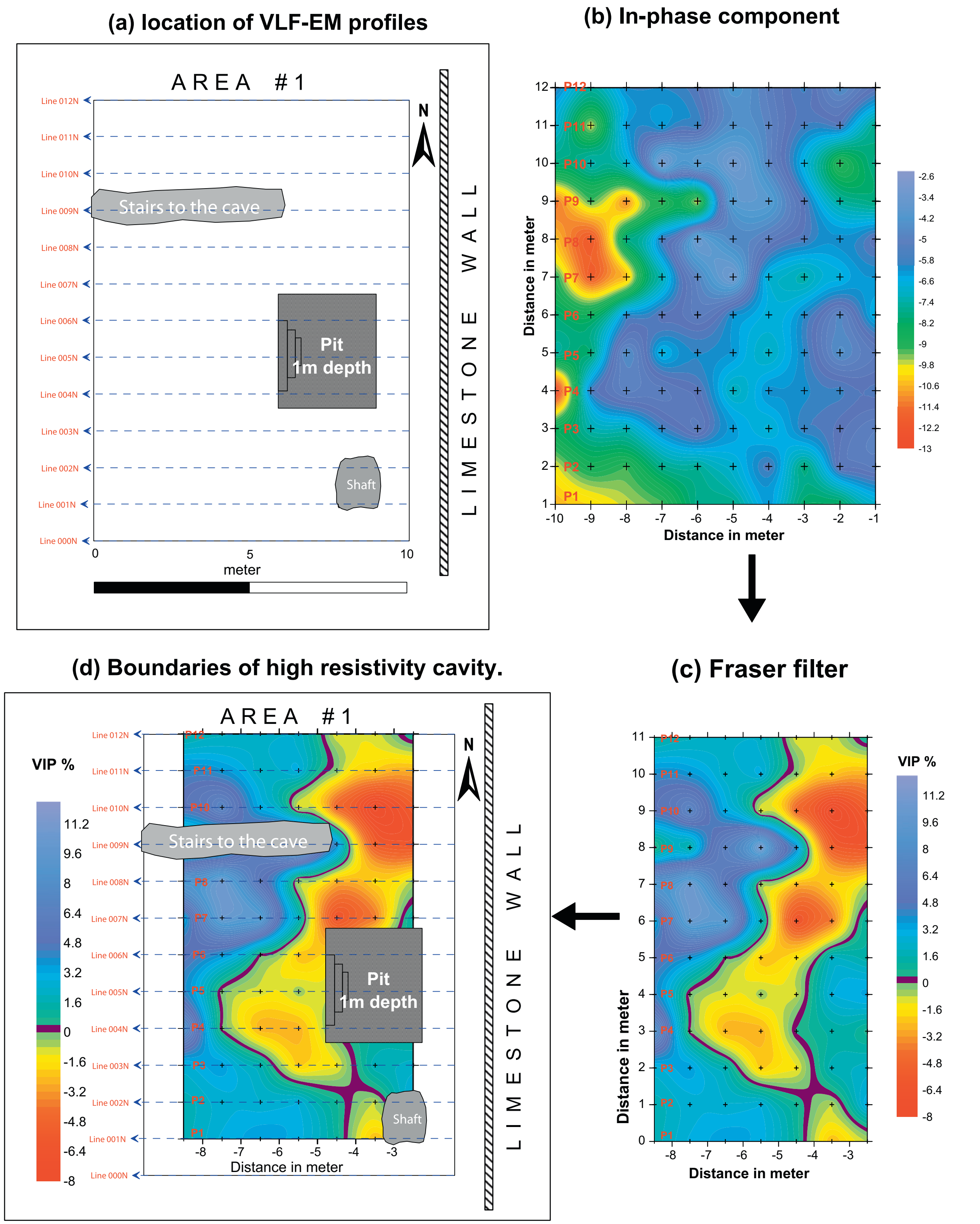


Fig. 4 (a) VLF-EM profiles in area-1(known area), (b) in-phase and (c) Fraser filter of the data.

ser filter VLF-in phase (VIP) component that is corresponding to conductive anomalies and the negative ones that are corresponding to resistive anomalies. There is a significant negative Fraser VIP zone extending N–S direction, which is tentatively associated with a resistive zone, extending from south to north tracing the cavity zone. Comparing between Fraser filter VLF-in phase (VIP) map (Fig. 4c) and in-phase component map (Fig. 4b) shows the advantages of Fraser filter in tracing resis-

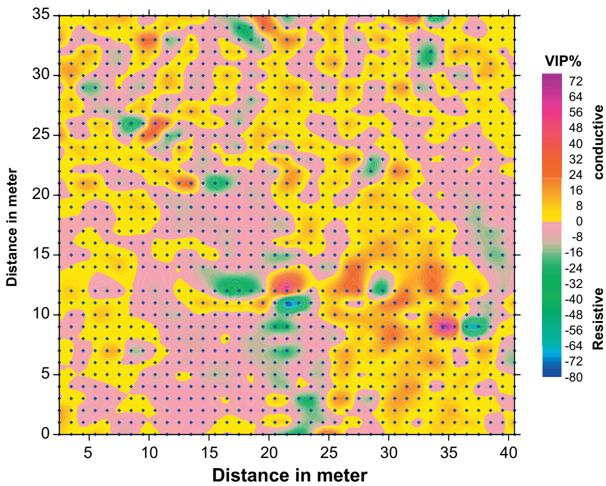


Fig. 5 Fraser filter contour map of the unknown area, proposed location of tomb of Cleopatra, and Mark Anthony under Osiris temple.

tive zone of the cave and conductive zones around. Plotting the Fraser filter VLF-in phase (VIP) map (Fig. 4c) in the location map shows quiet well matching between the cave and the surface terrains such as stairs.

The Fraser filter (Fraser, 1969) was applied on the 35 profiles of the unknown area. Fig. 5 is a contour map collects the filtered data of all profiles.

From Fig. 5 there is obvious contrast between resistive and conductive zones in the area. The area could be separated into two zones. The first zone begins from profile 0 to 20, which is characterized by a large resistive zone, about 20 m length × 15 m width in contact with a conductive zone, approximately the same size. This zone is located directly on the Osiris temple, the proposed location of tomb of Cleopatra, and Mark Anthony. The second zone begins from profile 21 to 35. This zone is characterized by a large number of intercalated resistive and conductive elongated pathways. The resistive zones in Fig. 5 may refer to a subsurface cavities and tunnels and/or lithologic variations in the limestone bed rock. Since the filtered data limits of unknown case (−80 to 72) differs from the filtered data limits of the known case (−8 to 12), so the filtered data of unknown case (Fig. 5) is separated into three zones, (1) in the limits of the known case data (−8 to 12), (2) more conductive (12–72), (3) more resistive (−8 to −80) (Fig. 6).

The separated Fraser map in the limits of known case data (−8 to 12) (Fig. 6a) is approximately the same as the original Fraser map (Fig. 4), and the high resistivity or conductivity parts of data appear as randomly distributed patches.

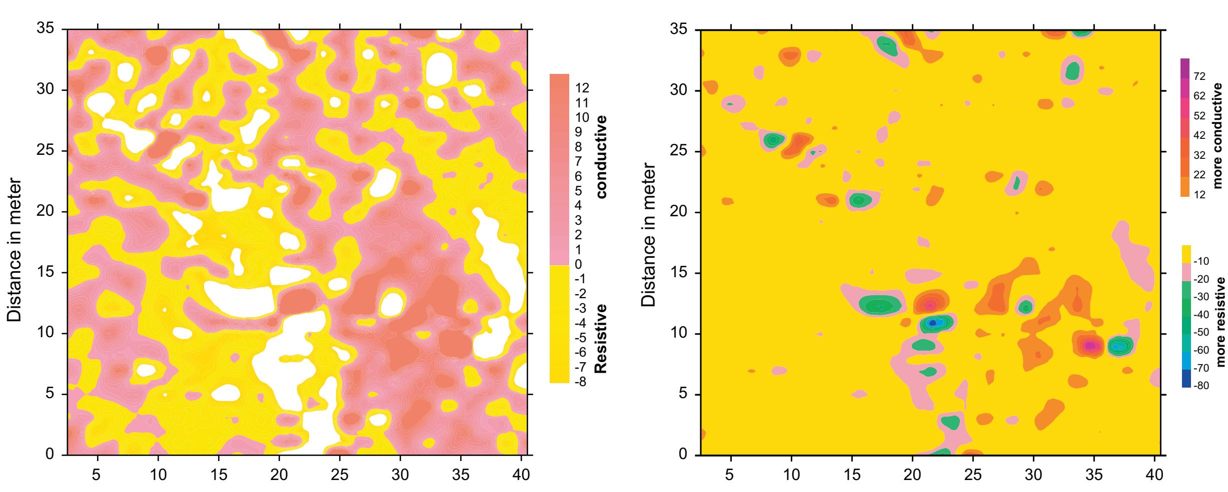
Quantitative interpretation

The main target of the quantitative interpretation of VLF-EM data is to identify the location and depth of the resistive and conductive zones, with special interest to know the expected depth of resistive zones based on the frequency of the transmitter and resistivity of the environment.

Monteiro Santos et al. (2006) developed software (Inv2DVLF) for quantitative interpretation of the single-frequency VLF-EM data via an inversion of the tipper data using a 2D regularized inversion approach (Sasaki, 1989, 2001). Their code for the 2D regularized inversion of the VLF-EM data was developed based on a forward solution using finite-element method. The objective of the inversion is to obtain a subsurface distribution of the electrical resistivity, which generates a response that fits the field data within the limits of data errors.

Quantitative 2D resistivity inversion of the VLF-EM data have many returns compared to qualitative interpretation (filtering): (1) it provides comprehensive information of the subsurface resistivity distribution and (2) resistivity control can be done at some sites of the resistivity area.

The 35 VLF-EM profiles of the unknown area have been inverted using Inv2DVLF software. Environmental resistivity of 300 Ω m has been selected based on the measured 2-D resistivity cross-sections, as will be discussed later on. Fig. 7 shows some examples of the inverted data.



(a) Fraser map in the limits of known case data.

(b) Fraser map above and below the limits of known case data

Fig. 6 Separation of unknown case into (a) in the limits of known case data, (b) above and below the limits of known case data.

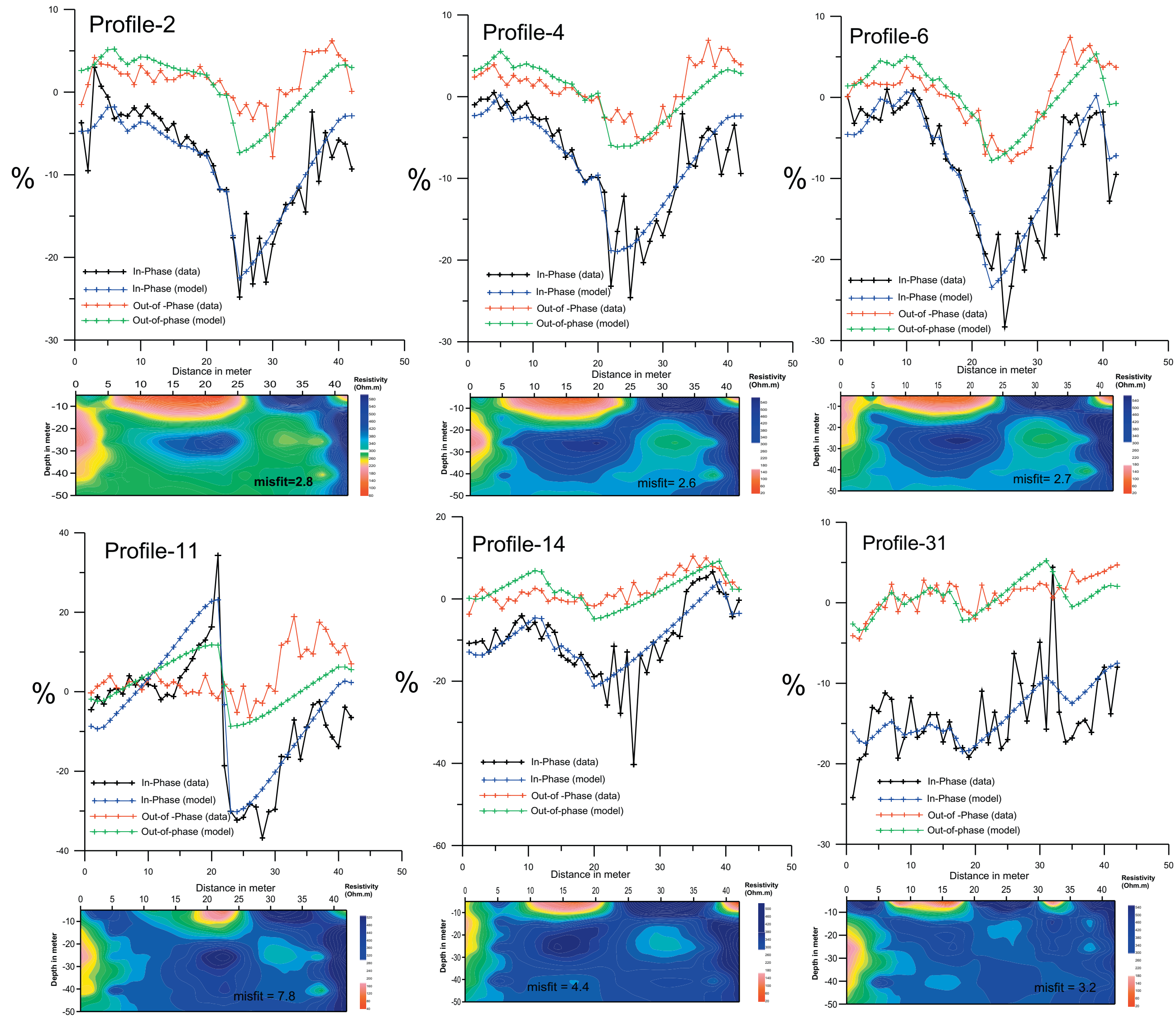


Fig. 7 Some examples of VLF-EM inversion using Inv2DVLF software.

Due to large number of profiles and difficulty of tracing the conductive and resistive zones vertically, they are collected in horizontal maps for definite levels (Fig. 8).

To check the reliability of the VLF-EM inversion and to know the environmental resistivity, five 2-D resistivity cross sections were measured in the area (Fig. 9).

Discussion

Examination of the quantitatively interpreted VLF-EM via Inv2DVLF software in Figs. 7 and 8 show that there are two subsurface high resistivity zones beneath Osiris temple, proposed place of Cleopatra and Anthony tombs. The first one appears at about 5 m depth as shown in the lift hand side of the map of 5 m depth in Fig. 8, as well as in cross sections of Fig. 7. The second one begins from 25 m depth as shown in the right hand side of the map of 25 m depth in Fig. 8, as well as in cross section of Fig. 7, either two resistive zones may be subsurface cavities or lithological facies change in the bed rock. So it is important in this part to study these two anomalies in details.

The shallow resistive zone

This shallow resistive zone appears in the inverted VLF-EM data at about 5 m depth, and supported by another obvious appearance in the 2-D resistivity cross sections (P20, P10, P18, and P5) at about 6 m depth. Matching between inverted VLF-EM data map at 5 m depth (Fig. 8), which showed the high resistivity zone in the lift hand side and Fraser filter map (Fig. 4a or Fig. 5) indicate disagreement, where Fraser filter map shows a conductive zone in the lift hand side. This may indicate that the shallow resistive zone reflects a lithological facies change in the bed rock. This result is supported by drilling, where three exploratory 2.5 inch boreholes were drilled in the study area (Fig. 1). Borehole B2, which penetrates the shallow resistive zone, is completely going through 15 m of limestone

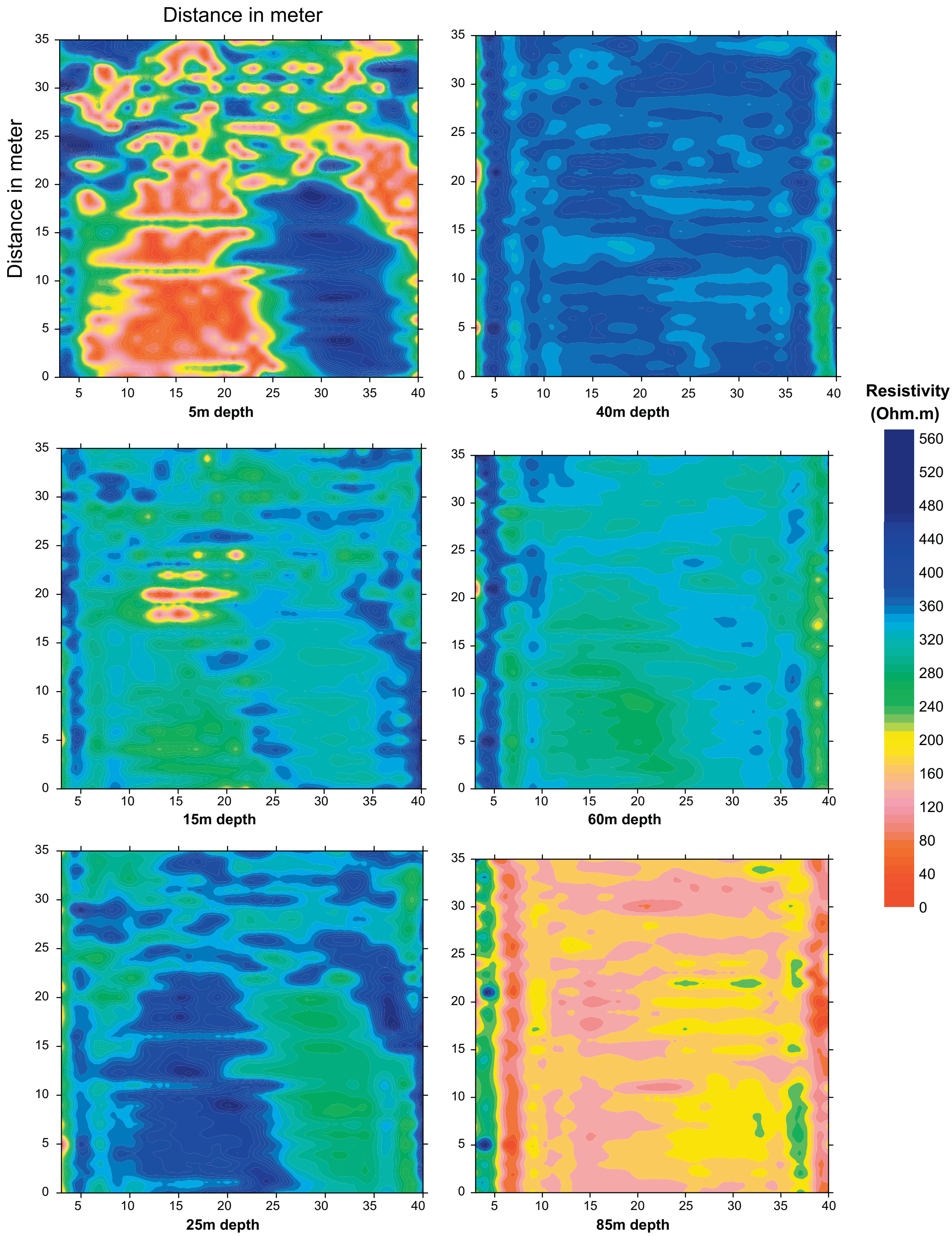


Fig. 8 Inversion of VLF-EM profiles in maps at different levels.

(Fig. 10). Accordingly, we can give much confidence to Fraser filter (Fig. 4) to outline the high resistive cavity zones, in the right side of the map, as showed before in the known case study of the cavity (Fig. 4).

The deep resistive zone

This high resistivity zone appears in the inverted VLF-EM cross sections (Fig. 7) at a depth from 25 to 45 m overlain

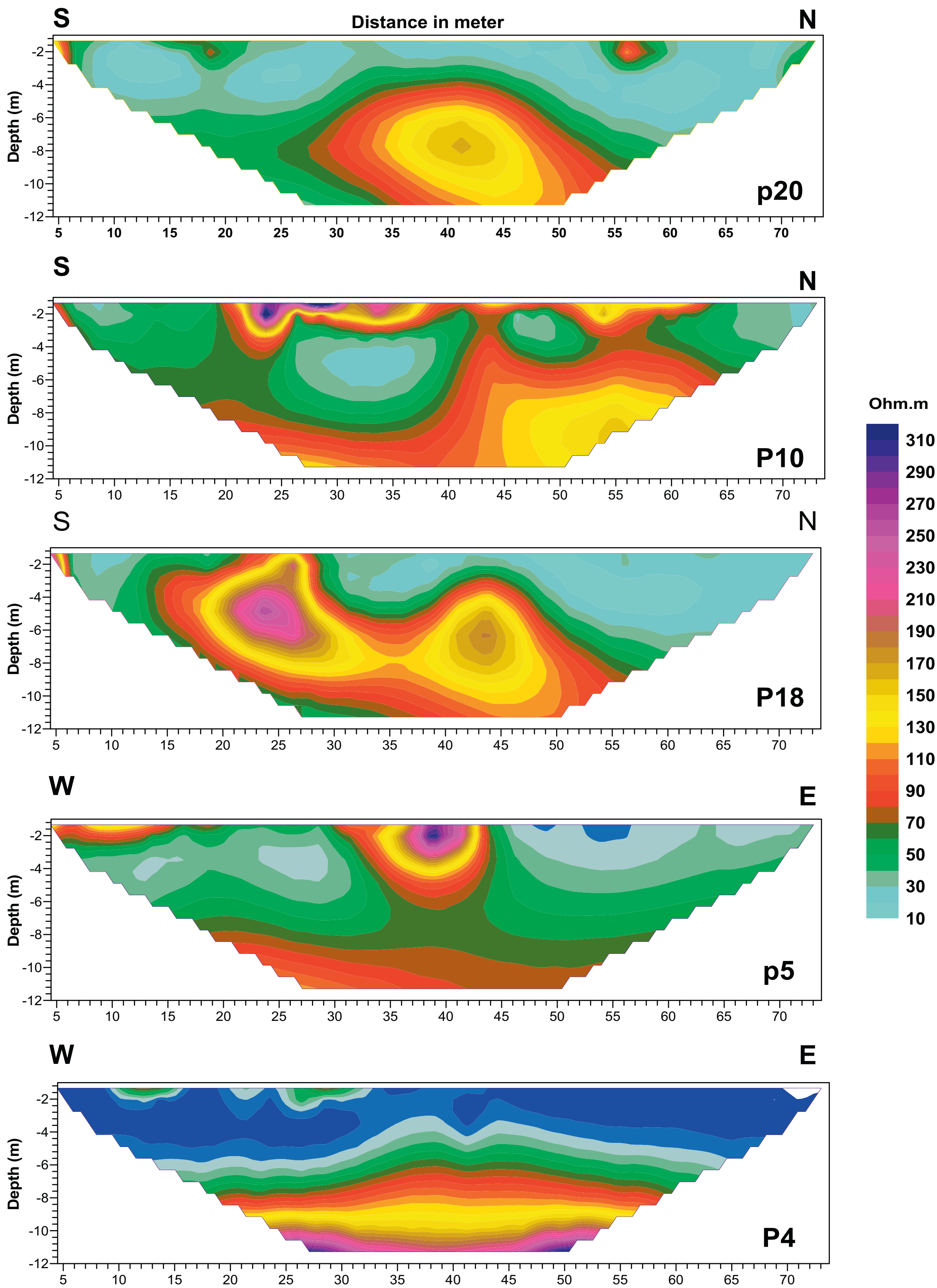


Fig. 9 2-D resistivity cross sections measured in Tap-Osiris Magna complex.

by a conductive layer. Unfortunately, neither resistivity cross sections nor boreholes did penetrate this depth. So, we cannot confirm this zone based on resistivity cross sections or boreholes. Meanwhile, this zone obviously appears in the Fraser filter (Fig. 4a or Fig. 5) to the right hand side of the map. Matching between Fraser filter map and inverted VLF-EM data map at 25 m (Fig. 8) showed a complete agreement. This may indicate a cavity zone in this area at a depth between 25 and 45 m. Forward modeling of VLF-EM data is proposed to support this hypothesis (Fig. 11).

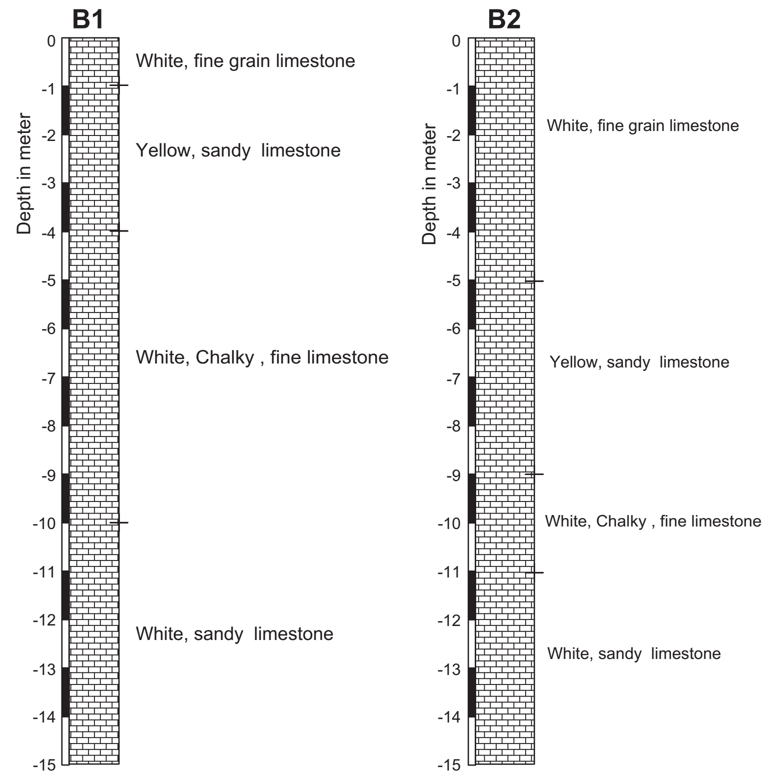


Fig. 10 Lithologic logs of borehole B1 and B2.

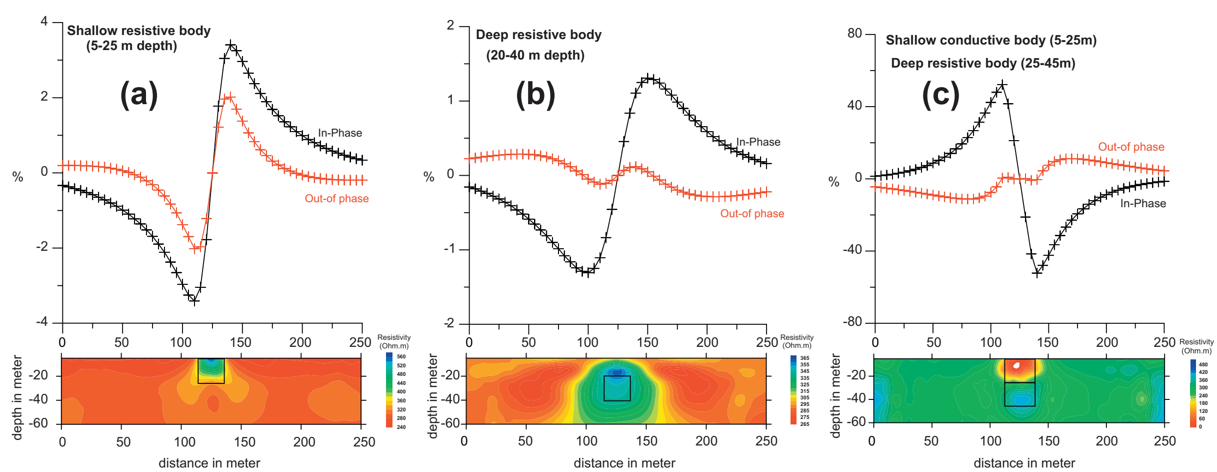


Fig. 11 Forward modeling for a hypothetical resistive body at 25 and 5 m depth.

As shown in Fig. 11, a hypothetical resistive body of 10.000 Ω m is proposed as a cavity zone. The dimensions of this resistive body are 20 m × 20 m. It is located from 115 to 135 m in *X*-direction, whereas in *Z*-direction, it is located between −5 and −25 m in case (A), and from −20 to −40 m in case (B) and from −25 to −45 m in case (C). Case (C) includes another conductive body with a hypothetical resistivity of 10 Ω m (deduced from the resistivity cross sections). It has the same dimensions, and directly overlain the resistive body. The environmental resistivity around resistive and conductive bodies is proposed as 300 Ω m. Forward modeling is processed using Inv2DVLF-forward modeling software (Monteiro Santos et al., 2006). The resulted synthetic data in the form of In-phase and Out of phase in both shallow and deep cases are illustrated in Fig. 11. The synthetic data is inverted again using the inversion part of the software to give the resistivity cross sections, which reflect a response that fits the synthetic VLF-EM data within the limits of data errors.

Comparing between the forward model and inverted resistivity cross section of the proposed deep resistive body overlain by a shallow conductive body (Fig. 11c), with the inversion of measured VLF-EM data in Fig. 7, shows a good agreement in locating the resistive and conductive zones in both. As well as the synthetic in-phase data in Fig. 11c have approximately the same trend of the measured and modeled VLF-EM data of profiles 4, 6, and 11 (Fig. 7). Whereas the inversion results of cases (A) and (B) are deviating from the inversion results of measured VLF-EM data.

Conclusion

Discovery of the tomb of Cleopatra and Anthony should be the most important archeological event in 21st century. Our attempt in this paper is made to discover this very important tomb by using geophysical methods, in particularly VLF-EM and resistivity imaging. Archeologists believe that the tomb of Cleopatra and Anthony is found under the Osiris temple inside Tap-Osiris Magna complex at a depth from 20 to 30 m. Recent excavations in the last 3 years supported this hypothesis. In this study VLF-EM data are collected above known tunnel, 5 m depth and in Osiris temple, which is unknown case. Five 2-D resistivity cross sections were measured using Wenner array in order to image the subsurface resistivity variations. VLF-EM data are processed qualitatively using Fraser filter (Fraser, 1969) to outline the subsurface conductive and resistive zones for known and unknown cases. VLF-EM profiles are inverted to their corresponding resistivity cross sections within the data limits. Inverted resistivity cross sections, also in the form of maps at different levels, are compared with the results of Fraser filter, 2-D resistivity imaging, and boreholes. Results of VLF-EM inversion and 2-D resistivity imaging showed a high resistivity zone at about 5 m depth, which could be a cavity zone. This hypothesis has denied by the results of Fraser filter and drilling in this zone. Another high resistivity zone appears in a depth from 25 to 45 m in the inverted resistivity cross sections of the VLF-EM profiles. This result is supported by Fraser filter. It shows a resistive zone in the same location as appeared in the known tunnel case. Forward modeling also support this result of the proposed cavity zone in the same depth with a proposed resistivity of 10.000 Ω m.

Accordingly, the present study expects a presence of a cavity zone from 25 to 45 m depth in the southwestern zone of Osiris temple; in particular this depth has not been reached by drilling and agrees well with the archeological expectations. We expect that this proposed tomb is accessed by a subsurface tunnel opening outside the Tap-Osiris Magna complex. We hope the site may be excavated in the future based on these geophysical results.

Acknowledgment

The main author is indebted to the Fundação para a Ciência e Tecnologia (Portugal) for his support through the post-doctor fellowship (SFRH/BPD/29971/2006). This work was partly developed in the scope of the scientific cooperation agreement between the CGUL and the NRIAG.

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