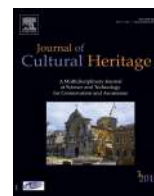




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Original article

Geophysical anomalies detected by electrical resistivity tomography in the area surrounding Tutankhamun's tomb

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ABSTRACT

Electrical resistivity tomography (ERT) of the area surrounding Tutankhamun's tomb (KV62) in the Valley of the Kings (Luxor, Egypt) reveals the presence of two anomalies located a few meters from Tutankhamun's funerary chamber. The strategy for ERT data acquisition and the adopted methods for data analysis are discussed in detail in this article, together with the possible archaeological significance of the detected anomalies.

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1. Introduction

The Valley of the Kings (VOK) in Luxor, Egypt, arguably the most important necropolis of Ancient Egypt, has always captured the attention and the imagination of Egyptologists and scholars as well as the general public. Most famous of all is the royal tomb of the golden young king Tutankhamun (code name KV62), who ruled Egypt from 1333 to 1323 B.C. by the end of the 18th New Kingdom Dynasty, discovered with a nearly intact funerary treasure by Howard Carter in 1922 [1]. In 2015, the Egyptologist Nicholas Reeves proposed a theory [2] according to which Tutankhamun's tomb may be part of a larger tomb belonging to the Queen Neferiti. Reeves' hypothesis was based on a close examination of high resolution 3D laser scan photos taken by the Factum Arte organisation to create a replica of KV62 [3]. To test this theory, a ground penetrating radar (GPR) scan from the inside of KV62 was authorized by the Egyptian Ministry of Antiquities (MA) and performed by Watanabe in November 2015. This preliminary GPR scan seemed to confirm Reeves' hypothesis. The finding was called "the discovery of the century" and was reported by news media around the world [4]. However, a second GPR scan performed in 2016 by a

National Geographic team [5] could not confirm the initial finding by Watanabe. Therefore, a third, hopefully conclusive GPR scan from the inside of KV62 was performed by our team in February 2018 and the collected data are still being analyzed.

Meanwhile, in 2016, the MA assigned to our team a wide-ranging project entitled "The Complete Geophysical Survey of the Valley of the Kings". According to this project, geophysical investigations mapping the entire VOK are carried out, although limited to outdoor measurements (i.e. excluding, for the time being, direct measurements from the inside of the VOK tombs). A report of the geophysical work performed during the first year of activity (2016–2017) within the framework of this project is presented in Ref. [6]. Our survey included electrical resistivity tomography (ERT) of the area surrounding KV62, which can be viewed as preparatory and complementary to the third GPR scan from the inside of KV62. This ERT survey revealed the presence of two intriguing geophysical anomalies located a few meters from Tutankhamun's funerary chamber. A detailed discussion on the ERT data acquisition and analysis and the possible nature of these anomalies is at the focus of the present article.

Geo-electrical methods have been widely used in archaeological prospection in different environments; in particular 2D and 3D ERT has been adopted since the end of the last century also in combination with other geophysical techniques [7–10]. As for any other geophysical method, the quality of the results depends on the contrast between the physical property of the target searched for and

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its hosting environment. Then, when searching for tombs, or other structures of archaeological significance, understanding the VOK geological environment is essential.

The area surrounding KV62 that we have investigated is located in the central portion of the eastern branch of the VOK. It comprises a sector of the valley floor, actually corresponding to the main tourist path between the rest house and the entrance to the tomb of Rameses V and VI (KV9) and Tutankhamun tomb's (KV62), together with the rocky hill where the two tombs are located and including part of the canyon leading to the Merenptah tomb (KV8).

Here, the subsoil is expected to be a combination of natural and anthropic materials deposited through the years, i.e., floods in the central valley and excavations in the area. Particularly, after a superficial, about 2 m thick, flood layer of fine grained silt material, limestone chipping clasts, usually 2–3 cm in size, in a limestone dust matrix are found in the layers reworked by excavations [11]. These anthropic reworked materials overlay a natural flood layer constituted by immature, poorly sorted, fluvial breccia with clasts from 0.05 to 0.75 m across, matrix supported, exhibiting no apparent structures [12]. The natural limestone bedrock depth below this layer is expected to be 5–6 m from the valley floor. Conversely, the hill above the KV62 tomb is constituted both by limestone of the Thebes formation and by natural aerated debris from the valley sides. Further details on the geology and on the properties of the materials can be found for example in Refs. [13–17] and other references cited therein.

This paper is organized as follows. Section 2 indicates the research aim. Section 3 details the strategy for ERT data acquisition in the area surrounding KV62, taking into account logistical constraints. Section 4 presents the model adopted for the analysis of ERT data. Section 5 presents our main findings and discusses their possible archaeological significance. Conclusions are presented in Section 6.

2. Research aim

The aim of the research reported in this article was to carry out preliminary geophysical prospections in the area surrounding Tutankhamun's tomb in the Valley of the Kings (Luxor, Egypt), using electrical resistivity tomographic (ERT) methods. This ERT investigation, carried out in May 2017, was considered as preparatory to ground penetrating radar (GPR) surveys that were later performed by our Team from the inside of Tutankhamun's tomb in February 2018 (and whose results are yet to be published). The main objective was to test a hypothesis, put forward by Egyptologist Nicholas Reeves, that Tutankhamun's tomb could be part of a larger tomb, possibly belonging to Queen Nefertiti.

As a by-product of our research, we tested the applicability and usefulness of ERT methods for a complete geophysical mapping of the Valley of the Kings – a project carried out under the auspices of the Egyptian Ministry of Antiquities. Indeed, ERT methods are more flexible and easier to implement than GPR surveys in the uneven and hilly areas of King's Valley. Our main ambition was to demonstrate the importance of a multidisciplinary approach, integrating geophysics, geology and archaeology, and the impact of new technologies on Egyptological research.

3. Data acquisition

Two extensive 3D ERT campaigns were conducted above and near the hill hosting the Tutankhamun KV62 tomb, the first in February–March and the second in May 2017. The positions of the acquired ERT datasets are illustrated in Fig. 1, where the coloured dots represent the electrodes placed into the ground. For the acquisitions we used a 72 channels resistivity-meter (IRIS SyscalPro Switch). These measurements have been divided into 9 datasets (see Fig. 1): each one of them identified by a progressive number,

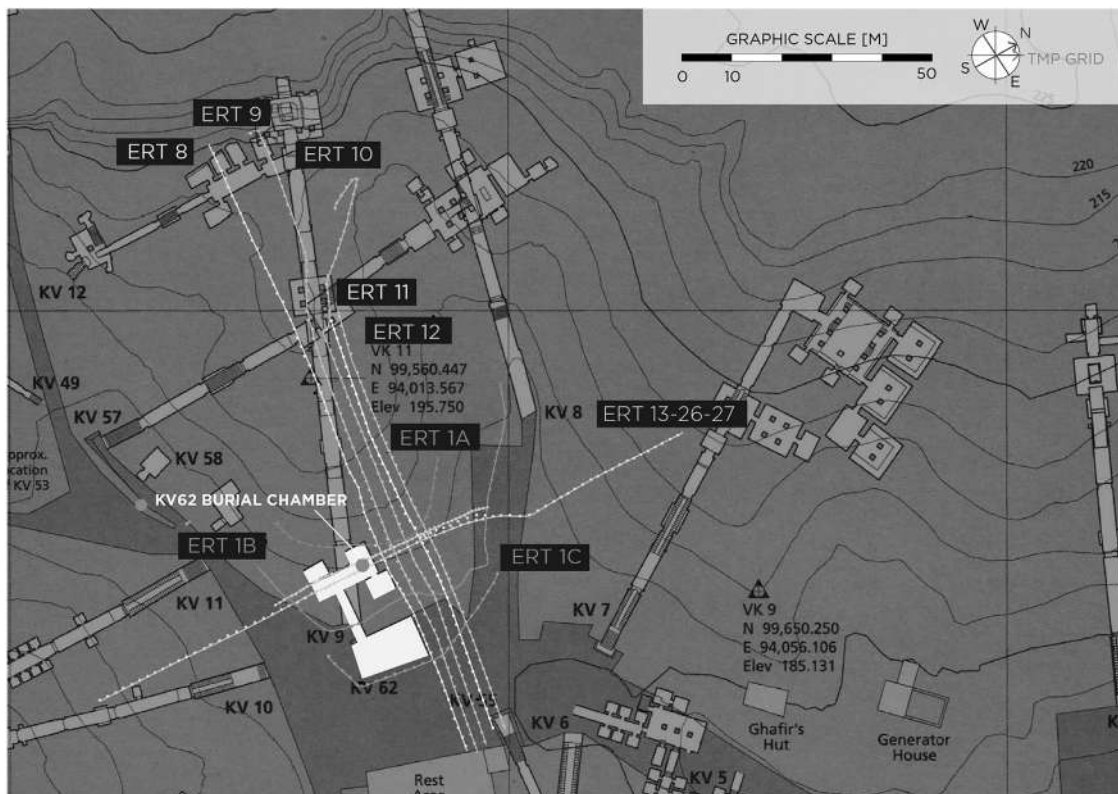


Fig. 1. Detail of the electrical resistivity tomography (ERT) surveys surrounding KV62.



Fig. 2. Data acquisition of the electrical resistivity tomography (ERT) lines 8–11.

Table 1
Details of the acquired ERT datasets.

ERT code	Geometry	Orientation	#electrodes	Spacing [m]	Survey date
ERT 1	2 ERT loops	–	96	2	02/26/2017
ERT 8	1 ERT line	E-W	70	2	05/17–18/2017
ERT 9	1 ERT line	E-W	72	2	05/18/2017
ERT 10	1 ERT line	E-W	66	2	05/18/2017
ERT 11	1 ERT line	E-W	48	2	05/19/2017
ERT 12	1 ERT line	E-W	48	2	05/19/2017
ERT 13	1 ERT line	N-S	72	2	05/19/2017
ERT 26	1 ERT line	N-S	48	1	05/23/2017
ERT 27	1 ERT line	N-S	48	1	05/23/2017

ERT: electrical resistivity tomography; E: east; W: west; N: north; S: south.

which increases with respect to the chronology of the acquisitions. The location of the electrodes is displayed coherently with the Theban Mapping Project (TMP) coordinate system [18]. In Fig. 2 photos from the data acquisition in the KV62 area are also shown.

The electrical resistivity distribution of the Valley of the Kings is typically 3D, both for the presence of tombs and corridors running on different directions and for the natural lateral heterogeneity in the electrical properties of rocks, related to the complex lithology of the site. Also, a marked 3D topography is present, especially around the KV62 area, which must be properly considered for a reliable modelling of the geophysical surveys.

Taking these geological features into account, we performed the ERT acquisitions mainly with linear or quasi-linear spreads of electrodes (see Fig. 1 and Table 1 for acquisition details). This choice has been driven by the following considerations: the main archaeological targets in the area are located at relevant depths below ground level (e.g., the roof of KV62 is around 13 meters below ground level, b.g.l.). The need to reach these depths while maintaining a good vertical resolution led us to prefer straight-line geometries. Moreover, we intended to maintain a simplified approach to acquisition, in order to have a tight control on data quality. The VOK site is very challenging in terms of contact resistances at electrodes, which often are in the order of hundreds of kOhm: this occurs particularly in the areas occupied by debris, where even large amounts of salt water around electrodes was not effective in reducing contact resistances. So, we could expect noisy datasets. Data quality control is more critical for 3D quadrupoles, where we lack the possibility of displaying pseudo-sections for evidencing data outliers and the

occurrence of negative apparent resistivity values may also muddle data interpretation.

Nevertheless, the use of linear or quasi-linear spreads did not limit the building of an accurate 3D resistivity model with a 3D approach to data processing. Indeed, the 5 parallel electrodes lines performed (i.e. ERT8 to 12) are around 2 meters spaced from each other. This allowed to achieve a good 3D sensitivity, even though this choice limited the survey to a relatively small sector of the hill.

Different issues guided our choice in defining the spatial location of the profiles on the area surrounding KV62. First, we intended to check the imaging capabilities of ERT on a known structure: the Tutankhamun's tomb. We designed with this aim the “control” line ERT13 to be located exactly along the main axis of the KV62 ante-chamber and burial chamber. Our second goal was to get a detailed imaging of the subsoil volumes close to the North wall of Tutankhamun's burial chamber. We designed ERT8 to 12 lines with this aim, to verify the possible northing extension of the burial chamber. With lines ERT26 and ERT27, both running close and parallel to ERT13, we also tried to check possible spatial resolution improvements by making use of a shorter spacing of the electrodes (1 meter).

Finally, the ERT1 dataset, included in this discussion, is the very first acquisition that we performed in the Valley and is the only three-dimensional arrangement for electrodes that we adopted. This acquisition is made by three branches of 24, 48 and 24 electrodes, respectively, acquired in two steps. Quadrupoles sequence generation for such geometry included both “common cable” quadrupoles (transmitting and receiving electrodes belonging to the same cable), and “cross cable” quadrupoles (all possible combinations where transmitting and receiving dipoles are not on the same cable, see Ref. [19]). Although characterized by a lower depth of investigation, this first test was valuable for a better understanding of the complexity of the site in terms of acquisition and data processing. Consequently, it also allowed us to improve the design of the following surveys. Data obtained from this first test were included in the processing and in the 3D sensitivity study of the final model.

For all the data set acquisitions, dipole-dipole, reciprocal Schlumberger and pole-dipole arrays have been used. Dipole-dipole measurements have been chosen for their good horizontal sensitivity that could help in laterally locating anomalies, in spite of their being highly sensitive to noise. Reciprocal Schlumberger arrays were also acquired to add sets of measurements with

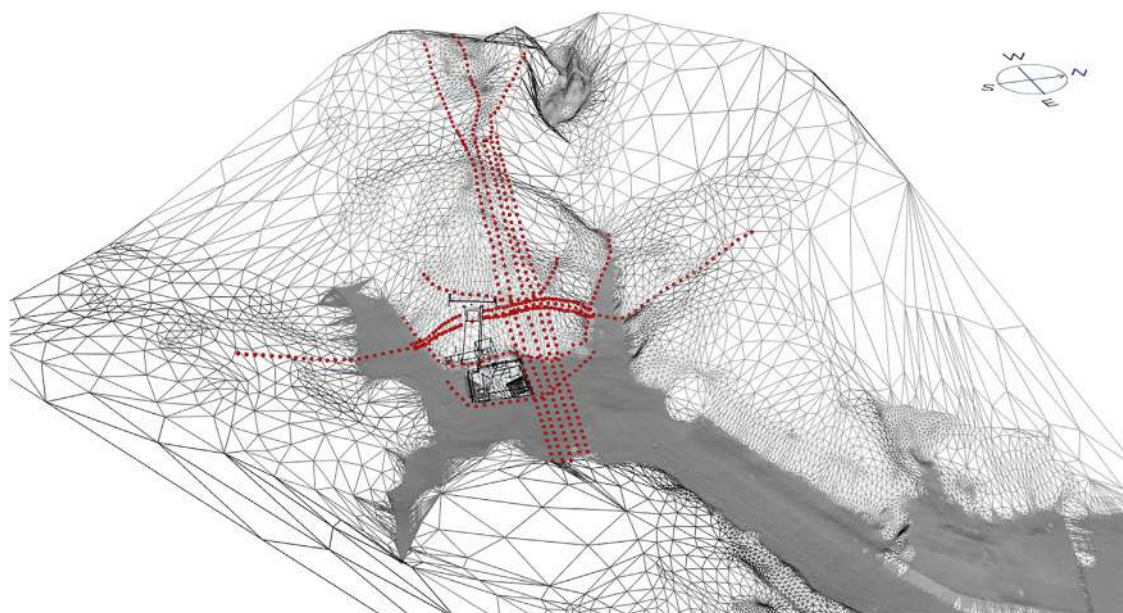


Fig. 3. Topographic survey and electrical resistivity tomography (ERT) lines positions in KV62 area.

higher signal-to-noise ratio. The small internal electrodes separation (“reciprocal” scheme) was employed to reduce the contact resistances at the current electrodes, to inject higher currents in the ground and to enhance the signal at receivers. Finally, we also made use of pole-dipole arrays to increase the depth of investigation of the whole survey. A complete run for the three different configurations on a 72 electrodes profile counted around 8000 measurements, and the full acquisition took around 40–45 minutes. On the whole, a total amount of 568 electrodes was used to collect about 35,000 ERT measurements.

A robotic total station was used to determine the exact positions of electrodes and to survey the topography of the study area (Fig. 3). All the measurements were referred to the topographic grid established by the Theban Mapping Project [18]. The local reference system of the electrodes was framed with the method of intersections between known coordinates points, hooking up the benchmarks VK11 (on the hill above Tutankhamun tomb), VK9 (near the KV7), VK2 (on the top of the hill above the Rest-House) and the VK3 (on the hill near the KV3 and KV4). Subsequently, to follow the change of “base-station” and to create a new topographic polygonal frame, benchmarks (one-time) were taken to position the total station even in areas not visible from the other topographic bases/stations. After having framed and linked the local system (TMP) with our topographic system, a plano-altimetric survey of the electrodes has been carried out in order to create a digital terrain model (DTM) to position and model the acquired geophysical data.

4. Data processing and inversion

4.1. Data quality

One of the most challenging tasks of the acquisition was related to the high contact resistances at electrodes. The average value of injected currents was around 5–6 mA, with a minimum of 0.1 mA in the debris areas and peaks of a few tens of mA on more conductive zones of the site. Anyway, due to the high background resistivity (around 5000 Ohm m), the measured potentials at the receivers could be considered satisfactory, with average values of around 90 mV. In ERT8 to ERT12 datasets the higher contact resistances

occurred at the electrodes located on the western area of the KV62 hill, the part covered by debris.

We removed highly noisy data from each acquisition adopting the following filtering criteria:

- measurements with an instrumental standard deviation greater than 5%;
- quadrupoles belonging to badly ground-coupled electrodes;
- quadrupoles with transmitted currents lower than 0.1 mA;
- quadrupoles with potential's difference at the receivers lower than 0.1 mV;
- negative apparent resistivity values;
- apparent resistivity values higher than 50,000 Ohm m.

Lastly, the outliers identified by the visual analysis of the apparent resistivity pseudo-sections were removed.

The final pseudo-sections for some example lines are reported in Fig. 4. The quality of the data inside the volumes of interest is overall good. The good repeatability of the measurements on adjacent lines makes us confident on the accuracy of the measured apparent resistivity values: this is evident in Fig. 4, in which the pseudo-plots of the ERT8, ERT9 and ERT10 are compared. In the same figure, the sparser points in the pseudo-plots due to the higher contact resistance in the western area can be also noted.

4.2. Sensitivity

A useful tool to obtain an estimate of the reliability of the ERT image after the inversion is the so-called sensitivity map. This map shows, given the electrode array, how much a resistivity change in a block of the model affects the potential readings. The higher the sensitivity, the more reliable is the final resistivity value of the block.

The sensitivity can be computed as the square roots of the values of the diagonal of the $J^T * J$ matrix, where J is the Jacobian (i.e. the matrix of the derivatives of the data with respect to the resistivity of each model block; T indicates transpose). In the following Figs. 5 and 6, a sensitivity analysis of the global set of measurements for a homogeneous resistivity model of the site is shown. Sensitivity values are normalized with respect to their maximum values; therefore, the highest sensitivity block has a ‘score’ of 1. Note that

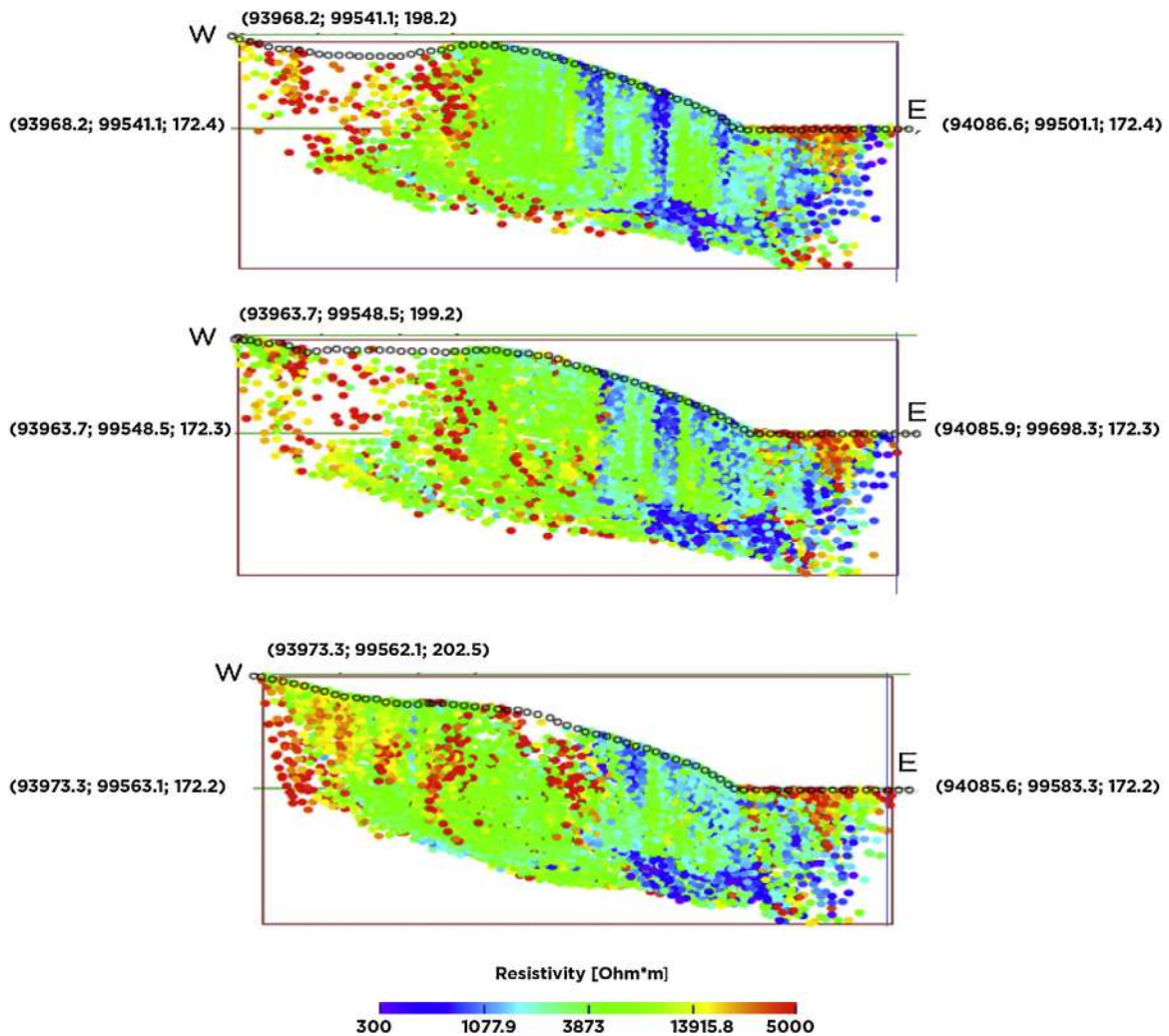


Fig. 4. Apparent resistivity pseudo-plots for electrical resistivity tomography 8 (ERT8), ERT9 and ERT10 after noisy data filtering (from top to bottom).

the global sensitivity, being the quadratic sum of the individual quadrupole sensitivities, is very high for the blocks immediately adjacent to the electrodes, which are involved in many measurements. Blocks with sensitivities above a 0.01 threshold (1% of the maximum) have to be considered as significantly influenced by the measurements. The colour-scale of Figs. 5 and 6 is logarithmic and the values above 0.01 are saturated with red colour for graphically grouping the model volumes with a good resolution. The analysis considers only the quadrupoles used for data processing after noisy data removals.

The north-south section along line ERT13 (top of Fig. 6) shows a good sensitivity for the subsoil volumes containing the KV62 tomb. A small decrease with depth of the sensitivity in the southern part of the KV62 is related to the presence of the main entrance of the KV9, where we could not place electrodes. The east-west section along profile ERT10 (bottom of Fig. 6) reveals a lower sensitivity at depth in the topmost part of the hill where, due to the debris, a larger percentage of measurements was removed from the dataset. Some local decreases are also due to few not-working electrodes for bad ground coupling.

4.3. Data inversion

Data inversion was performed by combining the different acquisitions and generating a single 3D model of the subsoil. Prior to the

final inversion, several preliminary tests were carried out on the individual lines and on lines combinations, to assess the quality of the data and obtain useful information for the final inversion step. Inversion tests have been carried out also with and without the contribution of the measurements of lines 26 and 27 at 1 m spacing. No particular improvement in the final model has been noted by including these last data in the inversion. While the reduced step is not decisive in the discrimination of deep structures, it could be useful for the identification of small surface structures, such as the entry to the tombs.

For the final inversion, the following configuration was used:

- 5000 Ohm m homogeneous starting model;
- standard deviation noise estimate at 3%;
- 1 m × 1 m × 1 m mesh size.

The full three-dimensional inversion of apparent resistivities was performed using ERTLab64™ 3D inversion software, developed by Multi-Phase Technologies and Geostudi Astier, which uses a finite elements (FEM) approach to model the subsoil by adopting mesh of hexahedrons to correctly incorporate terrain topography. The inversion procedure is based on a least squares smoothness constrained approach [20]. Throughout the inversion iterations, the effect of non-Gaussian noise is appropriately managed using a robust data weighting algorithm [20–22].

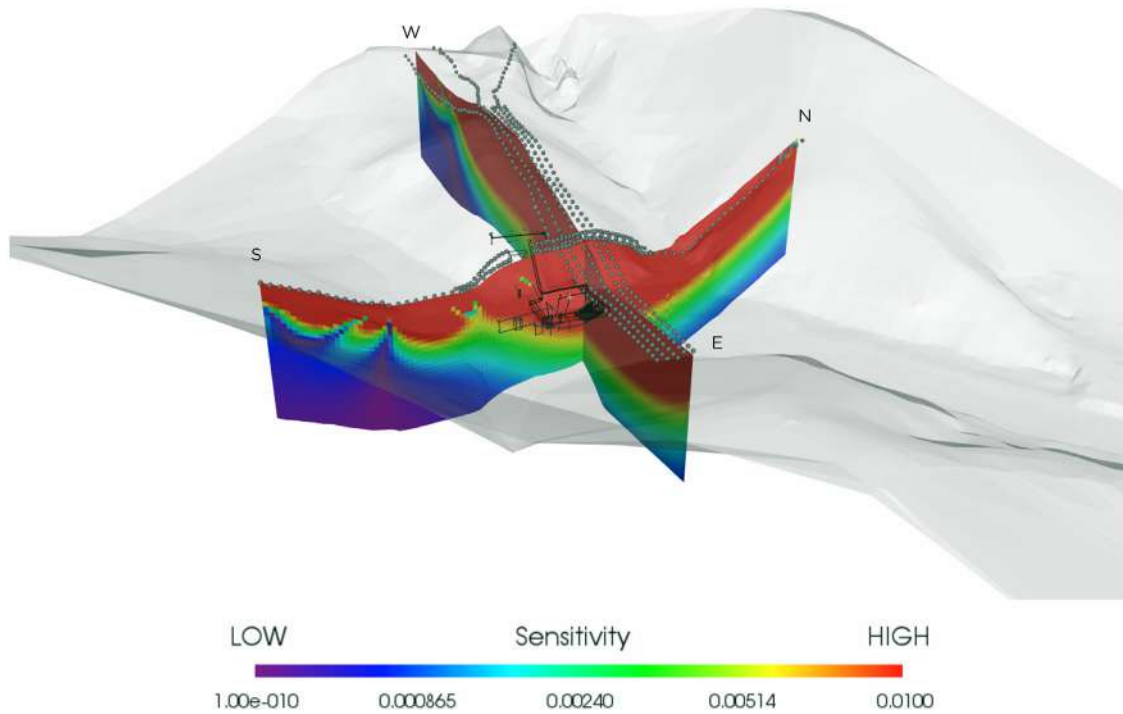


Fig. 5. Sensitivity analysis for the full set of quadrupoles on the KV62 area.

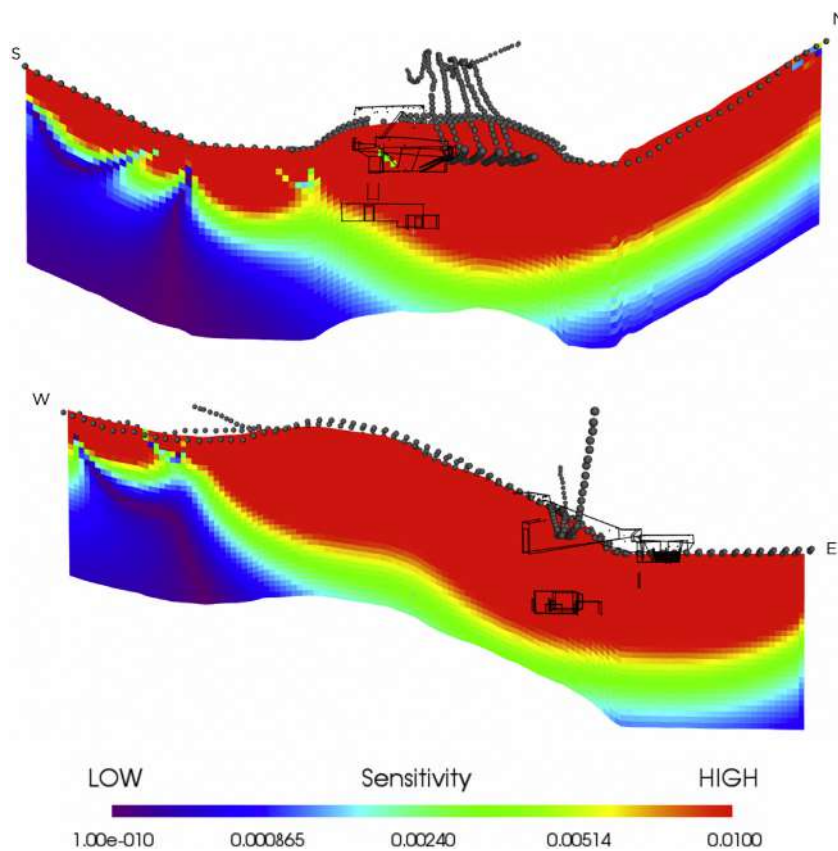


Fig. 6. Sensitivity maps for the full set of quadrupoles on the KV62 area. Top: section below electrical resistivity tomography 13 (ERT13). Bottom: section below ERT10.

The inversion progress is summarized in Fig. 7. Several iterations were necessary to achieve the convergence of the inversion process starting from a homogeneous model. This is typical in situations where high contrasts in resistivity are expected in the subsoil

(from few hundred to tens of thousands Ohm m). The noise control through the standard deviation reweighting algorithm on the outliers and the remodulation of the roughness factor were crucial in ensuring a final model robust enough against possible artefacts.

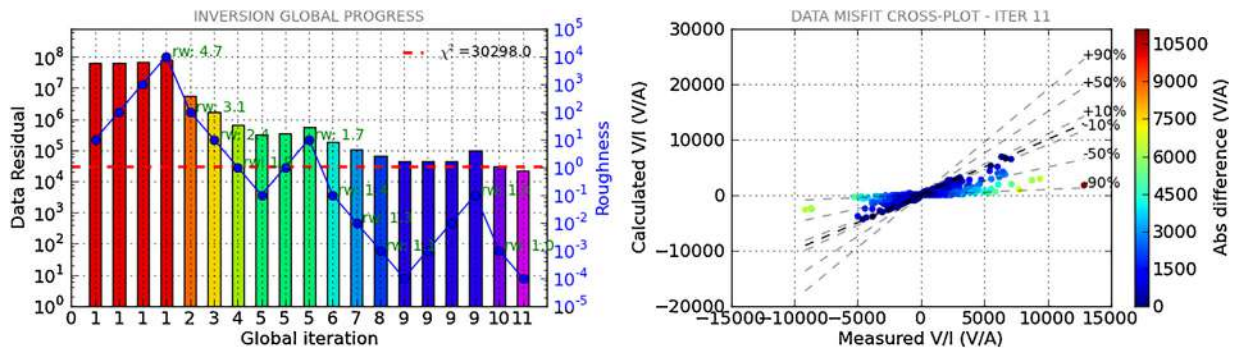


Fig. 7. Inversion progress. Left: data residual and roughness at each iteration trial. Right: cross-plot of measured vs. calculated data.

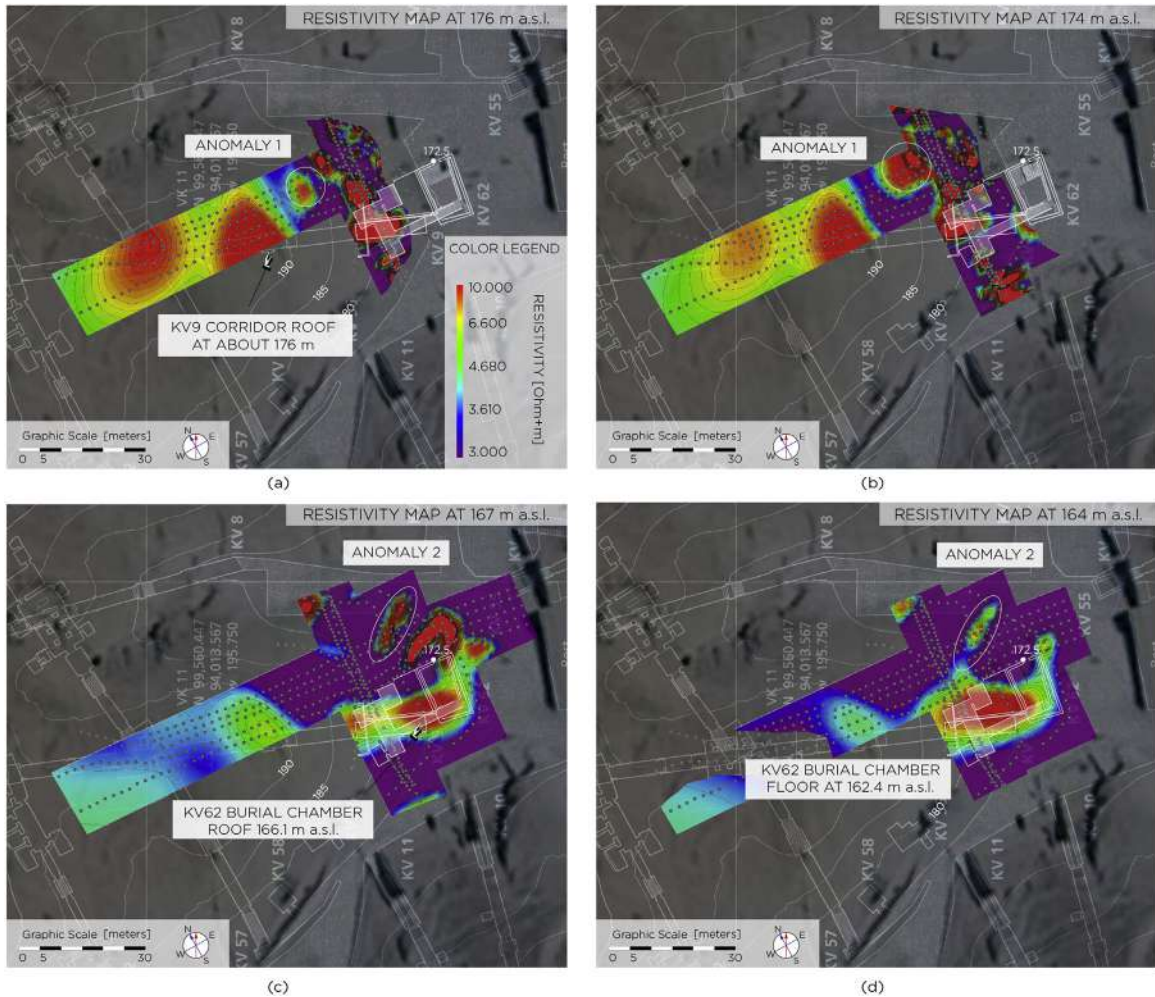


Fig. 8. Resistivity distribution at four elevation levels (a to d) between the KV9 entrance roof (176 m a.s.l.) and the KV62 burial chamber floor (162.4 m a.s.l.).

5. Results and possible archaeological significance

Results from ERT measurements performed around and over the Tutankhamun tomb are summarized in Figs. 8 and 9. Fig. 8 shows the resistivity distribution obtained at four elevation levels between the KV9 entrance roof (176 m above sea level, a.s.l.) and the KV62 burial chamber floor (162.4 m a.s.l.). Fig. 9 reports two example cross sections of the investigated 3D volume. A general high resistivity context, in agreement with the site lithology, emerges from data analysis. In the figures, the resistivity range is roughly between 3000 and 10,000 Ohm m, which have been selected as the cutoff values in the representation. High resistivity anomalies, with

values above 6000 Ohm m (yellow–red colors), may be associated either to voids within the bedrock or to shallow aerated debris. The limestone bedrock of the Thebes formation shows lower resistivity values (i.e. below 3500 Ohm m, purple–blue colors).

Some of the high resistivity anomalies are indeed due to well-known structures in the underground: depth slices at 176 m and 174 m a.s.l. (Fig. 8a–b) clearly show the effects induced on the data by the empty volume represented by the KV9 corridor; depth slices at 167 m and 164 m a.s.l. (Fig. 8c–d) intercept the void volume corresponding to the KV62 tomb, showing a large resistive anomaly that inscribes the perimeter defined by its external walls. The presence of these two tombs is also clearly visible in the ERT sections

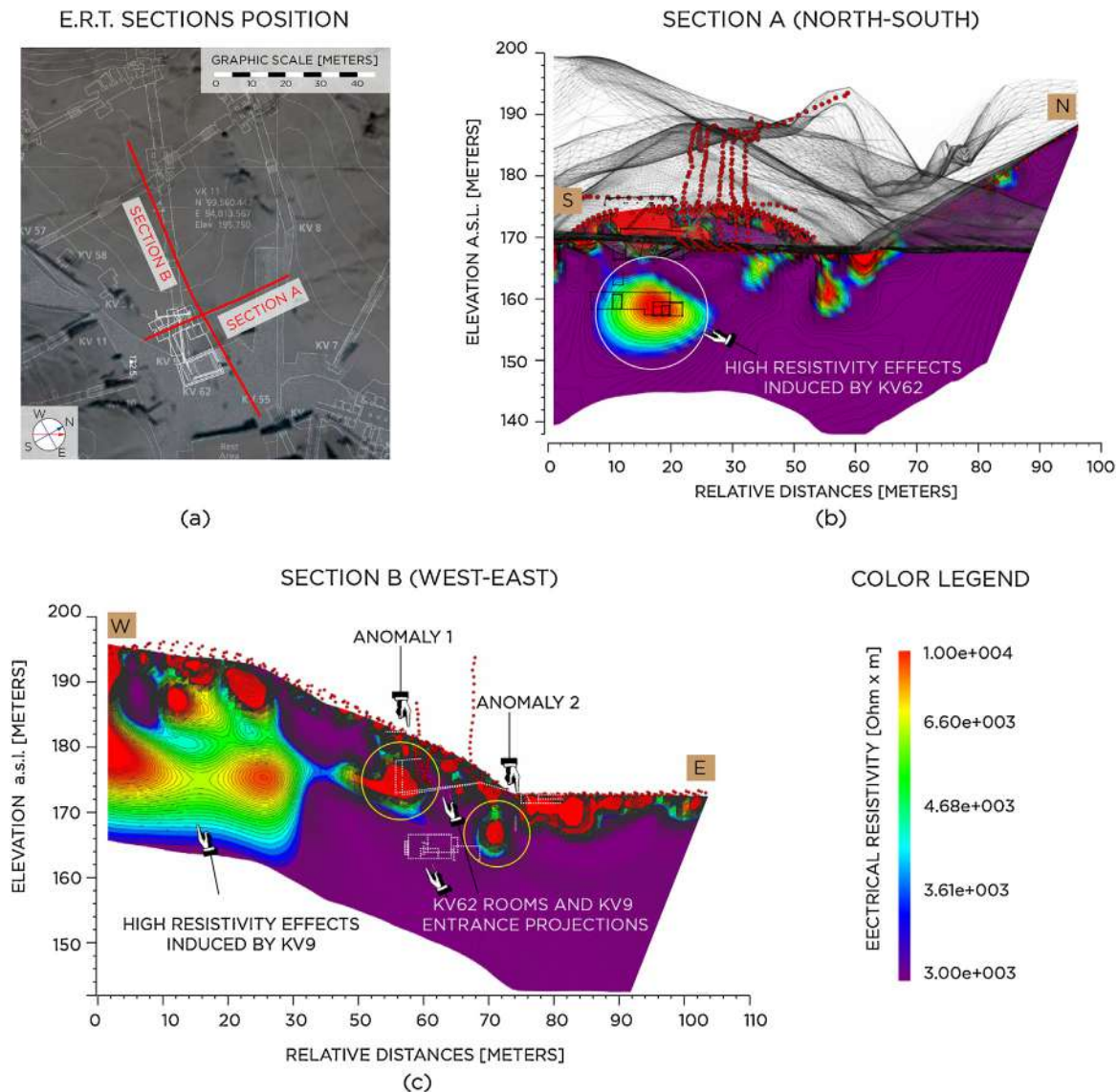


Fig. 9. a: map with the location of vertical electrical resistivity tomography (ERT) sections; b: NS ERT section; c: EW ERT section.

(Fig. 9). Particularly, in Fig. 9b, the anomaly caused by Tutankhamun tomb shows a peak of resistivity exactly centered on the KV62 burial chamber. The good correspondence of high resistivity values in the known location of these two structures provides confidence with respect to the quality of data and their interpretation.

Other shallow resistive anomalies located above the KV9 and KV62 entrances, covered by coarse grain sediments and debris, could be associated with recent human activity. High resistivity values are also detected under the flat area facing the external KV62 entrance (Fig. 9c) and are probably related with backfilling activities from past archaeological excavations.

Of more interest are two high resistivity anomalies evidenced in the maps and in the sections. They do not appear to be correlated with known underground cavities. The first, denoted by Anomaly 1 in Fig. 8a and b, defines a resistive body extending, at 174 m a.s.l., about 5 m in the NE-SW direction and about 8 m in the NW-SE direction. The centroid of this anomaly is roughly at about 6 m b.g.l. The second, denoted by Anomaly 2 in Fig. 8c and d, has the shape of an elongated ellipsoid roughly centered at depth of about 5 m below the valley floor. Its extension, at 167 m a.s.l., is about 15 m in the NE-SW direction and about 4 m in the NW-SE direction. ERT sections in Fig. 9b and c allow to further appreciating

the horizontal extensions and the vertical positions of these two anomalies.

Anomaly 1 is located at a horizontal distance of about 12 meters from the North wall of the KV62 funerary chamber (Fig. 8b). In the EW section shown in Fig. 9c, its elevation ranges between 170 m and 178 m a.s.l. Therefore, the lowest level of this anomaly is slightly above the elevation of the ceiling of KV62 (166 m a.s.l.), while its highest level is about 12 meters above it. Anomaly 2 is located under the flat area between the foot of the cliff and the modern-day KV62 entrance.

If these anomalies are of anthropic origin, their high resistivity may indicate void volumes, with potentially interesting implications. These anomalies are close to KV62, but do not appear to be directly connected with it. It is interesting to note that the centroid of the volume corresponding to Anomaly 1 appears to be located roughly along the same NS alignment of the antechamber and the funerary chamber of KV62 (see, in particular, Fig. 9c). The depth and size of Anomaly 1 appear consistent with a void having an extension comparable with the one of KV62.

Anomaly 2 is also particularly interesting. It is located North-East of the KV62 burial chamber, about 5 m below ground level, and it extends somewhat beyond the hill to the flat section between the

modern-day entrance of KV62 and the shade canopy. The interpretation of this Anomaly is at present rather dubious, as it is located in an area interested by previous archaeological excavations. We exclude at this stage that Anomaly 2 can be linked directly with KV62.

6. Conclusions

During the first semester 2017, we performed extensive ERT measurements in the area surrounding Tutankhamun's tomb (KV62) in the Valley of the Kings (Luxor, Egypt). The surveys were challenging due to the environmental and geological conditions of VOK: articulated topography, high contact electrode resistances due to aerated debris, complex underground resistivity distribution also due to several man-made structures. The adopted spatial distribution of electrodes, limited because of logistical constraints, nevertheless allowed a reliable reconstruction of a complete 3D resistivity model of the investigated area. Within this model, our investigation revealed the presence of two compact, high resistivity anomalies in the vicinity of KV62, in addition to the other well-known cavities (e.g. KV9 and KV62 itself). These two anomalies are particularly interesting in that they do not appear to be correlated with known underground cavities.

The first anomaly, denoted by Anomaly 1, lies below the hill where the tombs KV62 and KV9 have been carved. Given its location and depth below the ground level, it is unlikely that the area where Anomaly 1 is located was interested by recent excavations or recent human activities. Therefore, if anthropic, the origin of this Anomaly should be associated with Ancient Egypt. The anomaly's enhanced resistivity may indicate a void volume. Anomaly 1 does not appear to be directly connected with KV62.

The second anomaly, denoted by Anomaly 2, is also particularly interesting, although care is in order as it is located close to an area interested by previous archaeological excavations. We exclude at this stage that Anomaly 2 can be linked directly with KV62.

Thus, a definite conclusion about the origin of the detected anomalies cannot be established based solely on the present ERT measurements. Further ERT profiles could improve the data coverage around the detected anomalies and better constrain the interpretation of the reported findings. ERT data would also be valuable when compared and cross-correlated with GPR data taken from the inside of Tutankhamun's tomb and from the KV9 entrance floor.

Acknowledgements and dedication

We would like to dedicate our work to the lasting memory of Ayman Ibrahim, Director of the Valley of the King in Luxor, who passed away on 17 January 2018 while he was at work. We shall always be grateful to Ayman for facilitating our work, for his dedication, professionalism, good humor and friendship.

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References

- [1] H. Carter, A.C. Mace, *The Tomb of Tut*Ankh*amen*, Cassell and Company Ltd, London, 1923.
- [2] N. Reeves, *The Burial of Nefertiti? A publication of the Amarna Royal Tomb Project*, University of Arizona, Tucson, AZ, USA, 2015.
- [3] Factum Arte (2015) <http://www.highres.factum-arte.org/Tutankhamun/>, with additions, copyright © Factum Arte/Ministry of State for Antiquities and Heritage, Egypt.
- [4] El-Aref, Nevine (2015). *Discovery of the Century?* in *Al-Ahram Weekly* (Issue 1273, 3–9 November 2015); Michaelson R., Walker P. (2016). *Tutankhamun's secret? Experts hope new chambers could contain tomb of Nefertiti*, in *The Guardian*, 18 March 2016.
- [5] Hiebert, Fred (2016), private communication.
- [6] F. Porcelli, et al., *La Mappatura Geofisica Completa della Valle dei Re: Risultati preliminari del primo anno di attività (2016–2017) Ricerche Italiane e Scavi in Egitto*, Vol. VII, G. Capriotti Vittozzi, Italian Cultural Institute, Cairo, 2018, pp. 33–55 (ISBN 978-88-908752-4-3).
- [7] M.H. Loke, R.D. Barker, *Practical techniques for 3D resistivity surveys and data inversion*, *Geophys. Prospect.* 44 (1996) 499–523.
- [8] N.G. Papadopoulos, P. Tsourlos, G.N. Tsokas, A. Sarris, *Two-dimensional and three-dimensional resistivity imaging in archaeological site investigation*, *Archaeol. Prospect.* 13 (2006) 163–181.
- [9] E. Cardarelli, F. Fischanger, S. Piro, *Integrated geophysical survey to detect buried structures for archaeological prospecting. A case-history at Sabine Necropolis (Rome, Italy)*, *Near Surf. Geophys.* 6 (1) (2008) 15–20.
- [10] A. Arato, S. Piro, L. Sambuelli, *3D inversion of ERT data on an archaeological site using GPR reflection and 3D inverted magnetic data as a priori information*, *Near Surf. Geophys.* 13 (2015) 545–556.
- [11] S.W. Cross, *The Hydrology of the Valley of the Kings*, *J. Egyptian Archaeol.* 94 (2008) 303–310.
- [12] S.W. Cross, *The workmen's huts and stratigraphy in the Valley of the Kings*, *J. Egyptian Archaeol.* 100 (2014) 135–152.
- [13] A.J. Wust Raphael, J. McLane, *Rock deterioration in the royal tomb of Seti I in the Valley of the Kings, Luxor, Egypt*, *Eng. Geol.* 58 (2) (2000) 163–190.
- [14] M.-Y. Yi, J.-H. Kim, Y. Song, S.-J. Cho, S.-H. Chung, J.H. Suh, *Three-dimensional imaging of subsurface structures using resistivity data*, *Geophys. Prospect.* 49 (2001) 483–497.
- [15] M.P. Aubry, W.A. Berggren, C. Dupuis, H. Ghaly, D. Ward, C. King, R.W.O'B. Knox, K. Ouda, M. Youssef, W.F. Galal, *Pharaonic necrostratigraphy: a review of geological and archaeological studies in the Theban Necropolis, Luxor, West Bank, Egypt*, *Terra Nova* 21 (2009) 237–256.
- [16] C. Dupuis, M.P. Aubry, C. King, R.W.O'B. Knox, W.A. Berggren, M. Youssef, W.F. Galal, M. Roche, *Genesis and geometry of tilted blocks in the Theban Hills, near Luxor (Upper Egypt)*, *J. Afr. Earth Sci.* 61 (3) (2011) 245–267.
- [17] C. King, C. Dupuis, M. Aubry, W.A. Berggren, R.O'B. Knox, W.F. Galal, J.M. Baele, *Anatomy of a mountain: the Thebes Limestone Formation (Lower Eocene) at Gebel Gurnah, Luxor, Nile Valley, Upper Egypt*, *J. Afr. Earth Sci.* 136 (2017) 61–108.
- [18] K. Weeks, *The Atlas of The Valley of the Kings*, Theban Mapping Project, American University in Cairo Press, 2003.
- [19] E. Santarato, G. Ranieri, M. Occhi, G. Morelli, F. Fischanger, D. Gualerzi, *Three-dimensional electrical resistivity tomography to control the injection of expanding resins for the treatment and stabilization of foundation soils*, *Eng. Geol.* 119 (2011) 18–30.
- [20] D.J. LaBrecque, M. Miletto, W. Daily, A. Ramirez, E. Owen, *The effects of noise on Occam's Inversion of resistivity tomography data*, *Geophysics* 61 (1996) 538–548.
- [21] G. Morelli, D.J. LaBrecque, *Advances in ERT inverse modelling*, *Eur. J. Environ. Eng. Geophys. Soc.* 1 (2) (1996) 171–186.
- [22] E. Cardarelli, G. De Donno, I. Olivetti, G. Scatigno, *Three-dimensional reconstruction of a masonry building through electrical and seismic tomography validated by biological analyses*, *Near Surf. Geophys.* 16 (2018) 1–13.