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Electrical Resistivity Tomography Methods for Archaeological Prospection

Abstract: Two advanced applications of electrical resistivity methods in archaeological prospecting are presented. The approach is based on new inversion techniques, which enable the modelling of the resistivity distribution below any arbitrary topography. The results of 2D and 3D electrical resistivity measurements on Tell Jenderes in Northern Syria show images of subsurface resistivity structures, which were not detectable by geomagnetics or GPR methods. The interpreted resistivity structures are related to different settlement phases from the Bronze Age to the Hellenistic period. The new 3D-inversion technique is also useful for data sets of complex resistivity. An example, from a slag heap in Morocco, presents the parameter distribution of a 3D-complex resistivity model deriving from Induced Polarisation (IP) measurements.

Introduction

A great variety of geophysical methods are currently available for specific archaeological demands. The choice of either a single method or combined geophysical applications depends on the particular characteristics of the site. In most cases, geomagnetics and ground penetreting radar (GPR) yield the best results due to the significance of the corresponding geophysical parameters and the high resolution of the advanced equipment available today. Certain conditions, such as an extensive investigation or a high conductivity ground, alternatively require the electrical resistivity tomography method (ERT).

Methodology – Principles of Electrical Resistivity Tomography (ERT)

Geoelectrical measurements are used to determine the specific electrical resistivity ρ of the ground. Geoelectrical mapping by means of surface measurements is standard practice in archaeological prospection. In the 1980s and early 1990s, increasing demand for engineering investigation techniques led to the development of multichannel instruments and new inversion software. The applications of 2D imaging and 3D tomography became more and more important for visualising and interpreting complex archaeological structures at various depths. So far, most of the resistivity models have used flat earth conditions, which are not applicable for archaeological objects related to a certain topography.

3D resistivity structures associated with an arbitrary surface topography were computed by T. Günther and C. Rücker using a recently developed 3D-inversion technique. The reconstruction of a 3D resistivity distribution comprising all single measurements is based on a sensitivity concept which assigns certain sensitivity to each spatial element. Sensitivities describe the influence of a spatial cell to each measurement, and these interactions link all cells in the model space. If the model space is not uniform but uneven at the surface, it must be adjusted. To do so, the new technique uses an unstructured tetrahedral mesh which allows adaptation to arbitrary model structures. Thus the geophysical prospection of archaeological objects characterized by a rough terrain, like the landfill of tells and slag heaps, becomes possible.

The sensitivity decreases with the distance from the surface; therefore, the size of the model cells increases with depth. The resistivity inversion includes an iterative algorithm which compares the calculated model with the measurements and gradually improves the computed model.

Example from Middle Eastern Archaeology – Tell Jenderes in Northern Syria

Representative information about the history of the Afrin region and its connections with international trade routes is the goal of the excavations at Tell Jenderes – a well-established regional centre of substantial economic and political importance. Specific excavations were carried out over several years,

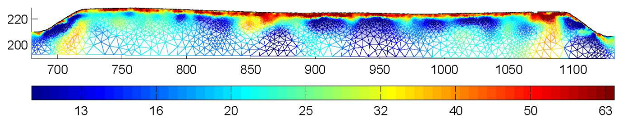

Fig. 1. Tetrahedral mesh of cells for computing a 2D resistivity model of a tell-section.

yielding important information about the 5000-year-long history of the tell. Given the large area of about 20 hectares and the multilayer structure, including layers from the Bronze Age up to Byzantine times, geophysical methods were applied in order to obtain more information before starting new excavations. The geophysical survey at Tell Jenderes was based on a multimethod approach, using geomagnetics, GPR and geoelectrical methods. The initial geomagnetic survey produced a complete map of the Greek town of Gindaros, recognizable by a Hippodamic system of streets and insulae.

The results of both the geomagnetic and the GPR survey show only poor indications of Bronze Age structures distinguishable from the Hellenisitic structures by a rotated orientation of buried structures at greater depths. The geoelectrical survey covered the Iron and Bronze Age structures of the multilayer site, which were partly excavated at a depth of more than 3m in excavation area 1 on the northeastern acropolis.

Imaging of ERT Profiles from Tell Jenderes

The geoelectrical survey was carried out in Spring 2005. Prior investigations have shown that in Middle Eastern archaeology, geoelectrical measurements are best made in winter and spring time when sufficient precipitation moistens the soil. Under arid conditions in summer and autumn, the transistion resistance is too high to guarantee a galvanic coupling of the current electrodes. The tens of thousands of individual measurements required for high quality 2D and 3D models were collected by a new 4-channel, multi-electrode complex resistivity meter, GeoTom.

At first, three 2D sections with lengths between 370–450 m were taken. The 2D resistivity models were based on measurements with an electrode distance of 1 m in dipole-dipole and Half-Wenner configurations. Approximately 10,000 individual measurements per profile were fed into the models. Very

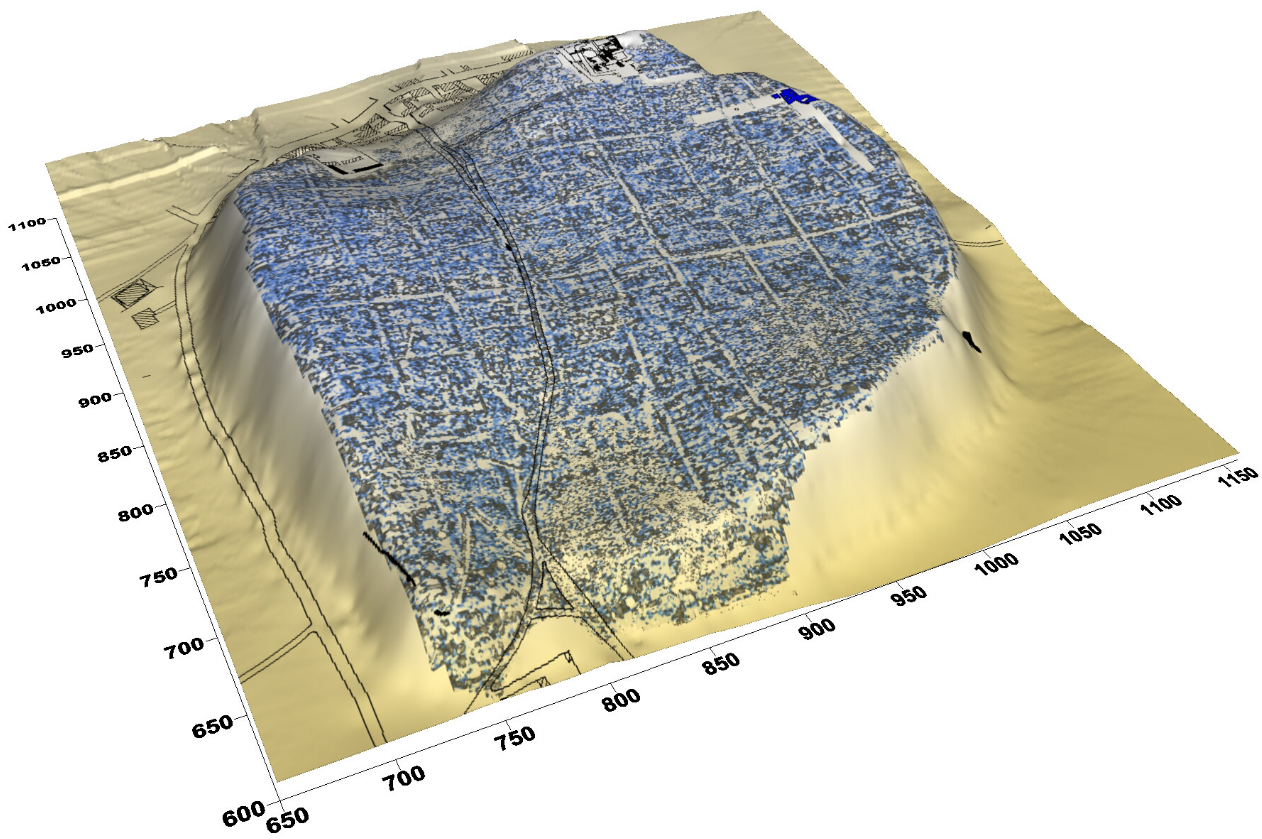

Fig. 2. Results of the geomagnetic prospection at Tell Jenderes.

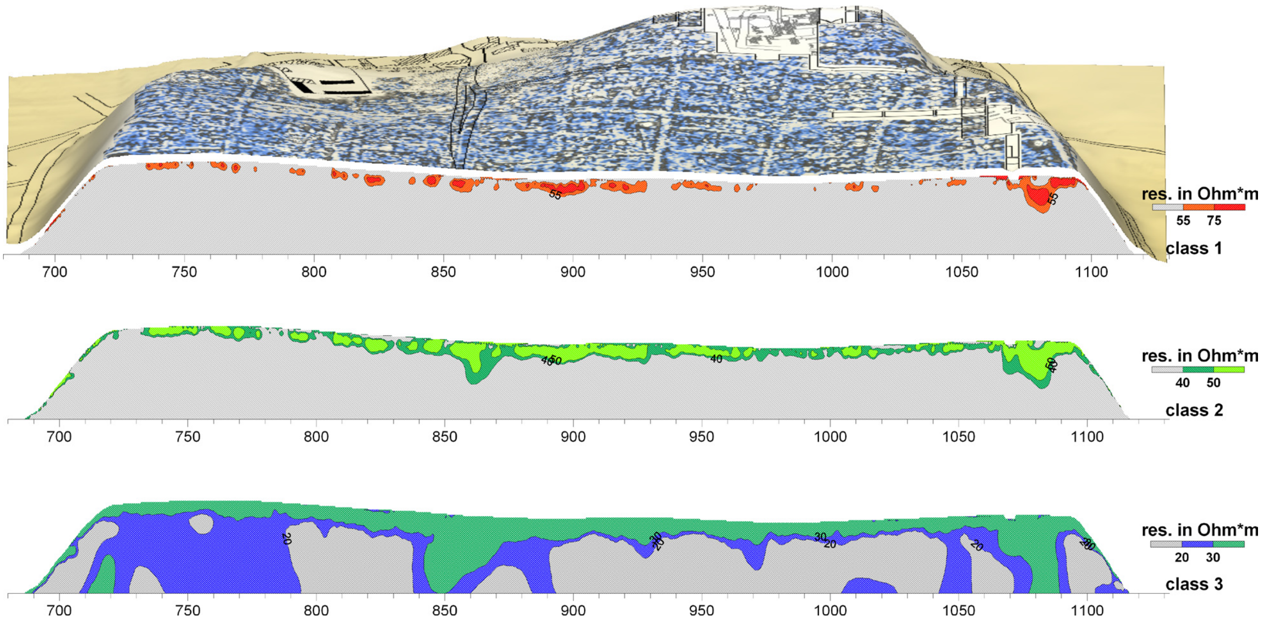

Fig. 3. Interpretation of different resistivity classes at the profile 850 m North on Tell Jenderes.

low values of specific electrical resistivity within the Tell were the most significant result concerning the development and use of geophysical methods based on electrical and electromagnetic principles. The electrical resistivities are limited within a range of 10–80 Ωm. The specific resistivities correspond to an extremely high electric conductivity between 12.5–100 mS/m. The reason for this is probably the very high humidity inside the tell. The high amount of cohesive and loamy sediments causes a strong capillary effect comparable to a sponge. In the end, the high conductivity values accounted for the disappointing GPR results.

In spite of the small dynamic range of the resistivity distribution, it is possible to interpret the resistivity anomalies. Building materials from different initial substrates, like mud bricks or limestone foundations, are distinguishable by their specific electrical resistivities. In addition, it is assumed that this specific electrical resistivity correlates with the degree of compaction. In areas of compacted materials, the pore volume decreases. This in turn decreases the amount of electrolytic conductivity within the pore space, and thus, the specific electrical resistivity increases. These facts were included into our interpretation using resistivity classes.

An example for an archaeogeophysical interpretation is proposed in *Fig. 3* for the East-West profile at 850 m North. The following resistivity classes correspond to structures.

Class 1: Specific electrical resistivities 50–60 Ωm

The relatively high specific electrical resistivitiy corresponds to building structures of the Hellenistic-Roman settlement. These exist in two dimensions (as ascertained by geomagnetic prospection) and are therefore widespread on the surface. These structures mostly correspond to limestone constructions and foundations. They lie about 2 m beneath the modern surface of the tell. In the east, at 1080 m, the zone of high specific electrical resistivities reaches depths of more than 5 m, caused by the desiccation of the soil arround the excavation trenches.

Class 2: Specific electrical resistivities 40–50 Ωm

Structures with medium specific electrical resistivities occur along the whole profile on the surface. On the eastern edge of the tell, probably from profile meter 1065 m, but certainly from 1073 m, the substructure of the massive mud brick wall is recorded. This foundation is known to be east of the section at 1070 m and is situated on top of limestone foundations. The higher specific electrical resistivities in the area of the excavation section are more likely caused by desiccation of the soil than by different materials. The local resistivity anomaly between 860–865 m shows a very similar structure with medium specific electric resistivities at depths of up to approx. 8 m beneath ground level. This structure could be interpreted as the western part of the mud brick wall which therefore provides an indication for the existence of an upper town which covered large parts of the tell.

Class 3: Specific electrical resistivities 20–30 Ωm

Within the zones with relative low specific electrical resistivities, it is possible to distinguish massive and compacted building structures in the deeper ground from undifferentiated areas with low resistivities less than 20 Ωm (grey). Three areas with a low resistivity of 20–30 Ωm were detected on profile 850 m North. Firstly, a large area between 708–794 m is located on the western ridge. That part may indicate early settlement structures to a greater depth than previously assumed. Two class 3 resistivity zones appear between 838–893 m and 1042–1094 m. These areas extend over more than 50 m and correspond to what is assumed to be a mud brick wall surrounding an upper town settlement from the Bronze Age.

Tomography of the North-Eastern Acropolis of Tell Jenderes

The ERT survey on the north-eastern elevation is based on geoelectrical measurements in a 1 m grid (profile distance of 1m, electrode distance of 1 m). About 17,000 single measurements in a dipole-dipole configuration on 29 profiles were used for computing the 3D model. The topography of the tell including the excavation trenches was recorded in a topographic survey and inserted into the 3D model. The surface is displayed in shaded grey while the computed resistivity distribution is coloured. Both are shown in *Fig. 4*.

The model contains the area between 950–1001 m North and 994–1022 m East. The resistivity distribution is presented in a logarithmic scale from 10–100 Ωm. The two separated, highly resistant structures in the vertical section of the model (in the foreground of *Fig. 4*) are the most remarkable results. These structures range to a depth of more

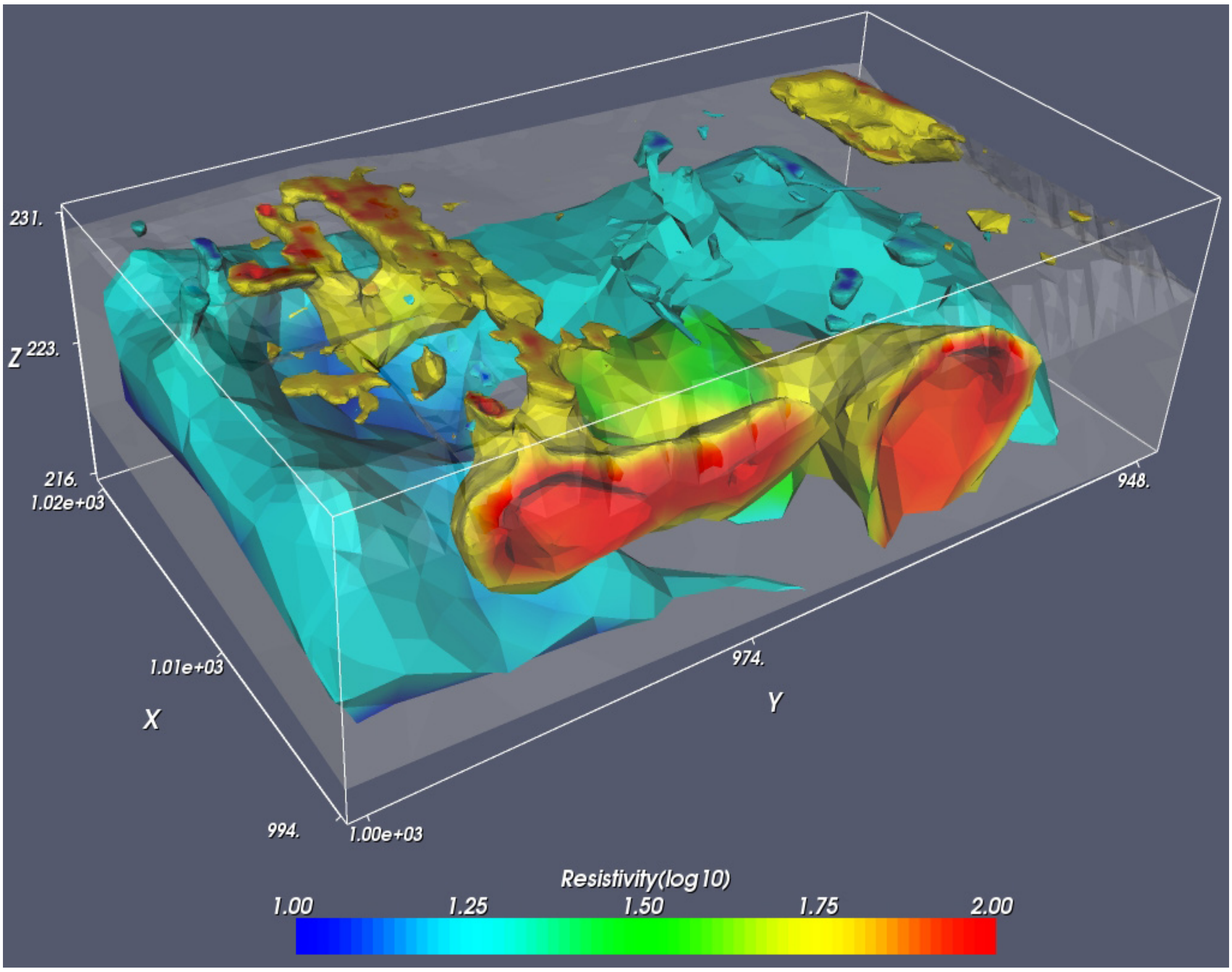

Fig. 4. 3D model of resistivity in the Northeastern Acropolis of Tell Jenderes.

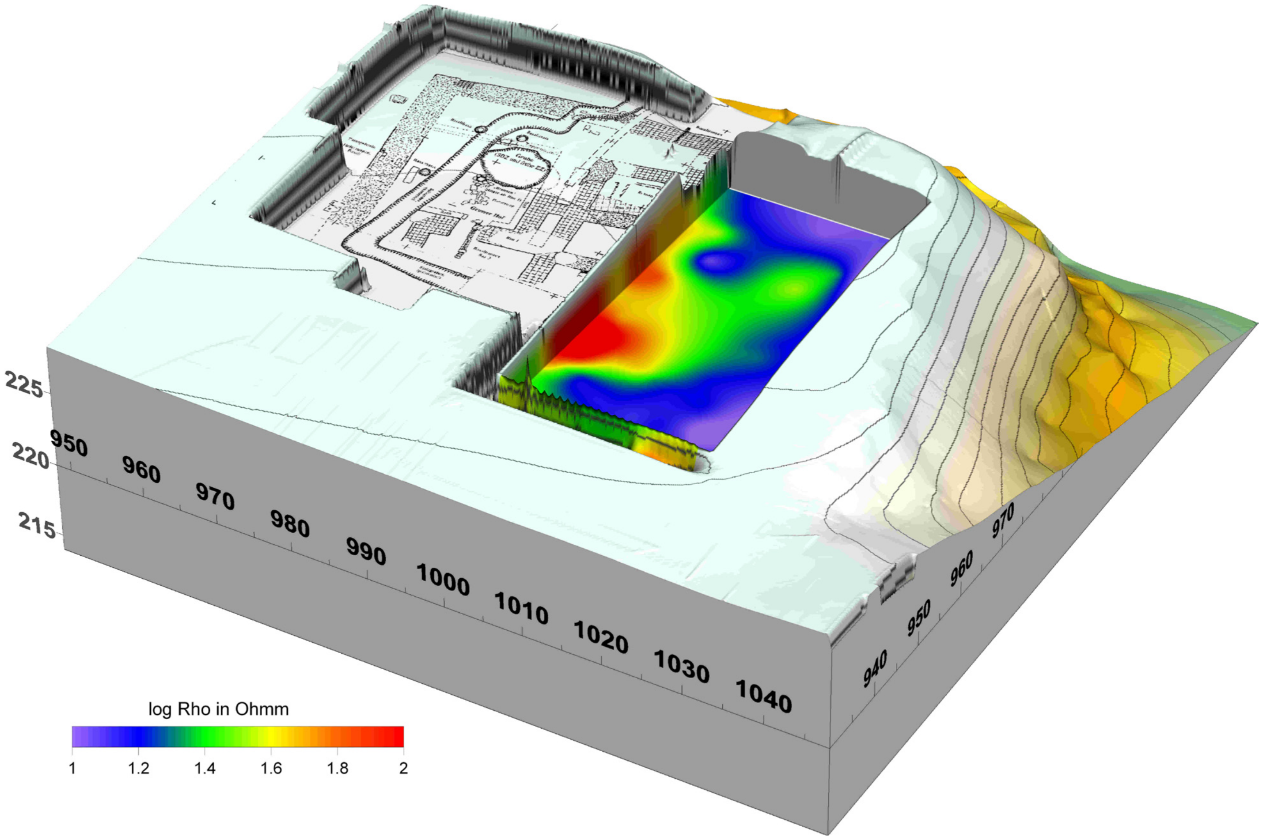

Fig. 5. Horizontal slice of the 3D model close to the excavation area 1 at Tell Jenderes.

than 3 m below the surface in the northern part. The bottom of the southern part is not determined by the resistivity model. The rectangular high resistivity values on the surface (left) are related to shallow excavation areas on the top of the tell. The high resistivity values in the southeastern corner of the model *(Fig. 4)* are caused by solid limestone structures from a nearby gate in the city wall. The cyan-coloured surface, modelled by a low resistivity value of 18 Ωm shows the variation of soil moisture and can be interpreted as the foundations of massive mud brick building structures corresponding to class 3 of the 2D interpretation concept.

The visualisation of the selected tomogram (a 2D horizontal section of the 3D model) relates to the results of the excavation shown in *Fig. 5*. The geomagnetic survey establishes a northeast-southwest orientation of structures from the Hellenistic period, whereas the Bronze Age structures uncovered by the excavations are aligned in a northwest-southeast orientation. The structures characterised by high resistivity values are clearly related to the orientation of the Bronze Age structures. High resistivity values of more than 70 Ωm are interpreted as massive foundations of solid limestone and basalt blocks. The horizontal section in *Fig. 5* shows the enlargement of the huge Bronze Age temple structure at a depth of approx. 3.5 m below the actual surface of the tell. The outer wall of the temple extends approximately 10–12 m into the unexcavated area of the northeastern acropolis of Tell Jenderes.

Archaeometallurgical Example – Slag Heap in Ain al-Hajar (Morocco)

The new 3D-inversion technique was used to analyse data obtained from an ancient metal production site in Morocco. Slag deposits often are characterised by a high resistivity due to its high porosity and metal content. It is difficult therefore to distinguish slag bodies from other archaeological features like walls and foundations and from the surrounding bedrock. However, the combination of metal content and electrolytic pore fluid causes a specific polarization inside the internal double layer when an electric current is injected. By recording the induced polarization (IP) effect, a separation of slag deposits may be possible. The behavior of polar-

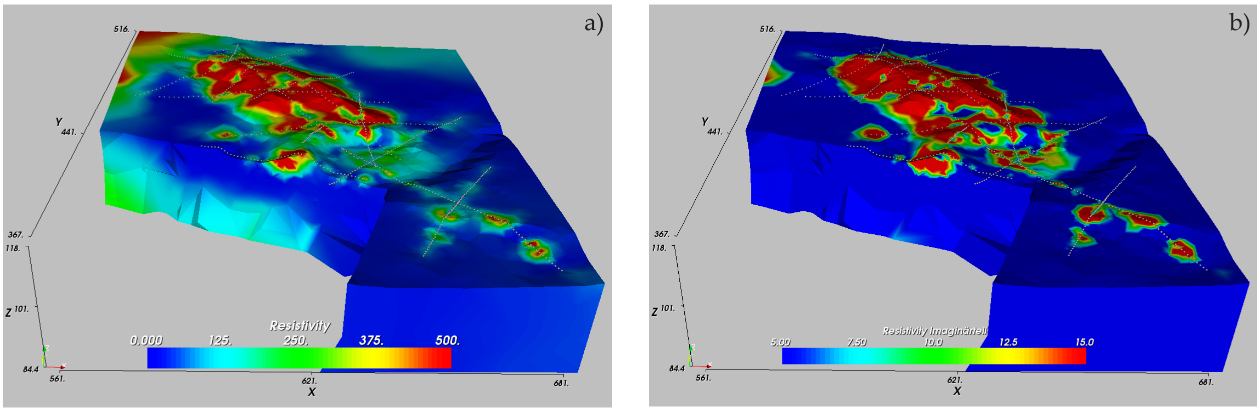

Fig. 6. 3D complex resistivity model of the slag heap showing real part (a) and imaginary part (b).

izable materials can be described by the complex resistivity

$$\rho = \rho' + i\,\rho'' \qquad (1)$$

where ρ' is the real and ρ'' the imaginary part (*i* is the imaginary unit). The complex resistivity can be adequately expressed by the amplitude and the phase angle. The latter represents the phase shift between the output signal of the measuring equipment and the measured voltage. The GeoTom equipment used is capable of registering even very small IP effects at different frequencies. So far, the main targets of the Induced Polarisation method in archaeological prospecting have been wooden artefacts (Schleifer et al. 2002) as well as furnaces and slag heaps (Weller et al. 2000).

For the IP measurements in Ain al-Hajar, we used the multi-channel GeoTom system at a frequency of 2 Hz. The irregularly-shaped slag heap was coverd by 14 geoelectrical profiles, with an electrode distance of 1 m. On each profile both dipole-dipole and Half-Wenner configurations were applied using metal electrodes. Approximately 18,000 single IP datasets were recorded within four days. The elevation of the slag heap and the surroundings were recorded by a total-station using a laser scanning system.

The 3D complex resistivity model was computed from more than 35,000 cells covering an area of 150 × 120 m and showed encouraging results: typical resistivity values are about 50 Ωm for the natural soil and 200–500 Ωm and above for the slags. But IP effects provided an even better contrast between the slag and soil. There is a sharp limit in the imaginary part of the resistivity around 5–10 Ωm. A vertical section of the 3D model shows more clearly the contrast betweeen the slag deposit and the bedrock, even for increasing depths in the imaginary part of the complex resistivity.

Conclusion

The two examples demonstrate the application of electrical resistivity tomography in archaeological prospection of a multilayer tell and a slag heap, respectively. In both cases, archaeological objects were detectable at a depth of approx. 4 m below the surface. The spatial resolution which can be achieved by the ERT method is less than the resolution of geomagnetics or ground penetrating radar, but the described method allows the investigation of buried archaeological features in cases when other methods like geomagnetics and GPR reach their limits due to the depth or the composition of the targets.

Acknowledgements

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