Geophysical prospection of iron slag heaps at Hamadab, Northern Sudan

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ABSTRACT: This paper discusses the results from the geophysical survey of ancient slag heaps in Hamadab in Northern Sudan. The aim of the survey was to evaluate the potential of Electrical Resistivity Tomography (ERT) and Ground Penetrating Radar (GPR) for non-destructive prospecting in arid environments. Complex Resistivity (CR) measurements were taken along five profiles on two slag heaps. The resulting 3D-models show great variation of the CR parameters amplitude and phase. The high amplitudes of between 1.000 and 10.000 Ωm correlate with a concrete slag layer on the surface of the heaps. The phase models show high polarisation effects in the interior of the heaps. The GPR results reveal structural information up to 1.5m below the surface. Tilted layers of slag are recognised by high reflection values. Areas of low reflection amplitudes indicate the location of furnaces, which are characterised by high absorption from clay artefacts.

Introduction

Today geophysical prospection is an integrated part of archaeological research. An entire range of non-invasive geophysical methods can be used to identify archaeological features. In archaeometallurgy, geophysical survey can help to identify and interpret metalworking structures like furnaces and hearths, as well as locating slag, crucibles, moulds, scrap metals and associated structures. A recent review (Bayley *et al* 2001) describes magnetometry and magnetic susceptibility techniques as suitable for archaeometallurgy, but points to the high noise in magnetic surveys on slag rich areas. As slag is the most abundant and best preserved archaeometallurgical residue, it is worthwhile evaluating alternative geophysical prospecting methods for slag heaps. Surveys using Electrical Resistivity Tomography (ERT) and Ground Penetrating Radar (GPR) have a great advantage over magnetometer surveys, as they allow collection of 3D-datasets for a more quantitative interpretation (Ullrich *et al* 2007). Previous results from Southern Europe and Northern Africa provided encouragement for the use of these methods in the arid area of Northern Sudan. The slag heaps in Hamadab near the city of Meroe are small in comparison to those in Meroe itself, but their small size makes them suitable for testing 2D- and 3D-geophysical techniques.

Archaeological setting of Meroe and Hamadab

The large number of iron slag heaps next to the ancient city of Meroe, the former capital of the Kushite Empire, induced the title 'Birmingham of Africa' (Sayce 1912). Archaeological studies there have always been inspired by these imposing remains from traditional iron smelting. The rise and fall of Meroe was discussed in relation to iron production and the necessary natural resources. Detailed archaeometallurgical research (Tylecote 1982) and excavations (Shinnie and Kense 1982) focused on the development of iron technology in the Kushite kingdom. After excavations in the 1970s, the Meroe Joint Excavation (MJE) project revived archaeological fieldwork in Meroe City in 1992, including a topographical survey of the iron slag heaps, a test sounding of one of these heaps, and a geochemical analysis of

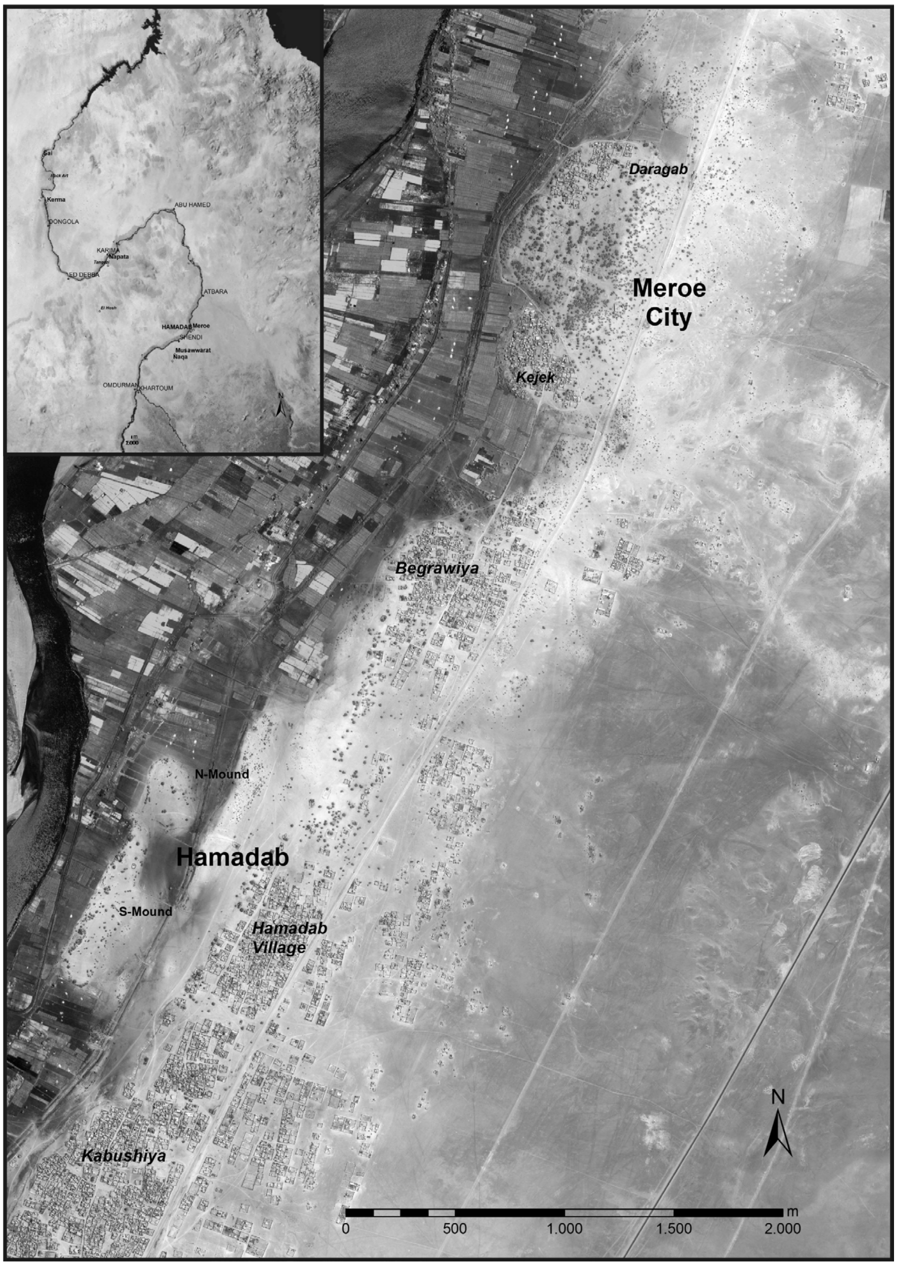

Figure 1: The location of Hamadab and the city of Meroe on the east bank of the Nile. The railway runs from NE to SW near to the modern villages and ancient Meroe City. The inset shows Sudan and Southern Egypt.

its contents (Eigner 1996). To quantify the extraction of iron, the volume of each heap was calculated using a simple elliptical model multiplying the height by the length of the two half-axes. In this way the total mass of iron slag in Meroe was estimated to be 5–10,000 tons (Rehren 1995).

Compared to Meroe the slag heaps next to the urban settlement of Hamadab, located three kilometres south of the site of Meroe, indicate rather limited iron production. The Meroitic settlement of Hamadab has been under excavation since 2001 by a joint Sudanese-German team. The site is characterised by two mounds rising about 4m above the surrounding fertile plain of the river Nile (Fig 1). The main focus of the present archaeological research is the partially fortified settlement at the northern mound with densely built brick masonry buildings and streets. According to the present state of research, this was founded at the end of the 1st century BC and existed throughout the Meroitic period into probably the 5th century AD (Wolf *et al* 2008). Two slag heaps are situated near to the fortifications of the so-called ‘Upper Town’: heap H 100-200, which consists of two merged heaps with an elevation of more than 1m, and heap H 300, 20m to the south. H 800, the largest heap at Hamadab, is situated about 150m further south, next to the limit of the unfortified suburbs (Fig 2). It rises about 2.5m above the surrounding landscape (Fig 3). Surface clearings and test excavations confirm that while the fortified ‘Upper Town’ basically served living, sacral and probably administrative functions, larger scale crafts,including workshops for iron smelting and pottery manufacture,

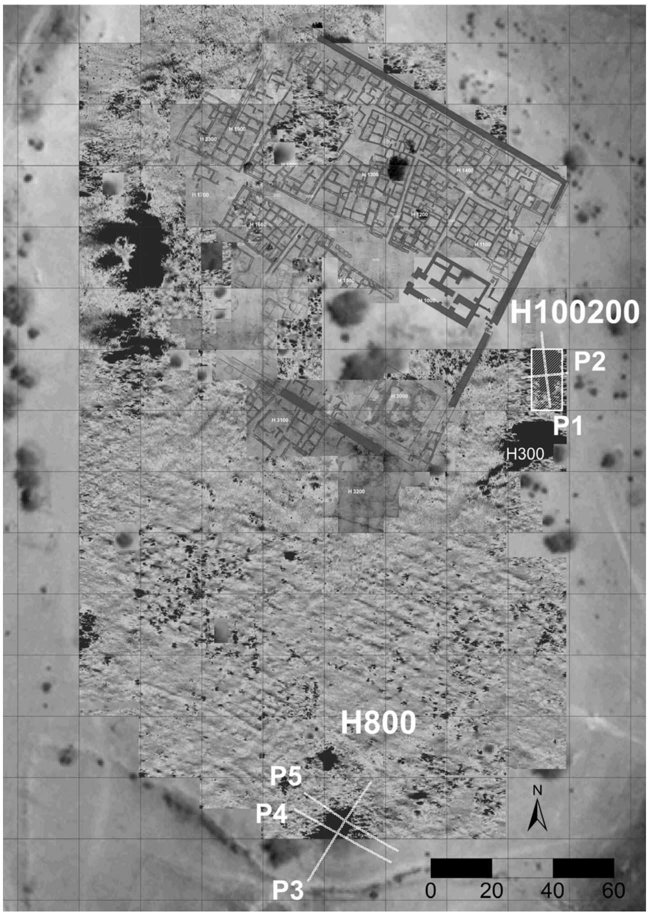

Figure 2: The northern hill of Hamadab showing the layout of the ERT profiles at the heaps H100-200 and H800 and the GPR area at heap H100-200 (shaded). The excavated settlement structures in the northern part and the results from the geomagnetic survey at the site are superimposed. High amplitudes of the geomagnetic gradient field are plotted in grey for positive and negative values (Goldmann et al *2007). The slag heaps east and south of the area as well as large amount of burnt bricks, ceramics and ash concentrations show high magnetisation values as well.*

were situated beyond its fortifications. A small scale excavation at the northern part of heap H 100-200 in 2002 revealed a tightly-packed slag layer containing tuyère fragments from iron smelting furnaces, coarse pottery and pieces of iron slag with large inclusions of charcoal, indicating that the iron smelting furnaces must have been situated next to the heap (Wolf 2002). While the dense iron slag layer belongs stratigraphically to the later periods of the town, deeper layers contain almost no iron slag but the remains of 'ordinary' refuse from the town and remnants of other crafts such as faience making. A geophysical survey using magnetic gradiometry was carried out between 2004 and 2007 (Goldmann *et al* 2007). As a result, the extension of the fortification was found. The slag heaps to the east and south of the fortified enclosure, as well as burnt bricks and ash hills, are clearly identified through high magnetisation (Fig 2, dark grey areas).

Methodology of applied geophysics in archaeometallurgy

In the last two decades, the application of geophysical prospecting methods has become widespread in field archaeology. These methods have been adopted from engineering and environmental geophysics to fit the needs of sub-surface archaeological investigations. The choice of a certain method or the combination of methods depends on the physical properties of the archaeological target and its environment, as well as other site-specific factors. Magnetometry, the standard method in archaeological geophysics, is also the first choice for archaeometallurgical surveys. A number of reports present total field or gradiometer results in combination with magnetic susceptibility (κ) measurements on samples to distinguish furnaces and slag, which are mainly from the Iron Age and medieval periods (Fluck 1993; Lindner and Käppler 1993; Vernon *et al* 1998; Walach 2008). The high residual magnetisation of most metallurgical objects, which is caused either by cooling fired or burnt materials below the Curie temperature, or results from large amounts of ferromagnetic minerals in ores and remains of smelting activities, generates a strong magnetic signal. Thus, magnetic dipole anomalies with high amplitudes in the 100 to 1000nT range can often be found. However, the magnetic map always gives an integral picture of all anomalies in the sub-surface, and so it is difficult to separate different archaeological targets such as furnaces within a slag heap. Therefore, we propose integrated geophysical prospecting methods using a wider range of electrical methods to obtain more detailed information. These different methods are classified by the frequency ω of the electromagnetic field, which defines the way in which the energy is conducted into the ground. The frequency ranges from very low frequencies around 1Hz for direct current (DC) electrical resistivity methods to the high-frequency MHz range used with ground penetrating radar. In the low frequency range, an electric current is injected into the ground via a galvanic contact through electrodes. In the high frequency range, electromagnetic waves are emitted from antennas.

The material properties which control the behaviour of electromagnetic energy in the ground are the dielectric permittivity (ε), the electrical conductivity (σ) and the magnetic permeability (μ). In the high frequency range, the propagation of the electromagnetic waves is mainly determined by the dielectric permittivity (ε). In the low frequency range, the conductivity (σ) or its inverse, the electrical resistivity ($\rho=1/\sigma$), is obtained (Landau *et al* 1984; Swift 1987). The frequency dependence of the complex electrical conductivity σ* can be expressed as:

$$\sigma^*(\omega) = \sigma'(\omega) + i\,\sigma''(\omega),$$

where σ' is the real part of the conductivity, σ'' is the imaginary part of the conductivity, and $i=sqrt(-1)$ the imaginary unit. An equivalent expression of the complex conductivity based on the amplitude $|\sigma|$ (in S/m) and phase φ (in rad) reads:

$$|\sigma| = sqrt\,[\,(\sigma')^2 + (\sigma'')^2\,]$$

$$\varphi = tan\,[\,\sigma''/\sigma'\,]$$

Similar expressions can be found for the complex resistivity ρ*. In the low frequency range of about 1Hz the amplitude |ρ| (in Ωm) is dominated by the DC resistivity due to small imaginary parts and therefore often defined simply as resistivity. The phase φ is a direct measure of the polarisation effect known as Induced Polarisation (IP).

Resistivity surveys on archaeometallurgical targets apply mainly conventional direct current (DC) resistivity methods in a 2D-mapping (Vernon *et al* 1998) or 2D-imaging mode (Schleifer 2007). Recent research has focused on Induced Polarisation (IP) and Spectral Induced Polarisation (SIP) methods, in order to obtain the polarisability of the material, which is caused by the displacement of free electrical charges within an external electrical field. The IP response can be obtained either in the time or in the frequency domain depending on the resistivity meter used. In either case, the voltage is registered as a decay function over time or at several frequencies respectively (Telford *et al* 1990).

The polarisation effect, induced by an alternating current, can be of different types. The effect of electrode polarisation used in base metal and ore exploration makes the IP method suitable for archaeometallurgical surveys. The polarisation effects are sensitive to grain size and textural parameters and can be analytically described by the relaxation model (Pelton *et al* 1978), for example as seen in the Cole-Cole-model. From laboratory measurements in the frequency domain, the model parameters can be derived from complex resistivity spectra for slag and ore samples (Weller *et al* 2000) and mixed sand-slag samples (Grissemann *et al* 2000; Slater *et al* 2006) in relation to the grain size and inner surface, respectively. Field surveys on smelting sites with a crystalline geological background show that the extension of buried slag accumulations may be fitted by the phase, rather than the amplitude, of resistivity (Schleifer 2007; Ullrich *et al* 2007). If dense IP datasets are obtained from surface measurements, the volume of a slag can be derived from CR-models (Ullrich *et al* 2009). Here, the development of multichannel AC resistivity meters and stable inversion routines for setups with arbitrary topography (Günther *et al* 2006; Rücker *et al* 2006) provides new possibilities. The inversion scheme adjusts an initial starting model of the sub-surface resistivity distribution through several iterations, trying to reduce the differences between calculated and measured apparent resistivity values. The accuracy of the results obtained from the inversion is monitored through the root-mean-square (RMS) error of the differences between measurements and model. The field data quality is crucial to the model. The high resistivity of the sub-surface in arid climates as in Hamadab and Meroe (Mohammed *et al* 2007) can pose a challenge to electrical resistivity methods. Here,

Figure 3: View from west towards the slag heap H800 during the resistivity measurements. The electrodes had to be watered to reduce the ground-coupling problems. The circular lining around the heap indicates different water levels of the annual flooding of the Nile.

the use of non-polarisable electrodes can improve the quality of IP data, but the available field equipment is not yet suitable for fast 3D-data acquisition.

Electromagnetic methods at low frequencies (kHz-range) or GPR are usually applied to avoid a galvanic coupling of the electric signal. Ground Penetrating Radar has become a standard technique used in archaeological prospecting today because of the high resolution which can be achieved. A reflection in a GPR measurement occurs if there is a contrast in the dielectric permittivity (ε) at a material border. The depth can be estimated from the travel time with the velocity of the electromagnetic waves, which is reciprocally proportional to the permittivity (ε). The electrical conductivity (σ) is the main material parameter relating to the attenuation (α) of the waves in the ground. A low conductive ground (or high resistivity respectively) commonly assumed in both arid areas and on slag heaps, are good preconditions for a GPR survey.

A large number of publications illustrate its usefulness for the detection of architectural elements such as walls and foundations, where a high reflection coefficient is given (see, for example, Goodman *et al* 2007; Leckebusch 2001; Meyer *et al* 2007). However, the target-orientated application of GPR in archaeometallurgy seems to be still in its infancy. This could be explained by the heterogeneity of the usually small sites and the great variability of the objects both in size and chemical composition. GPR surveys on slag heaps are similar to geoarchaeological surveys, where the depth and extension of stratified layers can be reconstructed by reflections (Neal 2004).

Collection and representation of geophysical data

The geophysical field survey was carried out on the two slag heaps H100-200 and H800 during a three day campaign in spring 2009. For the electrical measurements along five profiles, the resistivity meter GeoTom (GeoLog, Germany) was used with conventional stainless steel electrodes for effective data acquisition with a frequency of 4Hz. On the heap H100-200, two perpendicular profiles were measured, each with an electrode spacing of 0.5m. The NS orientated profile 1 has a length of 24.5m and follows the ridge of the heap complex. Profile 2 crosses the top of heap H200 in an EW direction and has a length of 15m. The large heap H800 was investigated with three profiles, with an electrode spacing of 0.8m each. The SW-NE oriented profile 3 had a length of 39.2m, the two profiles 4 and 5 perpendicular to profile 3 each had a length of 36m. The apparent resistivity and apparent phase were measured in a Half-Wenner array and the average values from measurements in normal and reverse configuration were used for further data processing. To minimise the influence of polarisation effects at the steel electrodes (Dahlin *et al* 2002), we used a schedule with a time delay between potential and current measurements at the same electrode. The quality of the measured apparent complex resistivity data was quite good for the resistivity values and reasonable for the phase shift values due to the difficult conditions for resistivity measurements in arid areas. The coordinates of each electrode position were measured with a total station. The 3D-models of the complex resistivity were calculated using the BERT software package (Boundless Electrical Resistivity Tomography: see Günther *et al* 2006; Rücker *et al* 2006). Due to the data quality, the

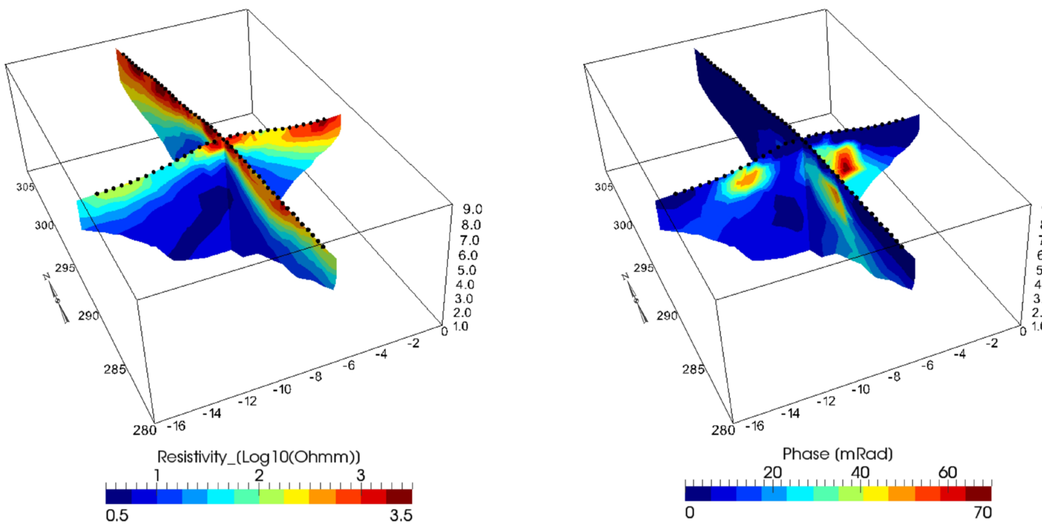

Figure 4: Complex-resistivity model of heap H100-200 with the resistivity (left) and the phase (right), seen from the southwest towards the heap.

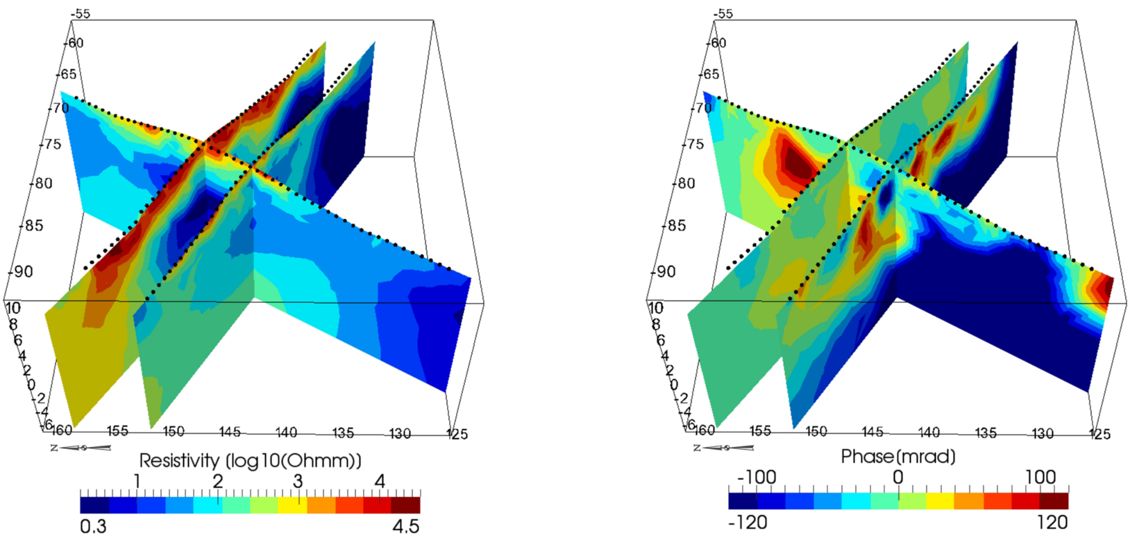

Fig. 5 : Complex-resistivity model of heap H800 with the resistivity (left) and the phase (right), seen from the east.

resistivity model is quite good while the phase model is acceptable. The CR-models of the heaps are presented in 3D-block-schemes showing the distribution of the two electrical parameters in a projection below the profiles (Figs 4 and 5).

The GPR measurements with a 500-MHz-antenna were performed on parallel profiles on heap H100-200 to obtain a 3D-dataset, and along the three ERT profiles of heap H800 (Fig 2). A SIR-3000 data acquisition system (GSSI) was used for recording with a time window of 45 nanoseconds (ns). The profile coordinates were registered by a survey wheel with a resolution of 0.04m point distance. The arrangement of parallel profiles at heap H100-200 covered an area of 20m NS and 9m EW, with a profile spacing of 0.33m. The data was processed with the REFLEX package from Sandmeier Scientific Software; this involved the removal of background noise and correction for static. Topography was included in the data processing; hence the GPR data are discussed relative to the top of each heap. A wave velocity of v=0.1m/ns has been used to convert the travel times to

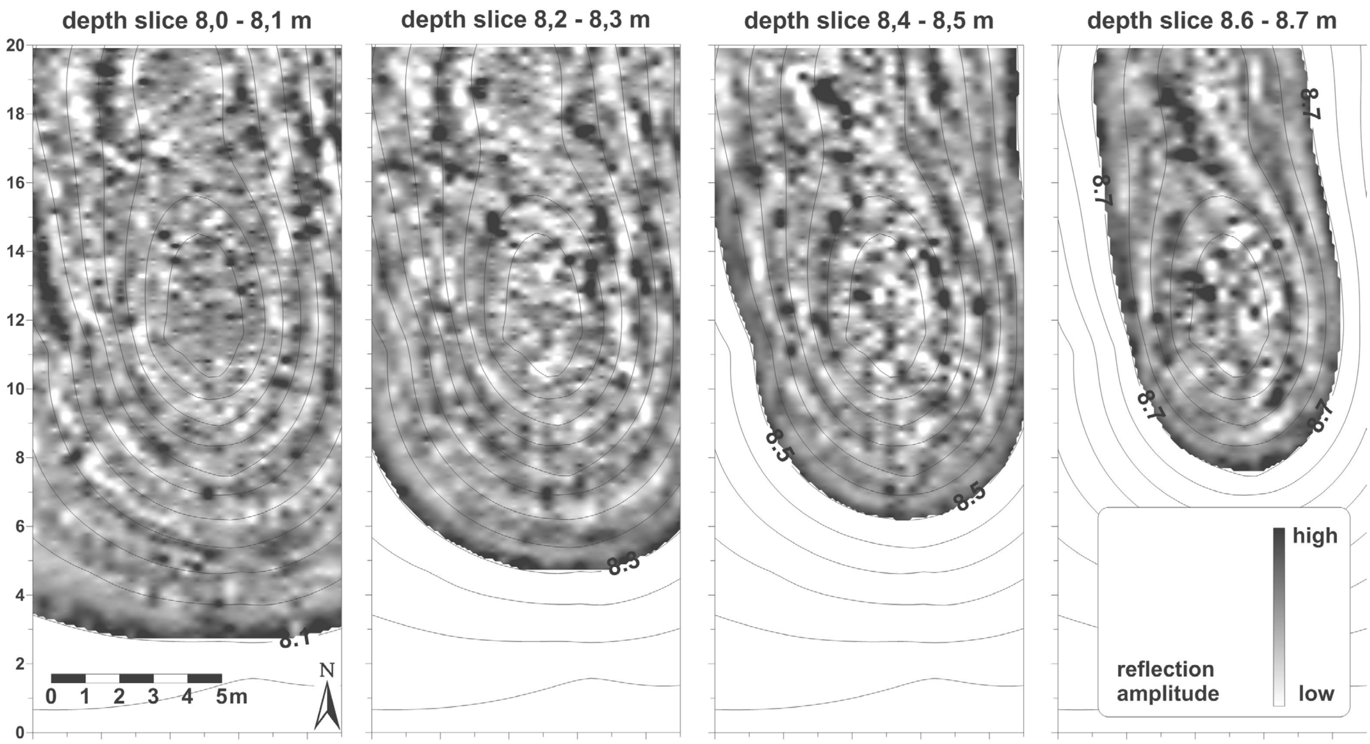

Figure 6: Results for the Ground Penetrating Radar survey along the southern part of heap H100-200. Shown are selected slices of 10 cm thickness for the area measuring 9 by 20m. The highest point is at 9.2 m.

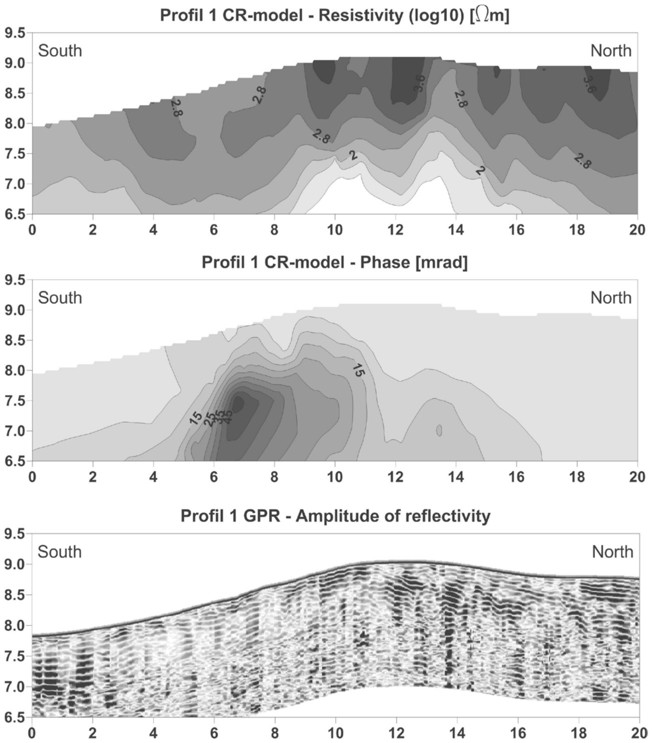

Figure 7: Vertical sections of the modelled IP amplitude (top) and phase (middle) and the result of the GPR measurements (bottom) along profile 1ont heap H100-200.

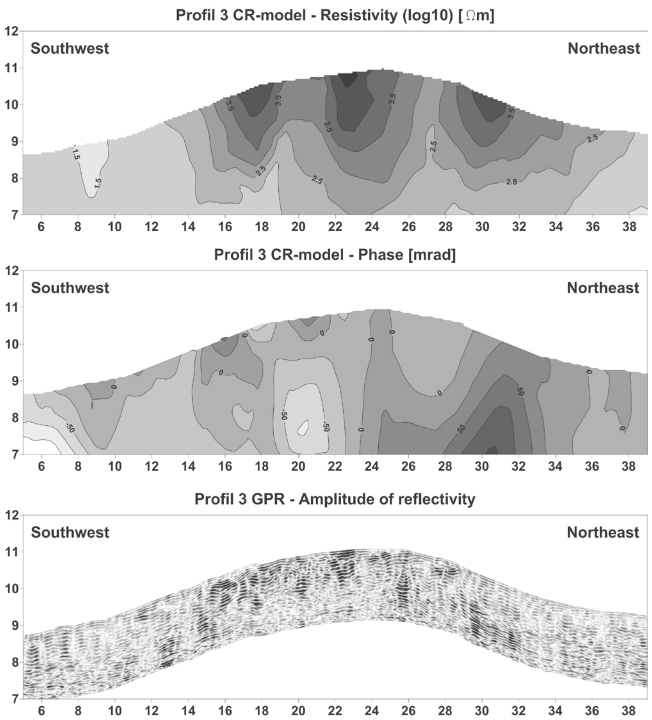

Figure 8: Vertical sections of the modelled IP amplitude (top) and phase (middle) and the result of the GPR measurements (bottom) along profile 3 on heap H800.

depth values. The achieved 3D-dataset from heap H100-200 can be presented in slices, in which the reflection amplitudes are added for layers of 0.1m thickness (Fig 6).

Results

The results of the integrated geophysical survey are discussed for profile 1 on heap H100-200 (Fig 7) and for profile 3 on heap H800 (Fig 8). The modelled resistivity distribution shows in general very high amplitudes along the surface for both heaps, with values between 1.000 and 10.000 Ωm and a decrease with depth. The high resistivity values correlate with a layer of compact slag of different thickness exposed on the surface. However, there are some significant differences in the spatial variation, noticeable along profile 2 (Fig 4) on heap H100-200 and between profiles 4 and 5 on heap H800 (Fig 5). Here, local anomalies with high resistivity values about 1m in size on the tops and the slopes of the heaps indicate changes in material and depositional conditions (Figs 7 and 8). The phase models for both heaps show local maxima in the IP response within the slopes of the heaps at 6–7m along profile 1 at a depth of about 1m (Fig 7), and between 30–31m along profile 3 about 2m below the surface (Fig 8). The high IP values can be related to a high volumetric concentration of iron (Fe), but the IP effect is also affected by parameters related to the capillary movement of fluids, transport and re-deposition of ions. The heterogeneity of the slag heaps known from the excavations in Hamadab (Wolf 2002) and Meroe (Eigner 1996) makes a clear interpretation even harder.

The GPR-sections show stratified reflections, which indicate the expansion of the heap to areas, where slag was deposited. The high-reflection amplitudes correlate with areas of high resistivity values at the top of the heaps along profile 1 from 9–13m and 18–20m (Fig 7) as well as along profile 3 at 16–18m and 22–23m (Fig 8). The change from high and low amplitudes indicates an alternating bedding of concrete materials (slag) and sand or clay layers in areas of low reflection. The high absorption may indicate remains of eroded or destroyed furnace pits within the heap. The GPR depth slices show shells of slag layers on the outside margin of the heap in different heights (Fig 6). Inside, especially in the northern part on the transition between heap H100 and H200, some linear structures are visible, which could be interpreted as remains from the production process as well as alignments from fillings.

Discussion and conclusion

Our combined ERT- and GPR-methods on slap heaps in Hamadab show the potential of 3D-geophysical prospecting techniques to interpret the interior of the heaps, using non-destructive measurements from the surface. Both methods provide estimates of different petrophysical parameters. The ERT models reveal the distribution of two independent parameters of complex resistivity down to 5–10m below the surface, with a resolution in the decimetre- to metre-range, depending on the electrode spacing and depth. The GPR results show high-resolution images of near-surface structures down to depths of 1 to 2 metres. However, the interpretation of the combined results is ambiguous in the case of heaps, which are composed of slag layers, furnaces as well as waste and ash layers. Vertical or horizontal slices of the ERT and GPR data can be used to derive information about the depth and the dimension of archaeological remains, which is not possible with a magnetic survey. The introduced multi-method approach can help to define different archaeometallurgical targets within slag heaps by their petrophysical properties. The links to a proper interpretation of complex-resistivity models from geophysical field surveys are laboratory and small-scale field measurements of IP spectra and additional geochemical and soil analysis (grain size, porosity). It should be clear, however, that the predicted structures must be verified or, respectively, falsified by archaeometallurgical investigations and excavations. The slag heaps in Hamadab and Meroe are a worthwhile subject for interdisciplinary archaeometallurgical research on an outstanding place of ancient iron production.

Acknowledgements

This study is supported by the DFG-Cluster of Excellence Exc264 Topoi – The Formation and Transformation of Space and Knowledge in Ancient Civilizations. Special thanks go to Carsten Rücker for calculating the 3D-CR-models from the measured data.

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