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Examples of application of electrical tomographies and radar profiling to cultural heritage

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Abstract

We present the results of an integrated application of the self-potential and resistivity methods to the recognition of buried remains in the archaeological site of Sumhuram (Khor-Rouri, Oman), and of the self-potential, resistivity and radar methods to the assessment of the state of conservation of the Aksum obelisk (Rome, Italy). A tomographic approach based on the concept of anomaly source occurrence probability was used for the analysis of the self-potential and resistivity data. Tomographic imaging provided reliable space patterns of the most probable specific target boundaries and notably improved the information quality of each single geophysical method.

Key words *applied geophysics – cultural heritage – electrical tomography – radar profiling*

1. Introduction

High-resolution data acquisition and processing procedures are increasingly applied in near-surface geophysics for archaeology and in micro-geophysics for monument preservation, due to the complex structural and physical conditions that can often be found. In these applications, a special place is held by tomographic imaging methods requiring a multi-illumination and multi-sensor prospecting strategy. Another important factor to obtain meaningful responses is to perform a survey with different methods, which can provide information on different physical aspects of the investigated media (Cammarano *et al.*, 1998).

In this paper, we present the results from the application of the Self-Potential (SP) and Resistivity (RS) methods to the recognition of buried remains in the archaeological site of Sumhuram (Khor-Rouri, Oman), and of the SP, RS and radar (RD) methods to the assessment of the state of conservation of the Aksum obelisk (Roma, Italy). For the SP and RS data analysis, which constitutes the main aspect of both applications, we followed the 3D tomographic approach based on the concept of anomaly source occurrence probability. An outline of this approach will be given before the presentation of the experimental results.

2. Outline of the probability tomography

The interpretation of the experimental data is a crucial point of the entire cognitive geophysical process. Among the many methods to date available, tomography is gaining increasing importance in current practice for its great resolving power and reliability. In particular, 3D probability tomography is a global pattern

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recognition approach that has the notable advantage of not requiring any *a priori* assumption about the structures to be imaged. The basics of this 3D approach were originally established for the SP method (Patella, 1997a,b) and then extended to the RS method (Mauriello *et al.*, 1998; Mauriello and Patella, 1999a,b). We now outline the practical solutions for the SP and RS method, separately.

2.1. *SP probability tomography*

The application of the SP method to archaeology and architecture is justified by the natural occurrence of electrical polarization phenomena in stony and muddy materials, mortars, plasters and concrete (Cammarano *et al.*, 1997a,b,c). SP signals in the cultural heritage domain can be related to redox reactions at the interfaces between pore-occluding mineral particles and interstitial humidity within stones and mortars. An important source of SP signals can also be the unsettling of the electric double layer across the walls of capillaries, cracks and fissures due to a naturally or artificially impressed movement of the electrolytic fluid saturating the voids in stony and muddy materials (Bogoslovsky and Ogilvy, 1973). Strong secondary effects related to primary SP sources of exotic origin can also be detected in correspondence with sharp resistivity boundaries. This is the normal situation in archaeology at the contact between buried remains and hosting soils and in architecture at the contacts between different stones, mortars and stones, plasters and stones, stones and metals, etc. Due to the complexity of the SP generation mechanism, the development of a high-resolution imaging technique is thus mandatory.

We outline now the SP tomographic approach useful for practical application in the case of a flat survey surface. This approach is a simplified version of the general theory formulated by Patella (1997b) for the case of measurements on uneven topography.

A reference coordinate system (x, y, z) is taken with the (x, y)-plane coinciding with the exposed surface where measurements are made and the z-axis taken positive inside the material. The electric field components on the exposed surface along the x- and y-axis, say $E_x(x, y)$ and $E_y(x, y)$, respectively, are estimated by interpolation from the SP survey map at the nodes of a regular square grid with constant step $\Delta x = \Delta y$.

The 3D SP tomography consists of a cross-correlation between the experimental data set $[E_x, E_y]$ and a theoretical scanner function $[\Im_x, \Im_y]$ representing the electric field generated by a positive point source with unitary intensity located in a generic point (x_q, y_q, z_q) of the surveyed volume. A normalised version of this cross-correlation is used to define the SP charge occurrence probability (SP-COP) function $\eta_S(x_q, y_q, z_q)$ as follows:

$$\eta_S(x_q, y_q, z_q) = \\ = C_S z_q \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} [E_x(x,y)\Im_x(x-x_q, y-y_q, z_q) + \\ + E_y(x,y)\Im_y(x-x_q, y-y_q, z_q)]dxdy, \tag{2.1}$$

where the normalisation coefficient C_S is given as

$$C_S = \left\{ \frac{\pi}{2} \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} [E_x^2(x,y) + E_y^2(x,y)]dxdy \right\}^{-1/2} \tag{2.2}$$

Each value of the SP-COP function is interpreted as the probability that a positive ($\eta_S > 0$) or negative ($\eta_S < 0$) charge accumulation located in the point (x_q, y_q, z_q) can be responsible for the set of the observed SP values. In practice, an elementary positive charge with unit strength is used to scan the whole (x, y, z) target-space (the tomospace) to search the location of primary and induced charges. The tomospace can be scanned along a sequence of slices spaced from each other by a constant increment of x_q, or y_q, or z_q. For each increment of the selected coordinate, a complete grid of regularly distributed values of η_S can be computed as a function of the other two coordinates, in order to draw a contoured or coloured slice, which gives an image of the source and induced charge geometry projected onto the chosen plane. The whole sequence of the slices gives the final 3D tomographic picture.

2.2. *RS probability tomography*

The use of the RS method in cultural heritage applications is a current practice. A wide variety of resistivity contrasts can be found that can all be resolved, in principle, adopting appropriate high-resolution acquisition and processing techniques. We now outline a 3D tomographic imaging method for a multi-illumination and multi-sensor RS data acquisition technique, following two approaches recently set forth by Mauriello *et al.* (1998) and Mauriello and Patella (1999a,b).

The RS survey is supposed to be performed on a flat surface S coinciding with a reference (x, y) plane, using two current bipoles, one A_1B_1 disposed along the x-axis and the other A_2B_2 along the y-axis. Following Bibby and Hohmann (1993), an apparent resistivity tensor $[\rho_a]$ is defined in terms of the x and y components of the electric field $\boldsymbol{E}_i$ and the primary current density $\boldsymbol{J}_i$, with $i = 1,2$ indicating the bipole in use, as

$$[\rho_a] = \begin{pmatrix} \rho_{a,11} & \rho_{a,12} \\ \rho_{a,21} & \rho_{a,22} \end{pmatrix} = \tag{2.3}$$

$$= \frac{\begin{pmatrix} E_{1x}J_{2y} - E_{2x}J_{1y} & E_{2x}J_{1x} - E_{1x}J_{2x} \\ E_{1y}J_{2y} - E_{2y}J_{1y} & E_{2y}J_{1x} - E_{1y}J_{2x} \end{pmatrix}}{J_{1x}J_{2y} - J_{2x}J_{1y}}.$$

From this quantity it is possible to extract tensor invariants P that are independent of the electric field direction and the current bipole used. Among these invariants we mention the determinant and the trace of $[\rho_a]$.

2.2.1. The first approach

The first approach to 3D tomography imaging (Mauriello *et al.*, 1998) is a straightforward adaptation of the method previously described for the analysis of the SP data. This adaptation is based on the fact that in the RS method the measured potential is the sum of two contributions, namely the primary potential related to the artificial sources (the A and B electrodes) and the secondary potential related to resistivity discontinuities in the target-space. The secondary potential is of importance, since the purpose of the survey is to infer the existence of resistivity boundaries. Therefore, one can always drop the primary contribution out of the field data set and consider only the secondary potential. This can be achieved by making a correct estimate of the resistivity about the current electrodes.

The RS secondary potential can be dealt with as in the SP method and the same eq. (2.1) can be used to detect the most probable location of the resistivity boundaries. In the RS method $\eta_S(x_q, y_q, z_q)$ will be identified as the RS-COP function.

If a combined SP and RS survey is carried out in an area where resistivity contrasts are present, a substantial similarity between the SP-COP and the RS-COP tomographies may result if only SP-COP signals of secondary origin prevail. Of course, this may happen when the SP primary sources are located such a long distance away from the surveyed volume as to give vanishing contributions within the tomospace.

The first approach was applied to the analysis of the RS data collected in the archaeological site of Sumhuram (Khor-Rouri, Oman).

2.2.2. The second approach

The second approach to the 3D RS tomography is based on the apparent resistivity function instead of the potential function. Therefore, objects of recognition become the volumes with anomalous resistivities instead of the boundaries where electrical charges accumulate. The rationale of the method is as follows (Mauriello and Patella, 1999a,b).

The whole prospected volume generating the P function is divided into a set of Q cells with a sufficiently small volume and true resistivities $\rho_q (q = 1, 2, \ldots, Q)$. The 3D RS multi-illumination and multi-sensor tomography consists of a cross-correlation between the experimental data set $\Delta P = P - P_0$ and the scanner function $\Im_q = \partial P_0 / \partial \rho_q$. P_0 is the tensor invariant for a reference model and $\partial P_0 / \partial \rho_q$ represents the Frechet derivative of P_0 for a variation of the true resistivity of the qth cell in the surveyed volume. A normalised version of this cross-correlation is used to define the Resistivity Anomaly Occurrence Probability (RAOP) function η_q as follows:

$$\eta_q = C_q \sum_S \Delta P \cdot \Im_q , \qquad (2.4)$$

where the cell-dependent normalisation coefficient C_q is given as

$$C_q = \left(\sum_S \Delta P^2 \cdot \sum_S \Im_q^2 \right)^{-1/2} \qquad (2.5)$$

Each value of the RAOP function is interpreted as the probability that a positive ($\eta_q > 0$) or negative ($\eta_q < 0$) resistivity anomaly in the qth cell, deviating from the selected reference model, can be responsible for the set of the measured apparent resistivity values.

In practice, an elementary positive resistivity anomaly with unitary strength and volume is used to scan the whole (x, y, z) target-space (the tomospace) to search where resistivity variations with respect to the reference model are located in a probabilistic sense. The tomospace can again be scanned along a sequence of slices spaced from each other by a constant increment of any of the three coordinates. For each increment of this coordinate, a complete grid of regularly distributed η_q values can be computed as a function of the other two coordinates, in order to draw a contoured or coloured slice, which gives an image of the resistivity anomaly pattern projected onto the chosen plane. The whole sequence of the slices gives the final 3D tomographic picture.

The second approach was utilised for the analysis of the RS data collected on the Aksum obelisk (Rome, Italy).

3. Case-histories

3.1. *Sumhuram town (Khor-Rouri, Oman)*

Sumhuram is a pre-Islamic town rising on a limestone-sandstone hill located near the mouth of a *wadi*. In accordance with the archaeologists, we investigated the still unexplored western part of the site, where three rectangular areas were selected (fig.1). The expected features are, generally, wall remains with an average width of 0.5 m and a vertical extent below the ground surface from a few centimetres to about 3 m. The fall of roofs and the deposition of various terrigeneous sediments have completely filled the spaces inside the walls.

The data acquisition scheme adopted for the SP and RS methods is reported in fig. 2a,b. For the purpose of this work, considering the dimensions of the structures and the resolution requested, we carried out a measure every 0.5 m for both the SP and the RS survey. For both SP and RS voltage measurements we used Cu-$CuSO_4$ porous pots as non-polarising electrodes. For the RS survey, the energising electrodes were iron rods grounded in such a way as to form two perpendicular bipoles (fig. 2a,b).

Figures 3, 4 and 5 show the SP and RS maps for the three investigated areas. A close correspondence exists between the SP and RS maps in the pattern of the anomalies. The presence of the wall remains is assumed to conform to the high values of the apparent resistivity determinant (the selected tensor invariant) in the RS maps, whereas in the SP maps the same structures are assumed to correspond to the zones where the SP gradient is higher, *i.e.* between close SP maxima and minima.

Figures 3, 4 and 5 also show the SP-COP and RS-COP tomographies for the three investigated areas. The distribution of the COP nuclei in the horizontal slices of both the SP and RS tomographies appear to follow a regular pattern, compatible with a well-structured environment. Finally, these tomographic images allow us to localise the exact position where the most probable anomaly sources occur. In each area, these sources occur close to the ground surface at depths ranging between 0.5 m and 1 m.

To conclude, it is worth observing the close similarity existing between SP-COP and RS-COP tomographies. This similarity virtually proves the absence of SP primary sources within the explored volumes. Only remarkable SP secondary effects associated with resistivity discontinuities were recorded. This is an important result issuing from the comparison between the SP and RS methods.

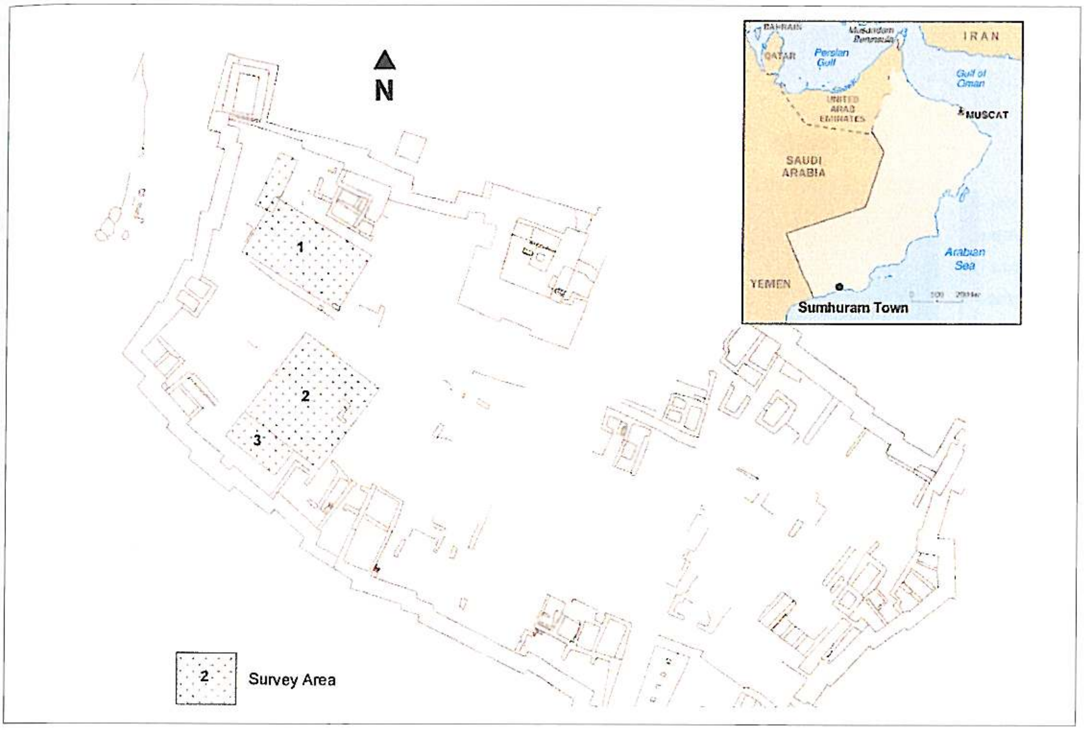

Fig. 1. The survey areas at Sumhuram (Khor-Rouri, Oman).

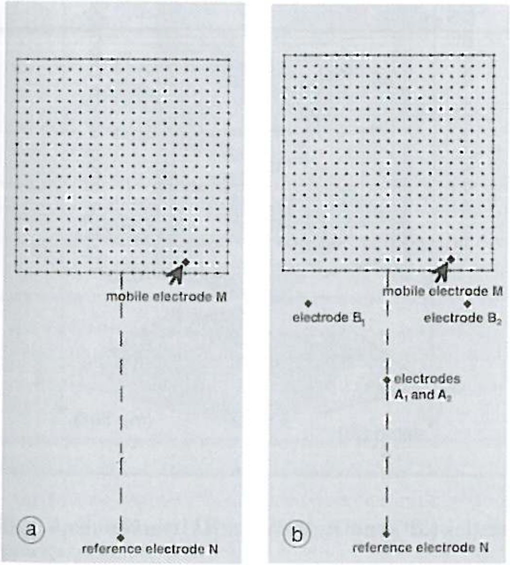

Fig. 2a,b. The 2D self-potential (a) and resistivity (b) data acquisition schemes.

On the basis of all of these geophysical results and with the help of an architectural model of the area, we have depicted in fig. 6 a qualitative sketch of the main features interpreted as wall remains in each area.

3.2. *Aksum obelisk (Rome, Italy)*

The Aksum obelisk (fig. 7) is a 24 m tall column dating back to the 4th century B.C. In 1937, it was transferred to Italy from Ethiopia in five separated blocks and then raised in Piazza Capena, Rome. In the framework of an operat-

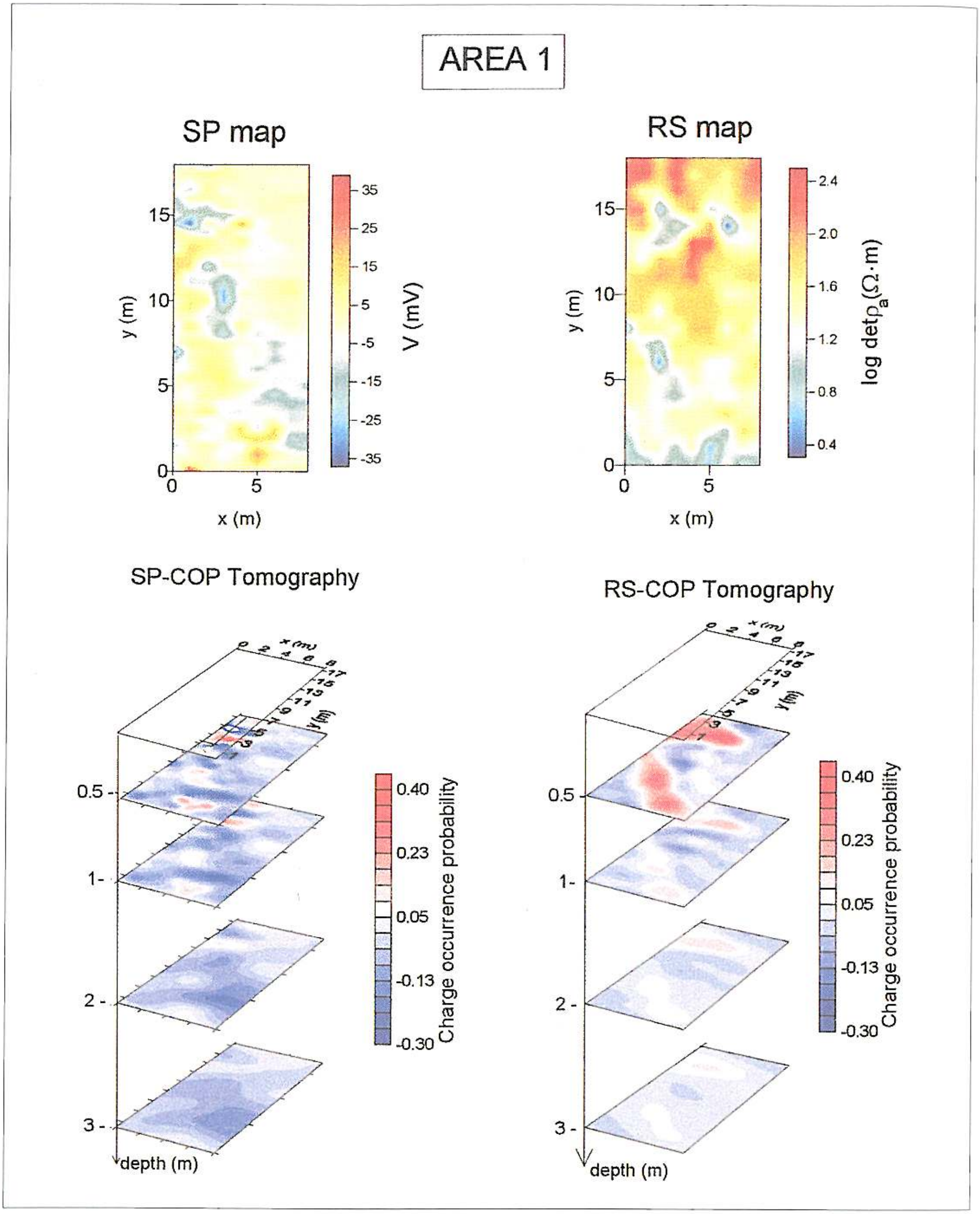

Fig. 3. Sumhuram (Khor-Rouri, Oman) area 1. Self-Potential (SP) and Resistivity (RS) survey maps and tomographies.

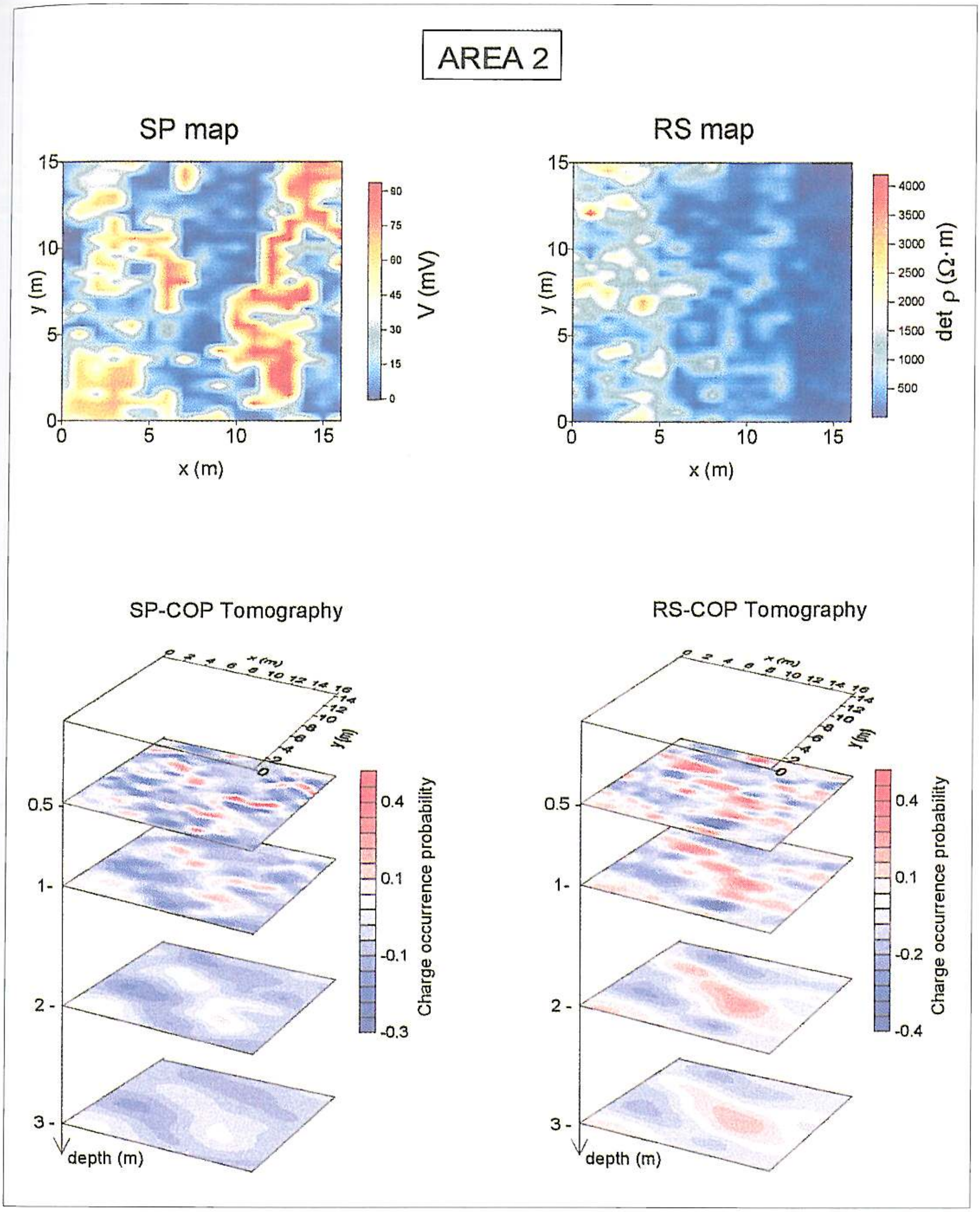

Fig. 4. Sumhuram (Khor-Rouri, Oman) area 2. Self-Potential (SP) and Resistivity (RS) survey maps and tomographies.

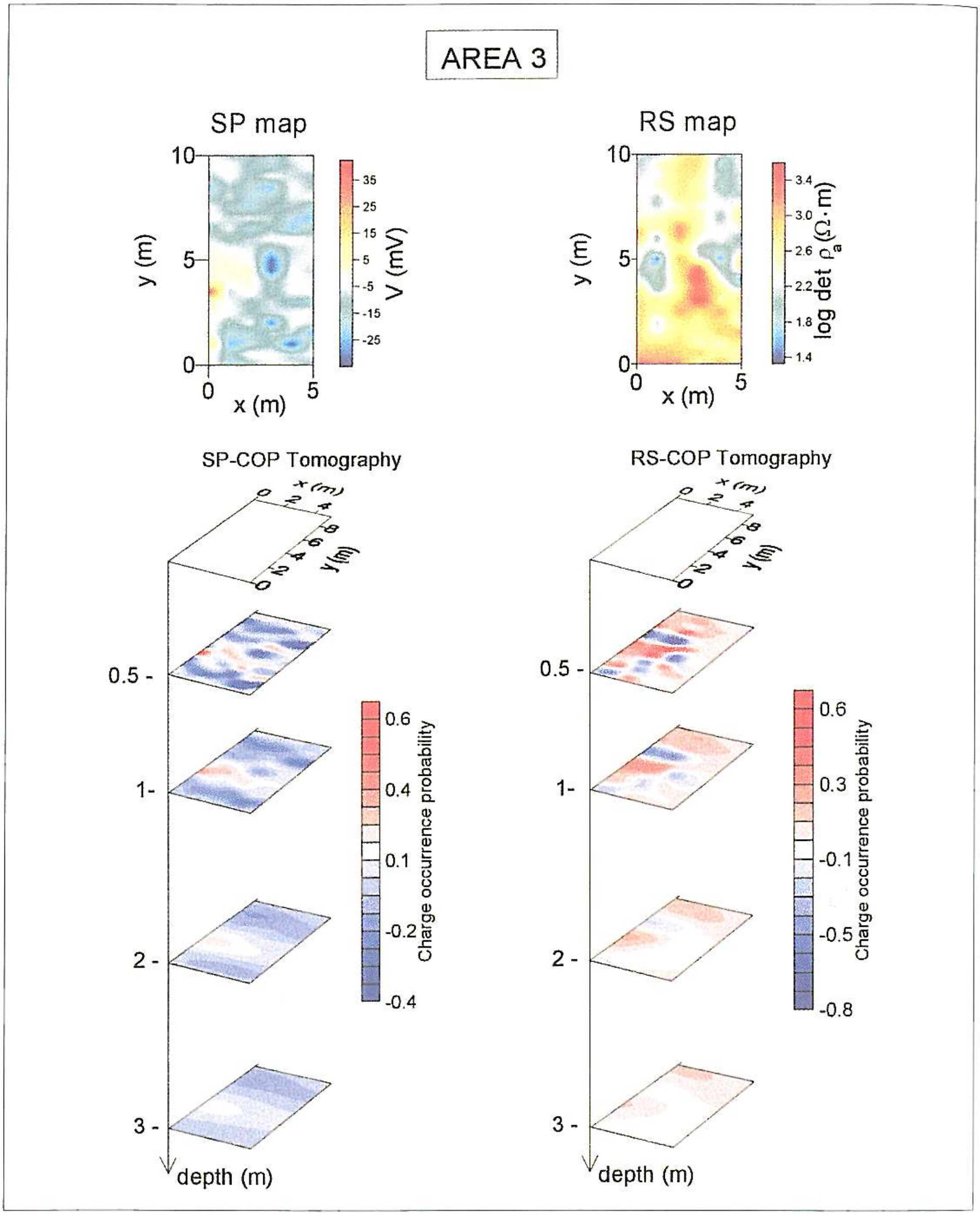

Fig. 5. Sumhuram (Khor-Rouri, Oman) area 3. Self-Potential (SP) and Resistivity (RS) survey maps and tomographies.

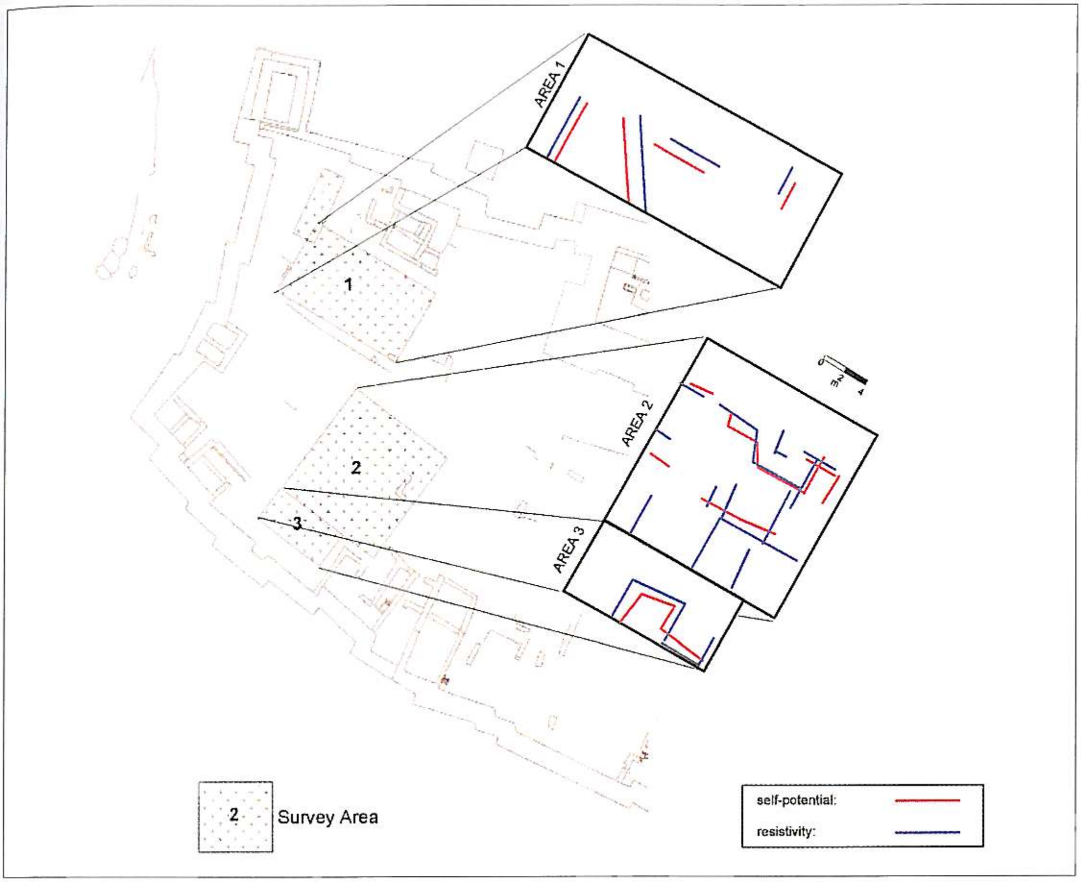

Fig. 6. The Sumhuram (Khor-Rouri, Oman) case history. Interpreted wall remains in areas 1, 2 and 3.

ing plan for the relocation of the obelisk in the original archaeological park of Aksum, Ethiopia, it was decided to carry out detailed micro-geophysical surveys with the SP, RS and RD methods. These surveys were required to assess the state of conservation of the obelisk (SP and RS) and to try to individuate the exact position of the metallic pivots (RD) that were used to reassemble the five different blocks forming the obelisk.

The obelisk rock material is a phonolytic nephelinite, easily alterable by weathering. Its exposure for more than 50 years to a polluted atmosphere conferred great importance on this study that had to condition the successive steps. A micro-geophysical survey was thus designed within three bands around the obelisk astride the three main junctions that were selected for the dismounting of the column (see fig. 7). Each band was uniformly investigated by the SP, RS and RD methods.

The SP and RS data acquisition scheme was the same as for the Sumhuram case (fig. 2a,b), except for the 2D sampling step on the vertical survey surfaces that was reduced to 10 cm. Non-invasive galvanic contacts were used for both SP and RS measurements, consisting of non-polarizable Ag-AgCl potential and current electrodes. In this case, the RS tomographies were elaborated using the second approach previously

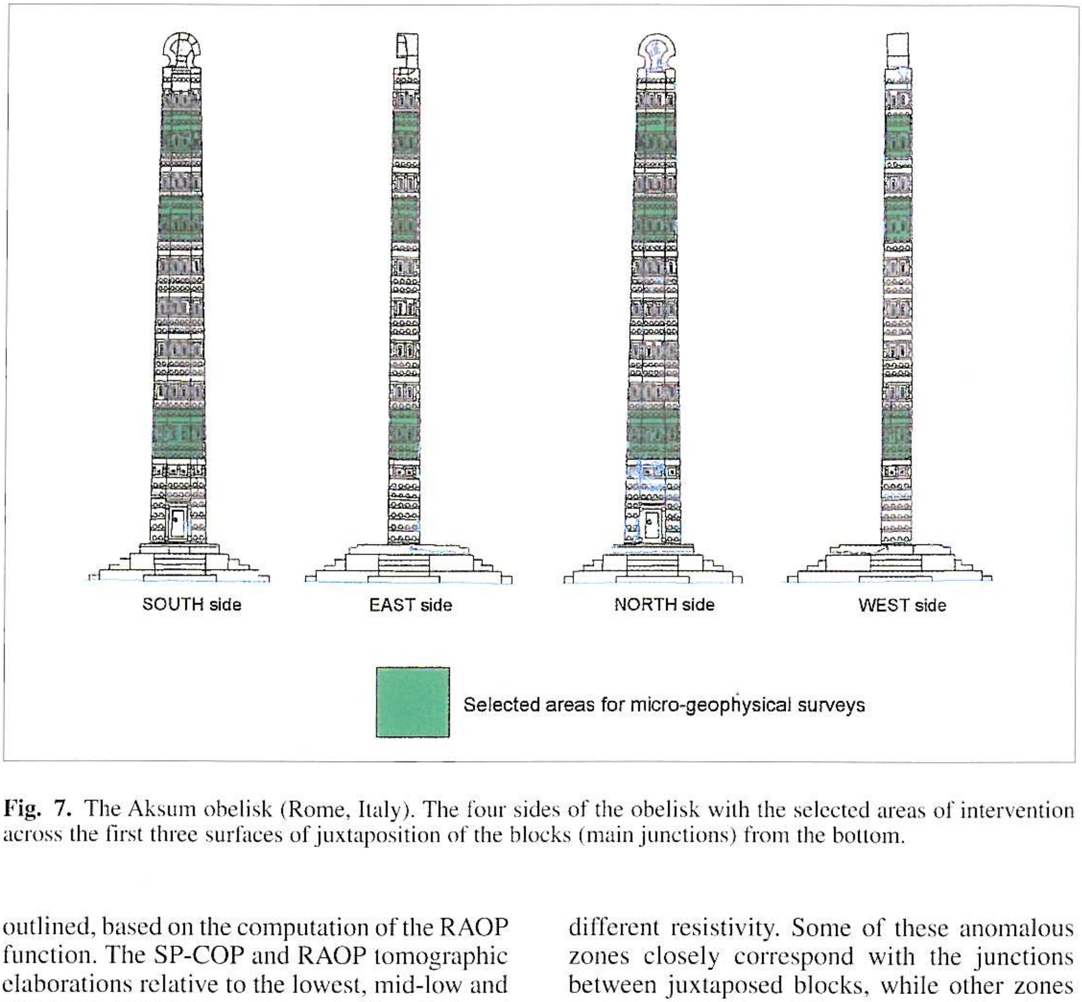

Fig. 7. The Aksum obelisk (Rome, Italy). The four sides of the obelisk with the selected areas of intervention across the first three surfaces of juxtaposition of the blocks (main junctions) from the bottom.

outlined, based on the computation of the RAOP function. The SP-COP and RAOP tomographic elaborations relative to the lowest, mid-low and mid-high junctions are drawn in figs. 8, 9 and 10, respectively.

These elaborations consist of a sequence of horizontal slices astride each junction, separated from each other by a constant step of 10 cm. The SP and RS data indicate a complex pattern, due to the presence of the metallic pivots and of pieces of similar rock added to replace missing parts, but mainly to a remarkable, diffuse inhomogeneity. In particular, the SP tomographies show the presence of many close-to-surface sources of anomaly, either positive or negative, ascribable to an advanced state of alteration of the stone, all around the obelisk. The RS tomographies are instead characterised by zones with different resistivity. Some of these anomalous zones closely correspond with the junctions between juxtaposed blocks, while other zones are to be related to a different conservation state.

RD profiles were carried out on each side of the obelisk in correspondence with the three main junctions, in order to identify the exact position of the metallic pivots that were used to reassemble the original blocks in Rome. A 1500 MHz bistatic antenna and the SYR-2 data acquisition system were used. A 16 bits dynamic range was used and 1024 samples per trace were recorded within a time range of 35 ns.

The presence of a metallic target is normally detected by analysing local anomalies of hyperbolic shape in a sequence of contiguous time traces along a given RD profile. Anomalies with this shape were indeed found only in the RD

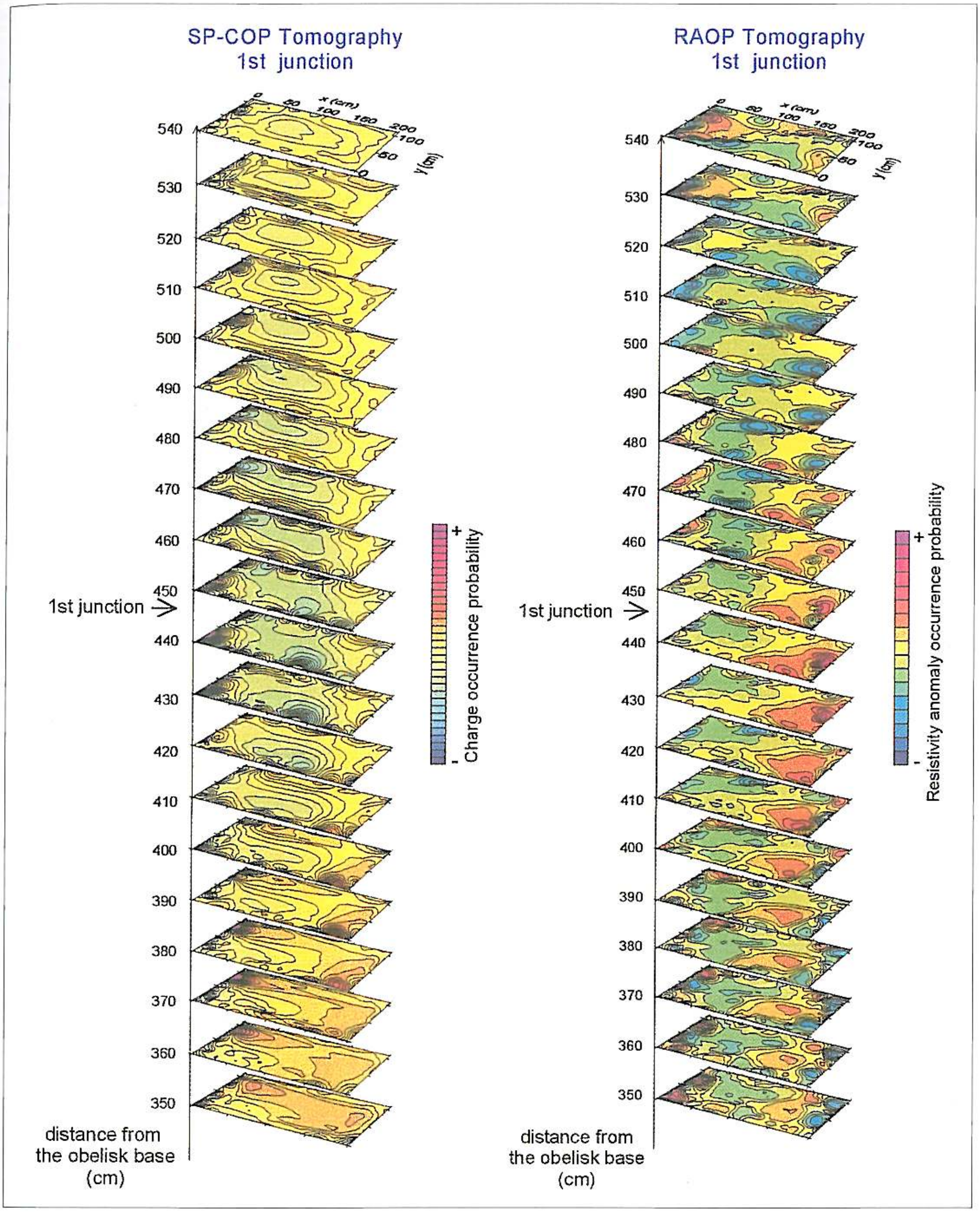

Fig. 8. Aksum obelisk (Rome, Italy). Self-Potential (SP) and Resistivity (RS) tomographies astride the first main junction from the bottom.

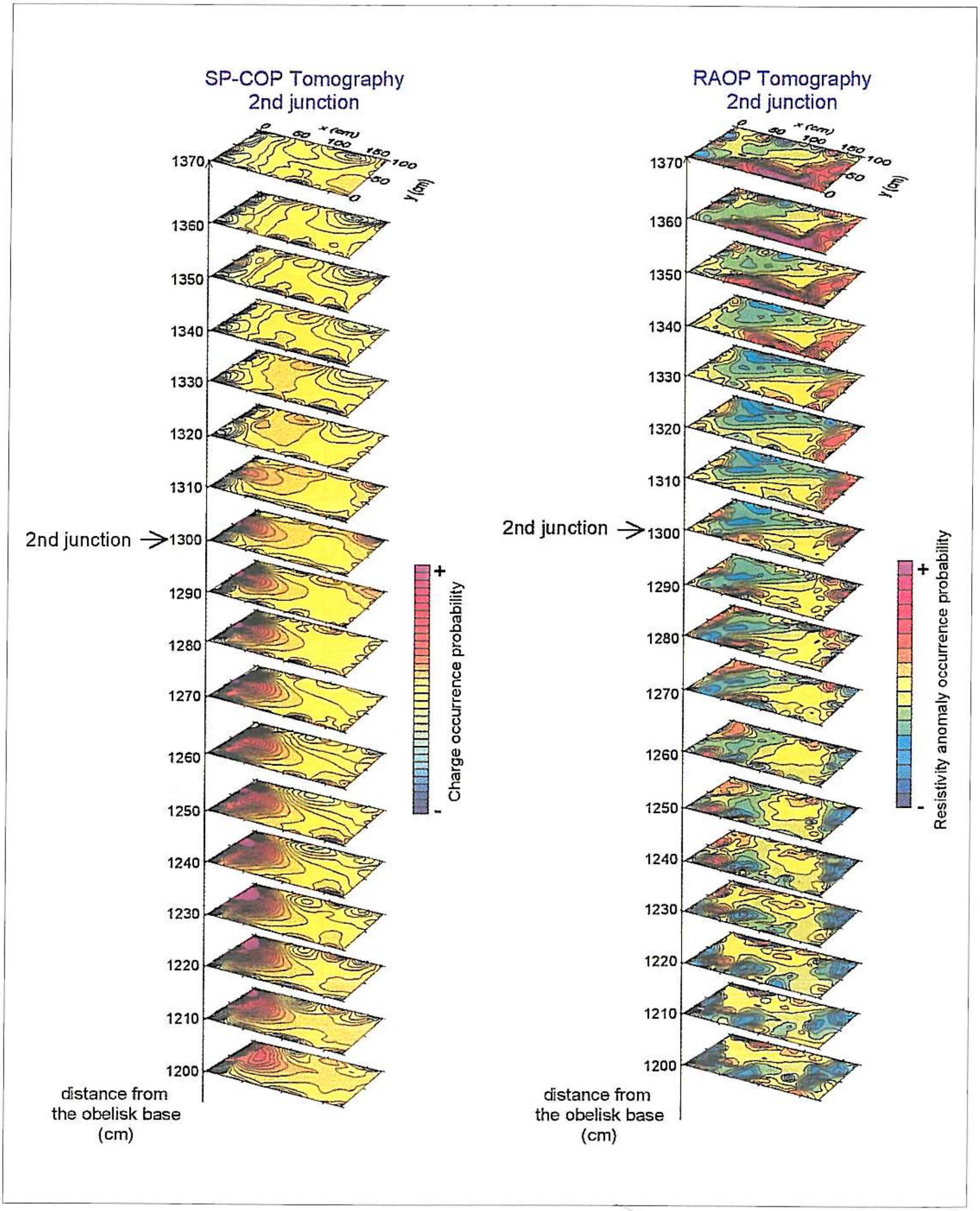

Fig. 9. Aksum obelisk (Rome, Italy). Self-Potential (SP) and Resistivity (RS) tomographies astride the second main junction from the bottom.

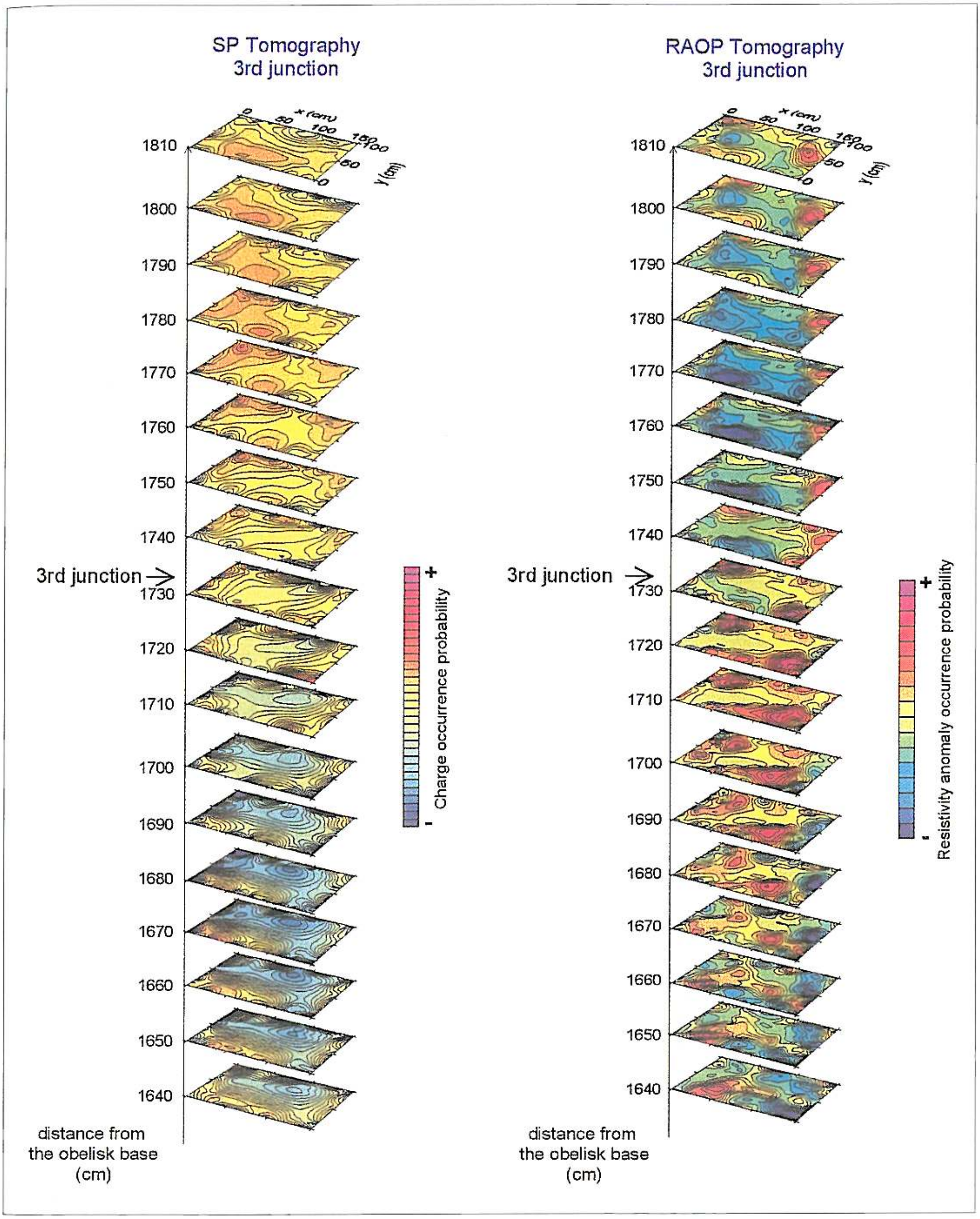

Fig. 10. Aksum obelisk (Rome, Italy). Self-Potential (SP) and Resistivity (RS) tomographies astride the third main junction from the bottom.

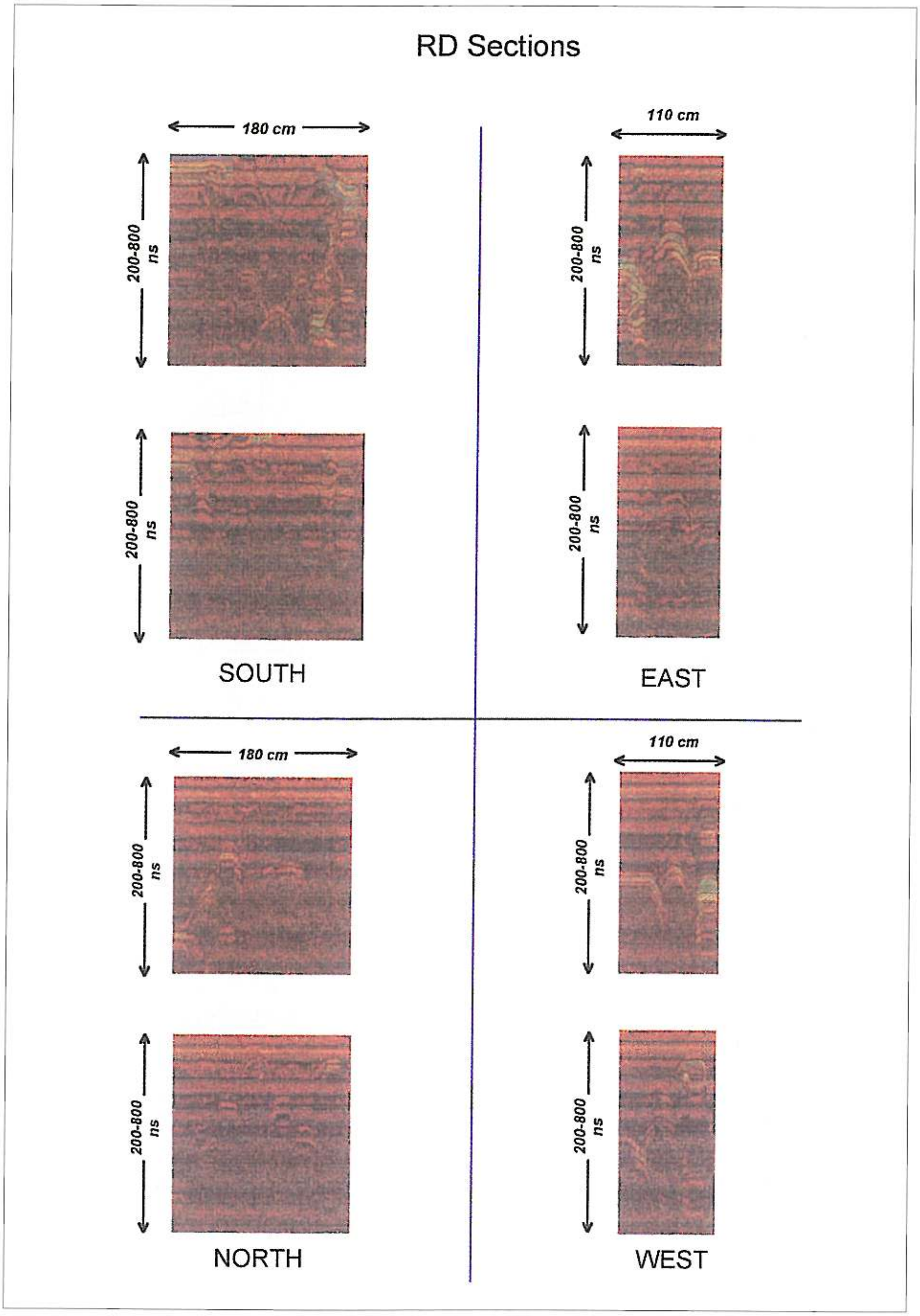

Fig. 11. The Aksum obelisk (Rome, Italy) case history. Radar sections astride the second main junction from the bottom. On each side of the obelisk two profiles are depicted. The top profiles are 20 cm above the junction, while the bottom profiles are 20 cm below the junction.

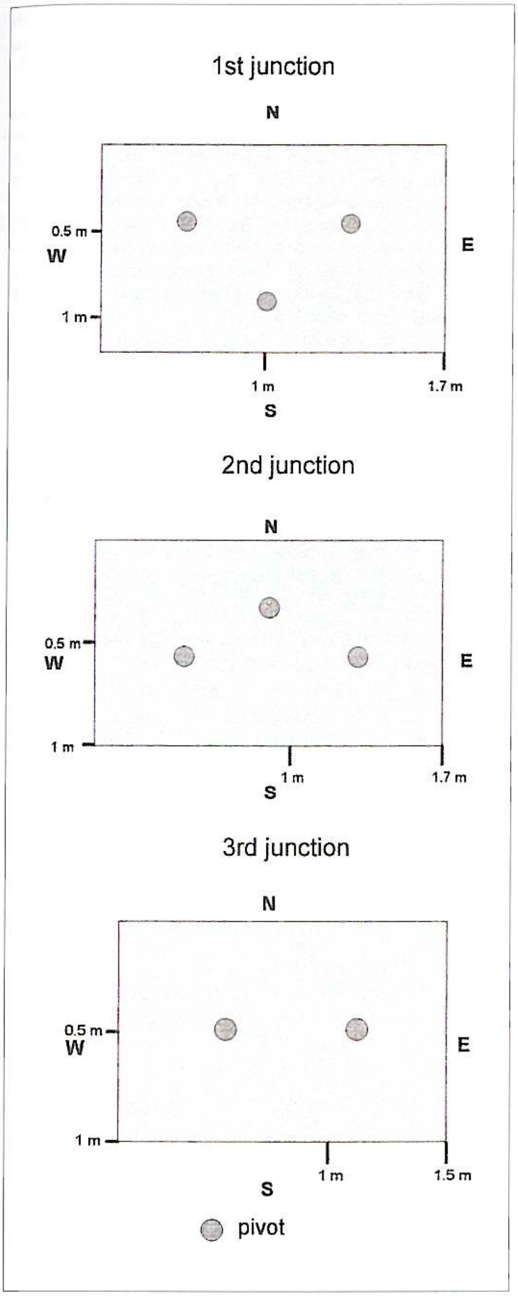

Fig. 12. The Aksum obelisk (Rome, Italy) case history. Locations of the pivots across the three main junctions from the bottom, resulting from the interpretation of the radar sections.

time sections close to the junctions as for example clearly shown by the radargrams reported in fig. 11, which refer to the second junction. These anomalies were attributed to the principal pivots inserted across the surface of separation of the blocks. We estimated an average propagation velocity of 9 cm/ns for the electromagnetic impulse in the rock of the obelisk. Using this velocity we were finally able to obtain information about the true position of the pivots inside the obelisk, as indicated in fig. 12.

4. Conclusions

We have presented the results of an integrated application of the self-potential and resistivity methods to the recognition of buried remains in the archaeological site of Sumhuram (Khor-Rouri, Oman), and of the self-potential, resistivity and radar methods to the assessment of the state of conservation of the Aksum obelisk (Rome, Italy).

A tomography imaging method based on the concept of anomaly source occurrence probability was used for the analysis of the self-potential and resistivity data. The rationale of the method is the search of similarities between the measured data sequence and the surface signature of the electrical signal generated by a scanning elementary source with unitary positive strength. The elementary scanner is ideally moved within a selected cross-section through the target-space and a regular 2D matrix of anomaly occurrence probability values is thus obtained. A sequence of parallel 2D tomographic slices is finally elaborated in order to outline the 3D anomaly source geometry within the explored structure. It must be stressed that the new tomographic approach, though following the same high-resolution strategy as other current methods, differs from them in that it does not require any fundamental *a priori* information. The new method deals uniquely with the pure physical aspects of the interaction of the impressed (natural or artificial) electric field with the buried features.

In the archaeological site of Sumhuram, the electrical tomographies integrated by an architectural model of the town allowed us to draw a map of the main features interpretable as wall remains. The electrical tomographies at different levels along the Aksum obelisk instead allowed us to distinguish stone blocks with different states of conservation. A complementary application of the radar method along profiles close to the junctions of the main original blocks forming the obelisk also allowed us to reconstruct the geometry of the pivots that were used to reassemble these blocks.

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