Joint application of radio-magnetotelluric and electrical imaging surveys in complex subsurface environments

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Introduction

Electrical resistivity surveying has long been recognized as an important tool in the investigation of the subsurface in groundwater and extractive mineral investigations. However, in many situations popular resistivity sounding provides only a simplistic model of the subsurface especially where, in reality, considerable heterogeneity may exist. In these cases other techniques such as electrical mapping and electrical imaging (tomography) may provide the additional details required. In this study the joint application of rapid resistivity mapping is investigated using the radio-magnetotelluric technique and electrical imaging surveys over two contrasting geological environments in the British East Midlands. One area comprises a thickness of around 6 m of sands and gravels overlying Triassic marl and is part of an area which is currently the subject of a detailed hydrogeological investigation. The second is an area where a varying thickness of Triassic mudstones overlie a buried Precambrian topography. Here the Precambrian comprises hard metavolcanics which are quarried locally for roadstone and other uses.

Radio-magnetotelluric surveys

Radio-magnetotellurics (RMT) is similar in principle to the very low frequency-resistivity technique (VLF-r), but electromagnetic fields used in RMT originate from remote radio transmitters in the 3–300 kHz frequency band. Measurement consists in obtaining the electric field (Ex) in the direction of the transmitter with a pair of electrodes pushed into the ground 5 m apart, and the magnetic field (Hy) with a coil of 0.4 m diameter the axis of which is horizontal and at right angles to the transmitting direction (Fig. 1). The apparent resistivity is calculated from the ratio Ex/Hy according to Cagniard (1953); the phase shift between Ex and Hy is also measured. The depth of investigation, according to the skin depth formula (Telford *et al.* 1990), can be varied by using different radio-frequencies at the same point; in this way a simple frequency sounding is carried out. Field data were collected with an RMT system developed at the University of Neuchâtel, Switzerland. Further information related to this equipment and its methodology can be found in Thierrin and Müller (1988) and Turberg *et al.* (1994).

Electrical imaging

Electrical imaging is a survey technique for the investigation of areas of complex geology. It involves measuring a series of constant separation resistivity profiles with the electrode separation being increased with each successive traverse (Fig. 1). Since increasing separation also increases the depth of investigation, the measured apparent resistivities may be plotted as a pseudosection in the normal way. Length of profile, depth penetration and resolution are determined by the unit electrode spacing which can be anywhere from 1 m to 50 m or more.

For the surveys described here, a Campus multicore cable imaging system, using electrode spacings of 2 m and 5 m, was employed with up to 50 electrodes being deployed at a time. The cables were connected to a switching module in a Geopulse resistance meter so that all electrodes were addressable as either C_1, C_2, P_1 or P_2. Although any electrode arrangement can be employed, the Wenner arrangement is found to be a good compromise between the lower resolution and greater imaging depth of the two-electrode array and the higher resolution and shallower imaging depth of the dipole–dipole array. All the resistance measurements were collected under the automatic control of a notebook computer linked to the Geopulse through an RS232 port.

The resulting pseudosections were inverted automatically using a two-dimensional algorithm recently developed by Loke and Barker (1995, 1996) with the results being presented as colour contoured depth sections (images) of true resistivity.

Survey 1: Bardon Hill

An area near Bardon Hill Quarry consists of a resistive basement of Precambrian Charnian metavolcanics overlain by Triassic Mercia Mudstones and Quaternary Drift (Hains and Horton 1969). Outcrops of the volcanics

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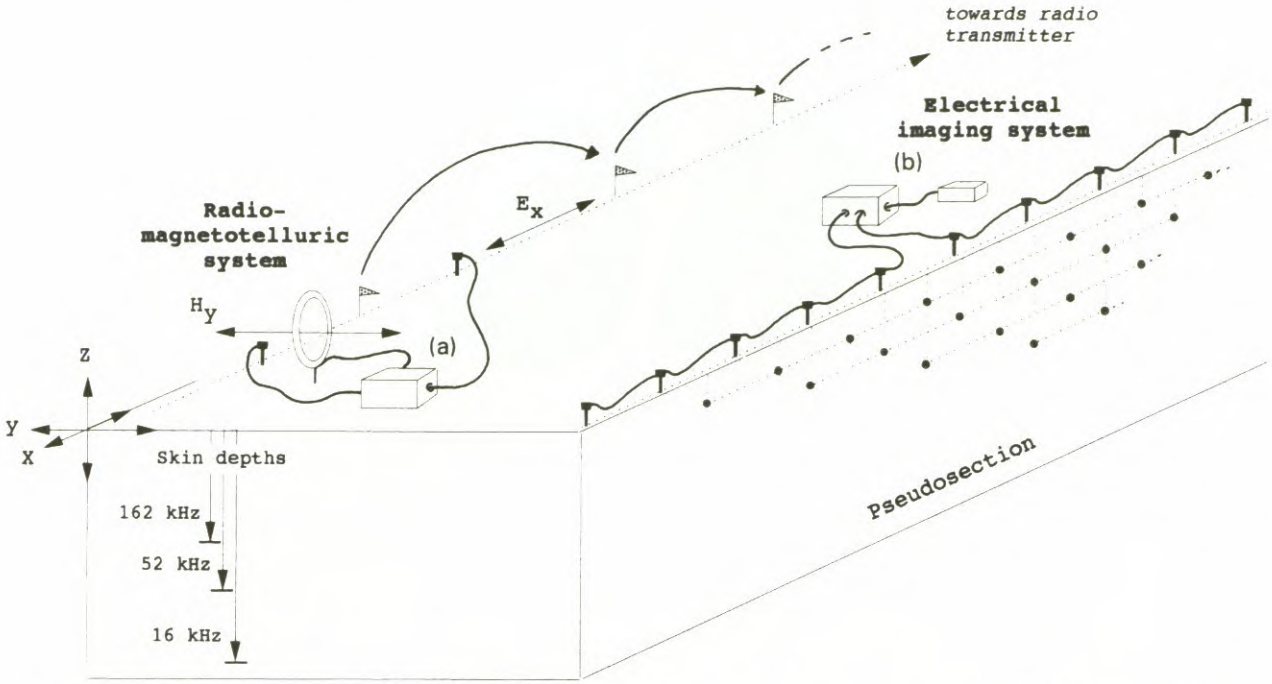

Fig. 1. Radio-magnetotelluric and electrical imaging field layouts; (a) is the resistivity meter and phase meter and (b) is the Geopulse and Imager system with notebook computer giving automatic data collection. In the RMT survey, the ratio Ex/Hy is measured at three frequencies, the three different skin depths giving three different depths of investigation. Dots in the electrical imaging pseudosection represent the depth positions to which the measured apparent resistivity measurements are initially referred.

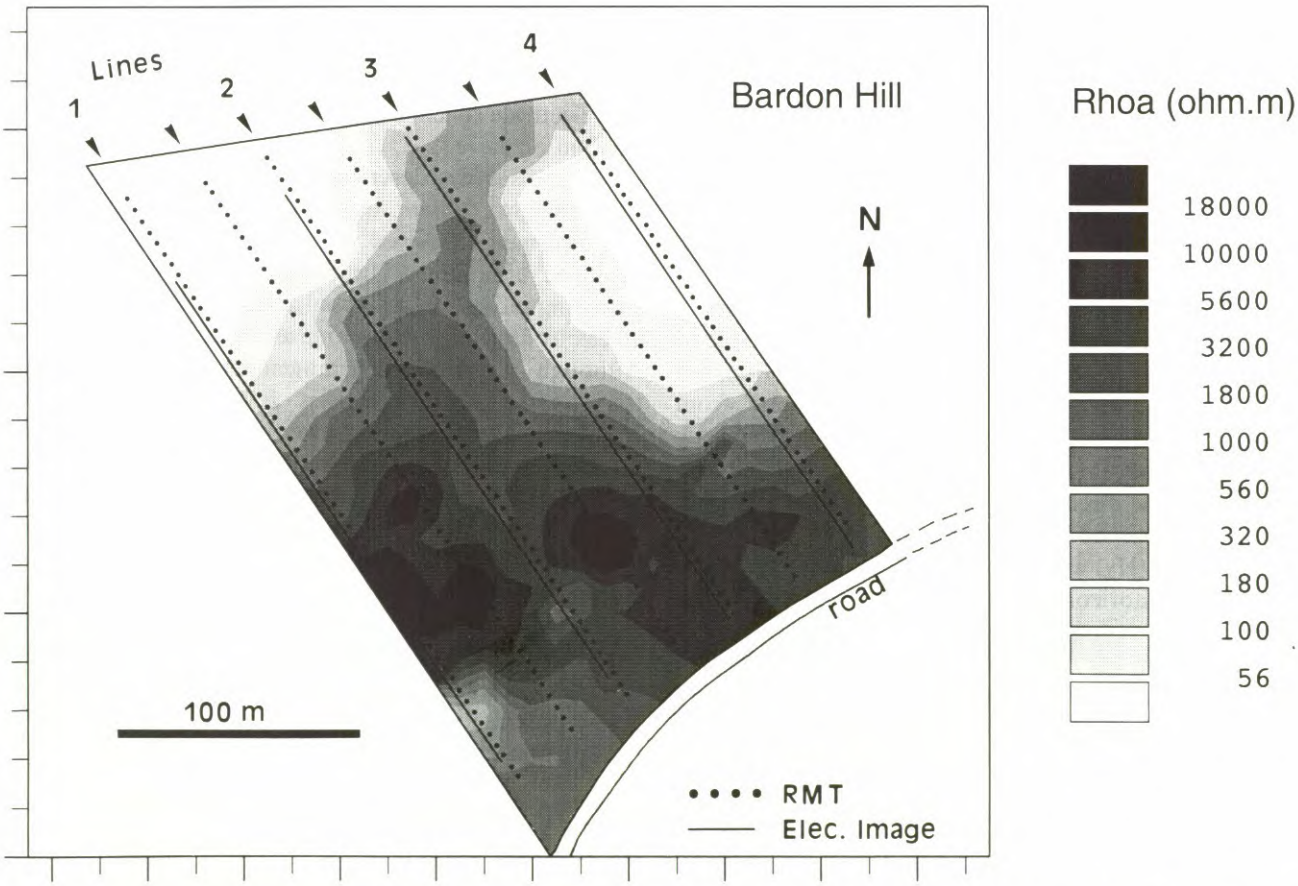

Fig. 2. Interpolated map of apparent resistivity observed by radio-magnetotellurics at Bardon Hill. Location of radio-magnetotelluric profiles (dots) and electrical images (lines).

were found close to the survey area but elsewhere the thickness of the Triassic mudstone was unknown.

Radio-magnetotelluric measurements were made at 5 m intervals using a frequency of 16 kHz (transmitting direction of N170°E) along parallel lines 25 m apart. Values of apparent resistivity are shown contoured in Fig. 2. The values of apparent resistivity have been interpolated by kriging using a spherical function of interpolation defined by variogram analysis. The high values of resistivity in the south indicate shallow bedrock and in fact an outcrop of metavolcanics occurs just to the west of the high-resistivity anomaly on line 1. Elsewhere the bedrock drops below low-resistivity Triassic marl.

Four electrical images were measured along lines 1, 2, 3 and 4 using a 5 m unit electrode spacing. The measurements were made using a Campus Geopulse and Imager system under full computer control so that it was possible to make the RMT measurements along one line while a notebook computer was interrogating 50 electrodes on a different line. This proved to be a very efficient two man field operation. The difference in frequency of operation of the two systems meant that they could be operated closely without interference. Each 200 m electrical image line took just over 2 h to complete including setting out and collection of the cables and electrodes. Although it is possible to collect as many as 300 RMT measurements per hour, this number was reduced to around 150 when both operators were required to reposition the imaging cables.

The apparent resistivity pseudosections were inverted assuming a 2D structure and are shown in Fig. 3. Considering that each line is more than 200 m long but

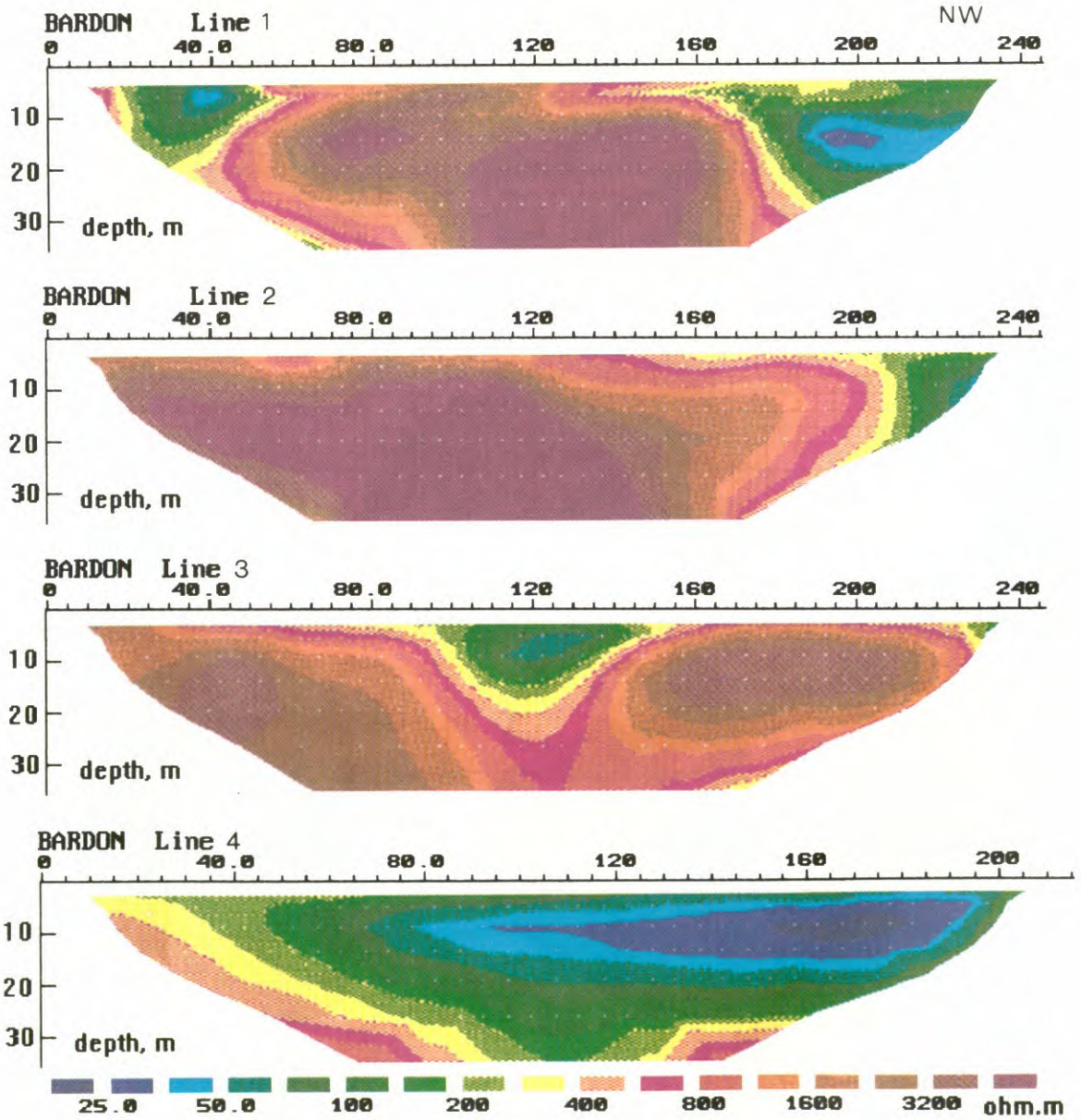

Fig. 3. Electrical images of true resistivity obtained at Bardon Hill along lines 1, 2, 3 and 4.

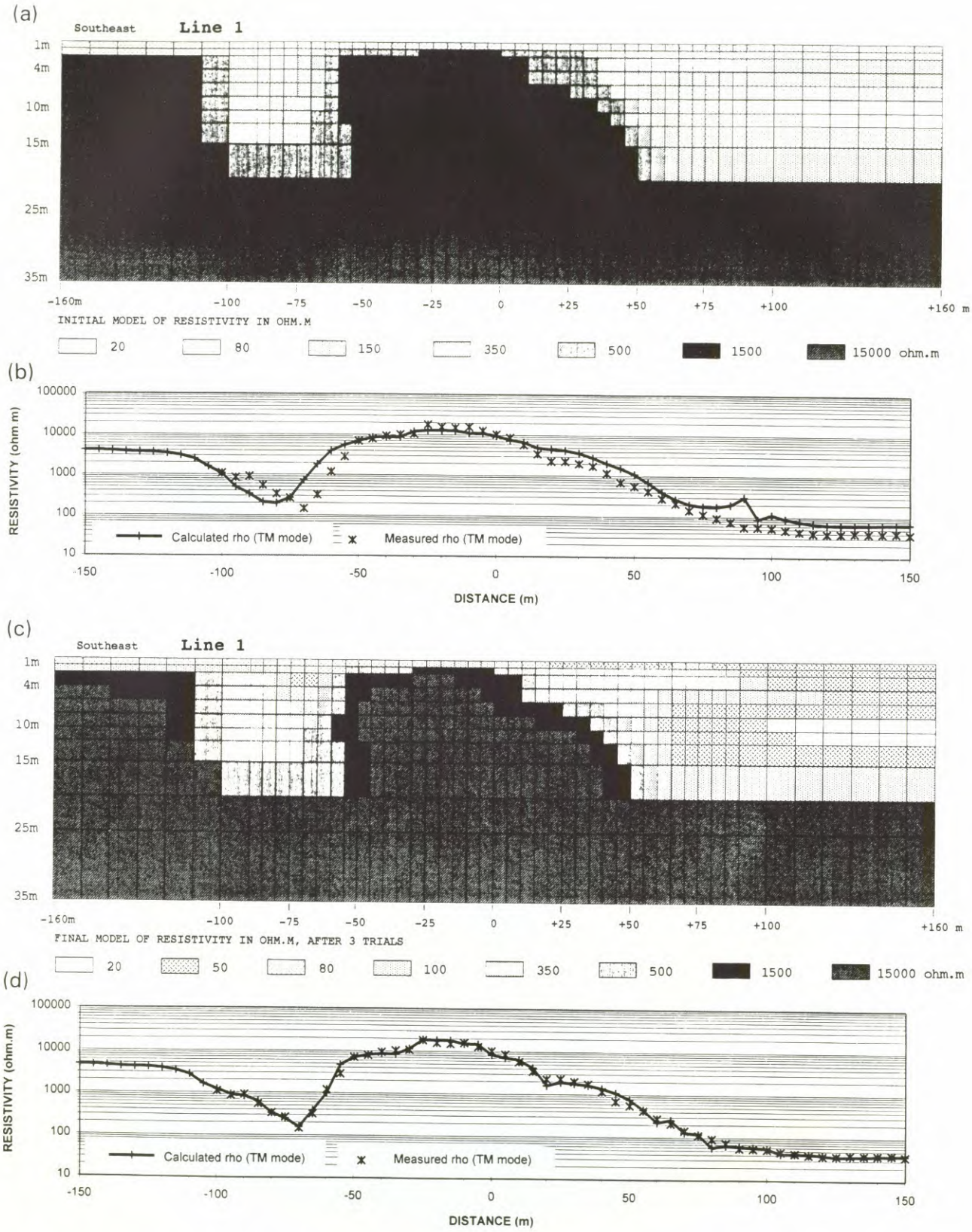

Fig. 4. (a) Simplified block model of resistivity extracted from electrical image along Line 1 at Bardon Hill. (b) Calculated radio-magnetotelluric resistivity from model (a) and comparison with observed data. (c) Final model of resistivity after modifications. (d) Calculated radio-magnetotelluric resistivity from model (c) and comparison with observed data.

separated from its neighbours by only 50 m it is clear that there are strong departures from two-dimensionality. However, the changes in resistivity, showing a variable increase of resistivity with depth, agree closely with the RMT data of Fig. 2.

Lines 1 and 2 suggest that high-resistivity bedrock is at or close to the surface. However, the bedrock drops away rapidly and on line 4 is only apparent on the southeastern end of the profile. Line 3 suggests the presence of a clay-filled valley but comparison with the map of Fig. 2 shows that this is the result of the survey line running close to the edge of the bedrock ridge — sometimes being over shallow bedrock and sometimes over thick clay.

The electrical image of line 1 was selected for detailed comparison with the RMT model. The contour pattern of true resistivity was converted to a block model (Fig. 4a) as input to a magnetotelluric 2D finite-

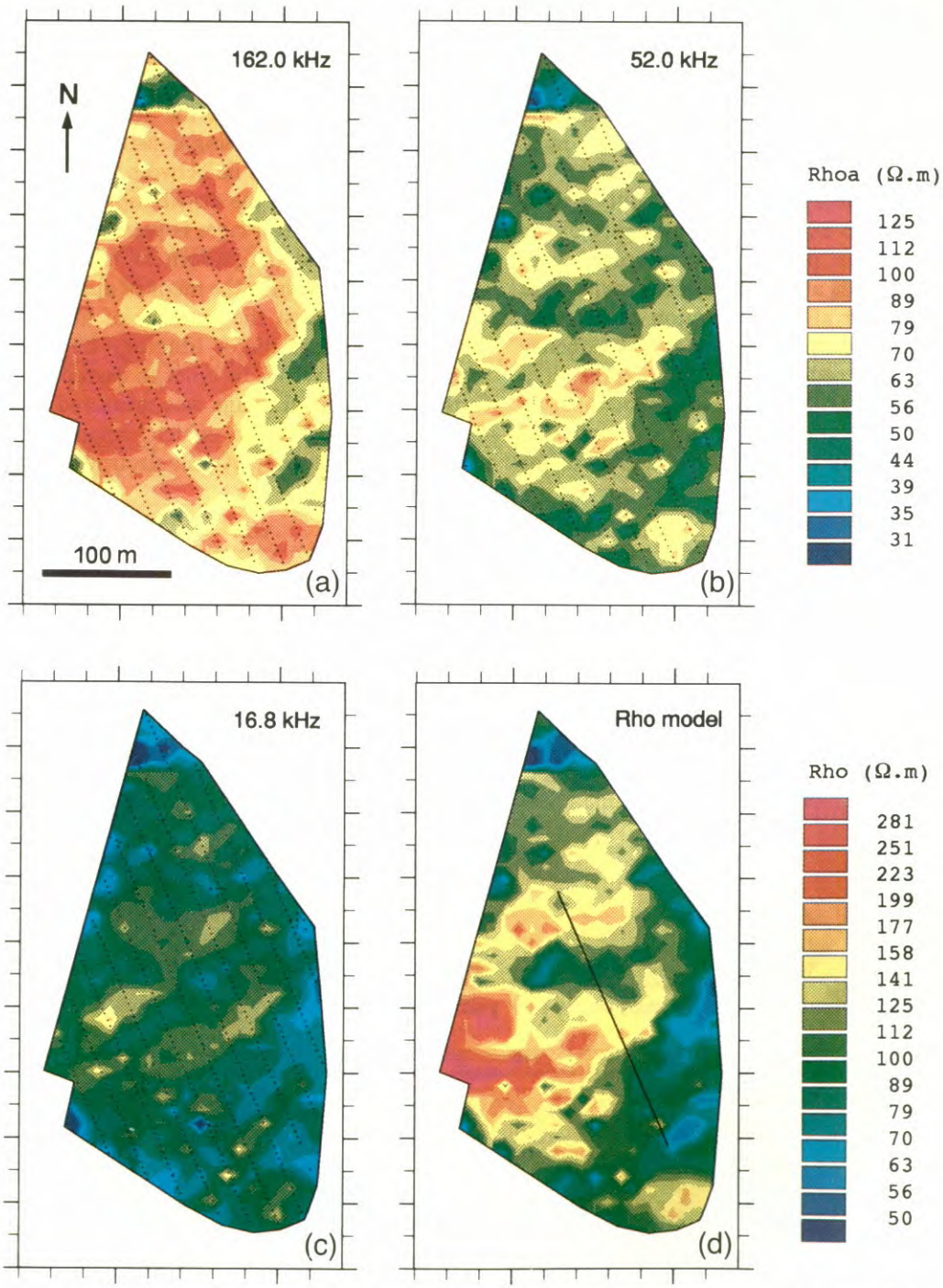

Fig. 5. Interpolated map of apparent resistivity observed by radio-magnetotellurics at Hoveringham at (a)162 kHz (b) 52 kHz and (c)16.8 kHz. (d) Map of the distribution of true resistivity in the gravel and sand layer assuming negligible change of its thickness. Location of radio-magnetotelluric profiles (dots) and electrical image (line).

difference forward modelling program (Steiner 1993). The comparison of the results with the observed RMT data (Fig. 4b) is so close that only minor modifications were necessary in order to achieve a near perfect fit (Fig. 4c and 4d). The necessary changes to the model mainly concerned the near-surface blocks including those which fall outside the field of the image.

Survey 2: Hoveringham Quarry

Thick sand and gravel deposits occur widely along the valley of the River Trent in the East Midlands. These have been extensively quarried and in Hoveringham a study of the hydrogeological impact of the quarrying is being undertaken by Tarmac Quarry Products Ltd. Here a number of boreholes indicate a thickness of ≈ 7 m of alluvium overlying Triassic Mercia Mudstones.

A detailed RMT survey was carried out over a selected area in order to examine the variability of the sand and gravel. Eleven profiles were surveyed with measurements being made at 5 m intervals at frequencies of 162, 52 an 16.8 kHz all in a direction of N340°E. Depth of penetration is dependent on both frequency and resistivity of the medium and skin depths in a medium of resistivity 20 Ωm will be around 6 m at 162 kHz, 10 m at 52 kHz and 17 m at 16.8 kHz and for a resistivity of 100 Ωm, will be 12 m, 22 m and 39 m for the same frequencies, respectively. This selection of frequencies should therefore provide information on thickness variations in the sand and gravel and possibly information on lithological variations.

Contoured apparent resistivities measured at the three frequencies are presented in Fig. 5. The map of Fig. 5a shows the apparent resistivity most responsive to the sands and gravels. As the depth of investigation increases from Fig. 5a to 5b to 5c the apparent resistivity drops as the observations become more responsive to the underlying mudstone. At each measurement point the data from the three frequencies have been interpreted automatically using a 1D inversion algorithm (Fischer *et al.* 1981) with the thickness of the high-resistivity gravel layer being constrained to agree with adjacent boreholes and lie between 6.5 and 7.5 m. This constrained model of the distribution of bulk resistivity of the sand and gravel layer is presented in Fig. 5d. As might be expected the pattern of resistivity change is similar to that shown in the maps of apparent resistivity.

The maps suggest the presence of linear changes in alluvium thickness and/or lithology trending approximately ENE to WSW. In order to examine these trends further an electrical image was measured along one of the RMT lines (Fig. 5d) which crosses the lineations almost perpendicularly. A unit electrode spacing of 2 m

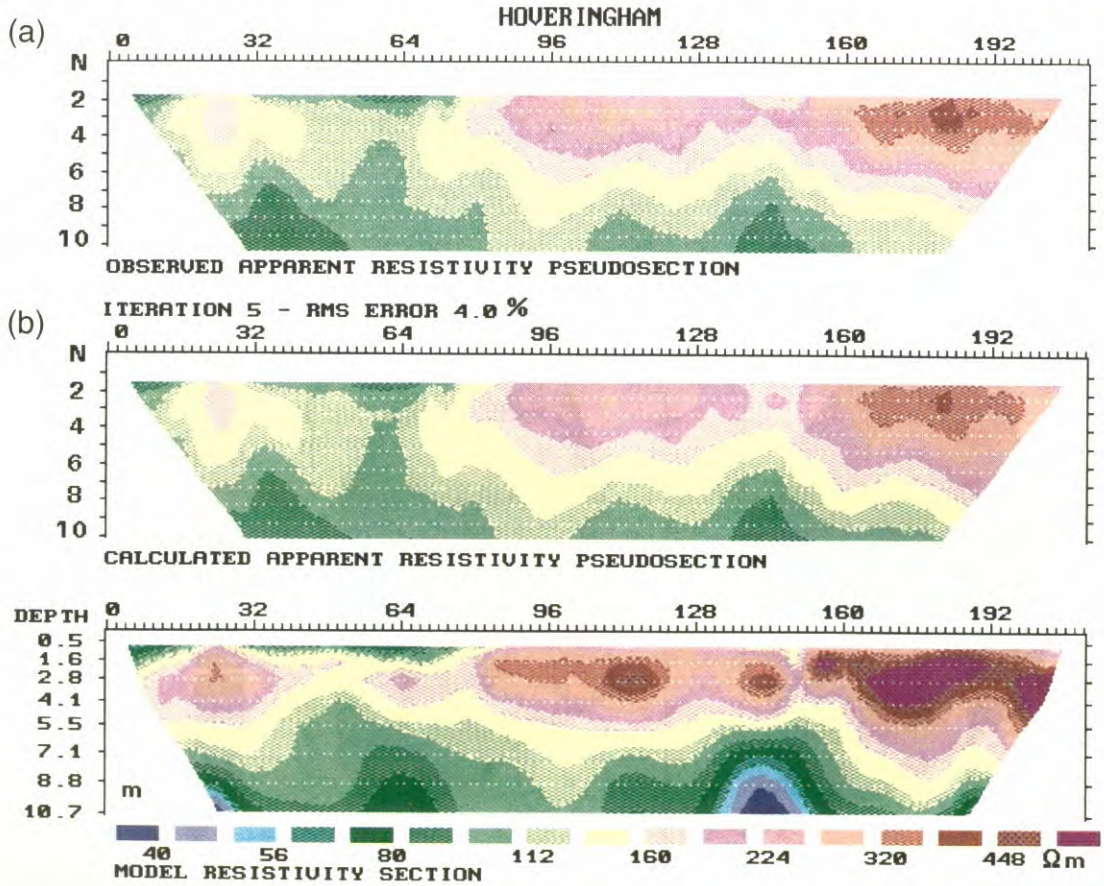

Fig. 6. (a) Pseudosection of apparent resistivity observed at Hoveringham. (b) Corresponding pseudosection of apparent resistivity computed from: (c) model of true resistivity produced from the automatic computer inversion of (a).

was employed with 50 electrodes deployed at any one time. Using a roll-along technique, a total of 107 electrode positions was used and measurements were made with multiples of unit electrode spacing from 1 to 10 giving an image depth of ≈10 m. The measured apparent resistivity pseudosection (Fig. 6) shows a variable high-resistivity layer (the sand and gravel) overlying lower resistivity material (Triassic mudstone) at depth. The inverted image (Fig. 6) has emphasized this variation and suggests changes in both thickness

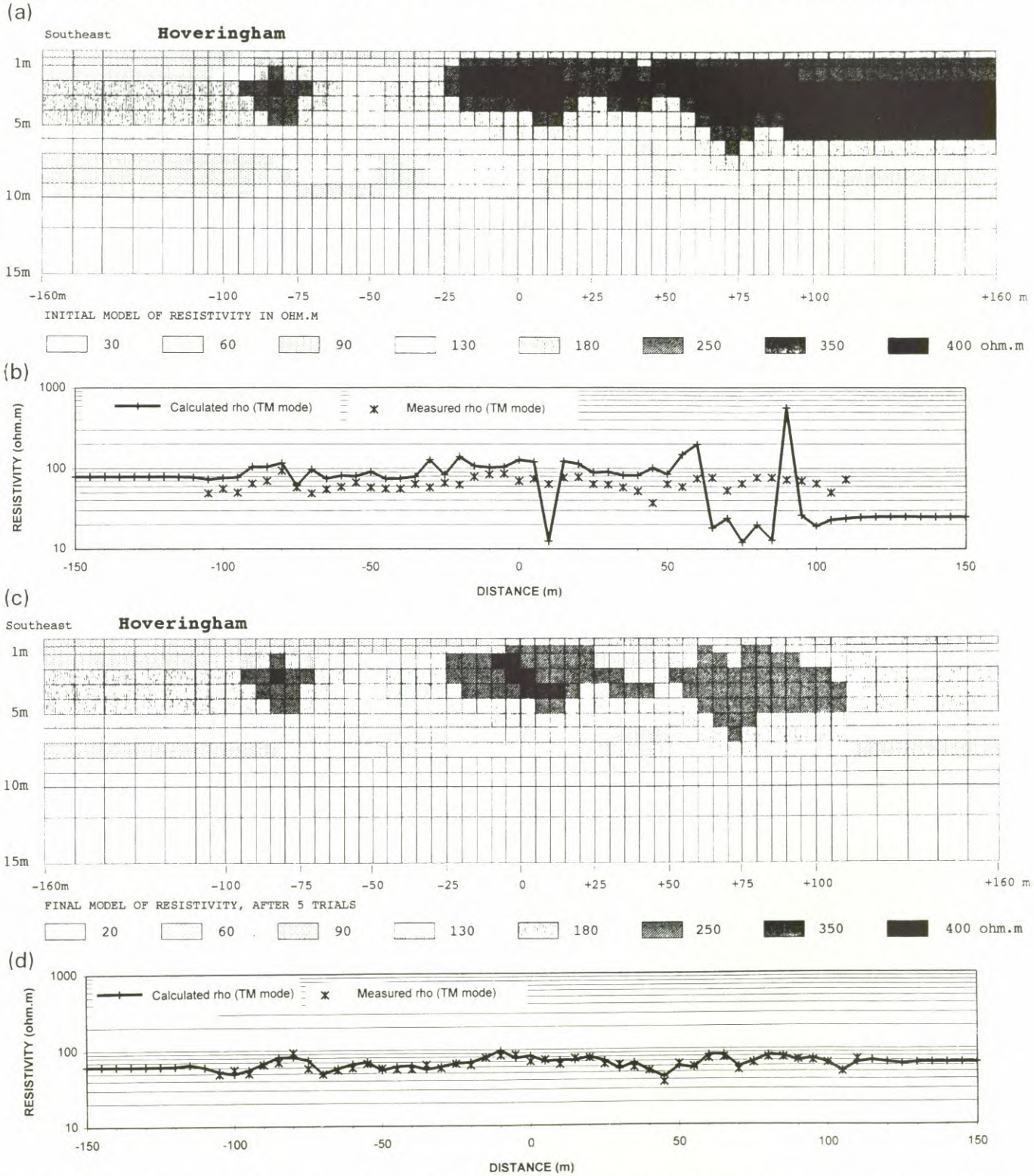

Fig. 7. (a) Simplified block model of resistivity extracted from electrical image at Hoveringham (b) Calculated radio-magnetotelluric resistivity from model (a) and comparison with observed resistivity. (c) Final model of resistivity after modifications. (d) Calculated radio-magnetotelluric resistivity from model (c) and comparison with observed resistivity.

and lithology of the sand. Nearby boreholes, however, suggest that the sand and gravel has a reasonably constant thickness

The RMT data were modelled at 52 kHz using the electrical image as a basis of a 2D model (Fig. 7a). The results do not agree well with the observed data (Fig. 7b) and several sharp drops in apparent resistivity occur. These appear to correspond to the occurrence of blocks of high resistivity in the model. By reducing the resistivity of these blocks and setting all blocks below 8 m, which represent the Triassic mudstones, to a resistivity of 20 Ωm, good agreement with the observed data is achieved (Fig. 7c and 7d).

The initial disagreement between the electrical image and the RMT data is probably the result of traditional 'equivalence' ambiguity problems which have affected the electrical image. However, it is not possible here to rule out over-sensitivity of the RMT model to the same high-resistivity blocks.

Conclusions

By applying joint electrical imaging and radiomagnetotelluric surveys, the determination of the subsurface distribution of resistivity is made more reliable for two reasons. First, the surveys guarantee a better geophysical coverage as RMT will provide a fast lateral imaging of the survey area while electrical imaging will provide detailed sections of it. Secondly, this kind of survey can point out specific pitfalls related to each method, possibly due to artifacts during the data processing or due to different sensitivities to lateral effects. A problem which affects the RMT survey and is not considered here is its high sensitivity to the direction of measurement in relation to the strike of the geophysical structure. The electrical image inversion is also sensitive to direction as it assumes a two-dimensionality. However, the errors can be reduced by siting the image lines on the basis of the RMT survey.

On both sites, the main geophysical variations were detected by both techniques. The comparative modelling of these variations shows, however, that differences between electrical imaging and radio-magnetotelluric models of resistivity can be locally significant, mainly in terms of absolute resistivity values (e.g. Hoveringham). Nevertheless, these differences do not alter the general structure of resistivity of the sites as Figs 4 and 7 show.

Surveys at both sites confirm significant lateral changes in resistivity of the subsurface. These variations are complex but clearly organized, even within geological units usually considered as laterally uniform (e.g. Hoveringham). This detailed information could not have been achieved through the use of classical electrical sounding which would appear improper, particularly at the Bardon Hill site. Greater accuracy could be achieved with 3D surveys but only at much greater cost. A combination of 2D imaging with a fast mapping tool appears to be a very cost-efficient combination of techniques.

Acknowledgements

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References

CAGNIARD, L. 1953. Basic theory of the magnetotelluric method of geophysical prospecting. *Geophysics* **18,** 605–635.

FISCHER, G., SCHNEGG, P.-A., PEGUIRON, M. and Le QUANG, B.V. 1981 An analytic one-dimensional magnetotelluric inversion scheme. *Geophysical Journal of the Royal Astronomical Society* **67,** 257–278.

GRIFFITHS, D.H. and BARKER, R.D. 1993. Two-dimensional resistivity imaging and modelling in areas of complex geology. *Journal of Applied Geophysics* **29,** 211–226.

HAINS, B.A. and HORTON, B. 1969. *British Regional Geology, Central England.* Natural Environment Research Council, Institute of Geological Sciences, London. HMSO, Third edn.

LOKE, M.H. and BARKER, R.D. 1995. Least squares deconvolution of apparent resistivity pseudosections. *Geophysics* **60,** 1682–1690.

LOKE, M.H. and BARKER, R.D. 1995. Rapid least squares inversion of apparent resistivity pseudosections by a quasi-Newton method. *Geophysical Prospecting* **44,** 131–152.

STEINER, T. 1993. Numerical electromagnetic magnetotelluric modelling and inversion. Thesis. Sopron.

TELFORD, W.M., GELDART, L.P. and SHERIFF, R.E. 1990. *Applied Geophysics*, 2nd edn. Cambridge University Press, Cambridge.

THIERRIN, J. and MÜLLER, I. 1988. La méthode VLF-Resistivité multifréquence, un exemple d'exploration hydrogéologique dans un synclinal Cretacé à la Brévine. Quatrième Colloque de Hydrologie en Pays calcaire et en milieu fissuré, Besançon 29 September–1 October 1988. *Annales scientifiques d'Université de Besançon* **6,** 17–24.

TURBERG, P., MÜLLER, I. and FLURY, F. 1994. Hydrogeological investigation of porous environments by radiomagnetotelluric-resistivity. *Journal of Applied Geophysics* **31,** 133–143.