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2D inversion of the Magnetotelluric data from Travale Geothermal Field in Italy

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Abstract

A detailed study of the exploited geothermal field of Travale in Italy was conducted using Magnetotelluric (MT) data in 2004. This paper detects the main features of the conductivity structures of this area. For subsurface mapping purpose, the long period natural-field MT method proved very useful. For processing and modeling of the MT data, 2D inversion schemes were used and to have the best possible interpretation all modes of data were examined.

The resistivity model obtained from MT data is consistent with the geological model of the Travale region down to five kilometers. The current MT results reveal the presence of a deep geothermal reservoir in the area. Recognition of the conductive zones in the resistive basement in many sites can clearly be interpreted as the flow of the fluids in the faults and fractures of the metamorphic rocks.

Key words: Geothermal field, Magnetotelluric, Travale, 2D inversion, Resistivity

تفسیر دوبُعدی داده‌های مگنتوتلوریک میدان زمین‌گرمایی تراواله در ایتالیا

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چکیده

بررسی تفضیلی میدان زمین‌گرمایی بهره‌برداری شده تراواله در ایتالیا با استفاده از داده‌های مگنتوتلوریک (MT) در سال ۲۰۰۴ صورت گرفته است. این بررسی، ساختارهای رسانای اصلی این منطقه را آشکار می‌کند. روش میدان طبیعی MT با دورهٔ بلند روش بسیار مفیدی در به نقشه درآوردن زیرسطح شناخته شده است. به‌منظور مدل‌سازی و پردازش داده‌های MT از برنامه وارون‌سازی دوبُعدی استفاده و برای داشتن بهترین تفسیر ممکن همه مدهای داده‌ها امتحان شده است.

مقطع مقاومت ویژه که از داده‌های MT به‌دست آمده با مدل زمین‌شناسی ناحیه تراواله تا عمق ۵ کیلومتر سازگار است. نتایج حاصل از این تحقیق، وجود مخزن زمین‌گرمایی عمیقی را در این ناحیه آشکار می‌کند. تشخیص زون‌های رسانا در سنگ‌بستر مقاوم در بسیاری از سایت‌ها به وضوح می‌تواند درحکم جریان شاره‌ها در گسل‌ها و درز و شکاف‌های سنگ‌های دگرگونی تفسیر شود.

واژه‌های کلیدی: میدان زمین‌گرمایی، مگنتوتلوریک، تراواله، وارون‌سازی دوبُعدی، مقاومت ویژه

1 INTRODUCTION

Geothermal resources are ideal targets for electromagnetic (EM) methods since they produce strong variations in underground electrical resistivity. In thermal areas, the

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electrical resistivity is substantially different from and generally lower than in areas with colder subsurface temperature (Oskooi et al., 2005). Of the various EM methods, magnetotelluric (MT) was found to be particularly effective in defining the subsurface geology since its ability to map deep conductive features let it play a valuable role in the reconnaissance of deep geothermal systems. The depth of investigation of MT is much higher than that of other EM methods, which are usually unable to define geological features and detect geothermal reservoirs deeper than 1-2 km.

This paper includes only two-dimensional (2D) inversion and aims at the recognition of the characterization of Larderello-Travale geothermal system in Italy (Fig. 1). MT survey was carried out using high and low frequency MT systems in Travale area in May-September 2004.

MT processing codes from Larsen et al. (1996), Smirnov (2003) and Egbert (1997) were investigated for data sets from high and low frequency systems.

The main faults, geothermal and volcanic areas in Tuscany, Italy, are shown in Fig. 2. A study by Fiordelisi et al. (1998) characterizes Southern Tuscany as a fairly uniform middle-lower crust with a resistivity of a few thousand ohm below 10 km. At shallower depth the resistivity is around 500 ohm. At geothermal fields, where deep conductors associated with geothermal fluids exist, lower resistivities are expected.

The model along BB' (see Fig. 2 and 3), shown in the middle is of interest since it coincides with our main MT profiles.

Southern Tuscany has been extensively explored by MT method for more than three decades. MT soundings in the Travale area were performed by Celati et al. (1973). Later Hutton (1985), Hutton et al. (1985), Schwarz et al. (1985) and Berktold et al. (1985) carried out more MT investigations in the area. The results were that Southern Tuscany is electrically very heterogeneous and the basement has a resistivity of only a few thousand ohm below 4 km, which is much lower than the resistivity of metamorphic formations in other parts of the world.

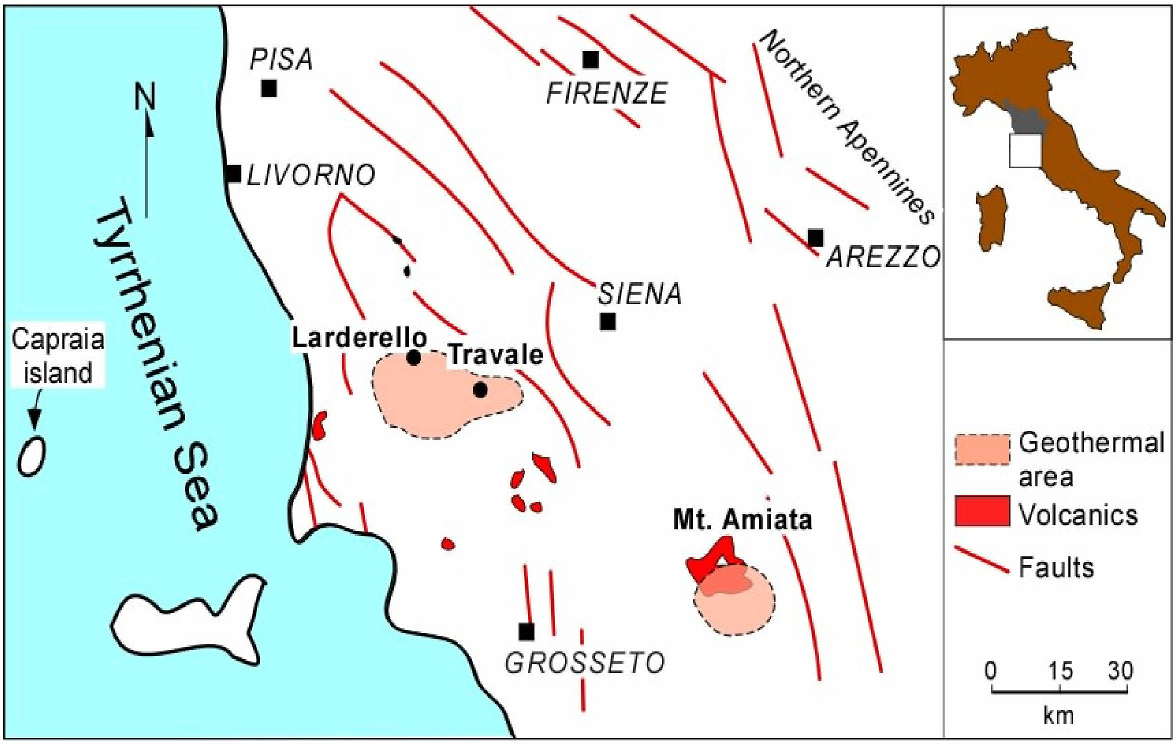

Figure 1. Simplified geological map of area of study.

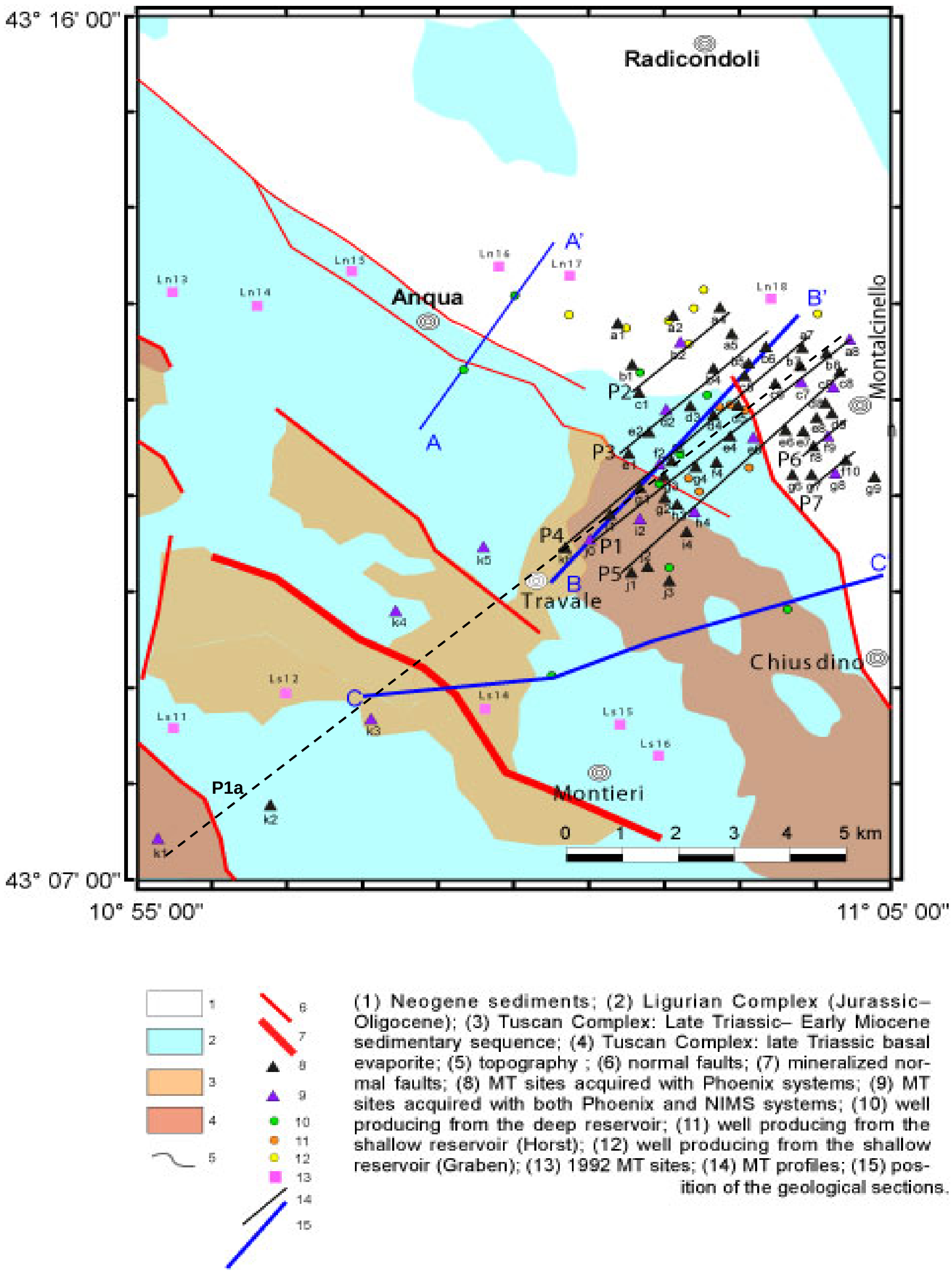

Figure 2. Simplified geological map of the Travale area. The locations of the geological cross sections, MT sites and MT profiles are shown (Manzella, 2004).

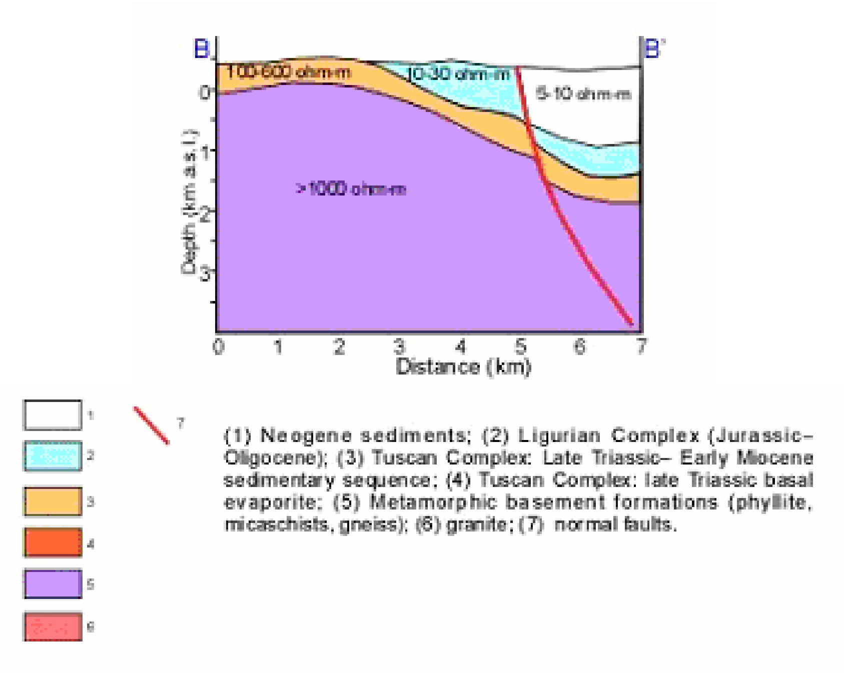

Figure 3. Geological cross-section, location is shown in Fig. 1 (Manzella, 2004).

2 MAGNETOTELLURIC CONCEPTS

MT uses the natural, time-varying electric and magnetic fields at the surface of the earth to make inferences about the earth's electrical structure which, in turn, can be related to the geology, tectonics and subsurface conditions. The MT method was first introduced by Tikhonov (1950) and Cagniard (1953) and developed further by Cantwell (1960) and Vozoff (1972, 1991). Measurements of the horizontal components of the natural electromagnetic field are used to construct the full complex impedance tensor (Cantwell and Madden, 1960), Z, as a function of frequency,

$$Z = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} \quad (1)$$

indicating the lateral and vertical variations of the subsurface electrical conductivity at a given measurement site. Impedance tensor provides information on dimensionality and strike of the conductive structures as well. Apparent resistivity, ρ_a, and phase, ϕ, are the desired quantities calculated through the following relations,

$$\rho_{ai} = \frac{1}{\mu_0 \omega}|Z_i|^2, \quad i = xx, xy, yx, yy, \ DET \quad (2)$$

$$\phi_i = \text{phase}(Z_i) \quad (3)$$

Where μ_0 is the permeability of free space, ω is the angular frequency and DET denotes the determinant data.

Time series measurements collected in various frequency ranges are transformed into frequency domain, and cross power spectra are computed to estimate the impedance tensor as a function of frequency. The determinant of impedance tensor which is also called the effective impedance, Z_{DET} (Pedersen and Engels, 2005), is defined as,

$$Z_{DET} = \sqrt{Z_{xx}Z_{yy} - Z_{xy}Z_{yx}} \quad (4)$$

Using the effective impedance, determinant apparent resistivities and phases are computed. The advantage of using the determinant data is that it provides a useful average of the impedance for all current directions. Furthermore, no mode identifications (transverse electric, TE mode: current in parallel with the strike; or transverse magnetic, TM-mode: current perpendicular to the strike) are required, static shift corrections are not made, and the dimensionality of the data is not considered, since the effective impedance is believed to represent an average that provides robust 1D and 2D models. However, the geology and tectonics of the area as well as the dimensionality analysis of the MT data may suggest a dominant geological structure strike direction. Therefore, joint inversion of the TE- and TM- mode data along profiles approximately perpendicular to the strike of the structure are performed. If the presumed strike is estimated precisely the results of a joint TE- and TM-mode data are comparable with the results of the inversion of the determinant data along the profiles, although there may be differences in resolving main conductors along the MT-profiles where the stations spacing are large.

For a 2D Earth, electrical conductivity is constant along one horizontal direction (along strike) and Maxwell's equations separate into TE (E-polarization) and TM (H-polarization) modes. Assuming a co-ordinate system with x-axis parallel to the strike (y-axis along the profile) where the profile is perpendicular to the strike and z-axis downwards, TE-mode describes the electric field component, Ex, and Magnetic field components, Hy and Hz. In TE-mode electric currents flow parallel to the structure strike. TM-mode describes field components Hx, Ey and Hz when currents flow perpendicular to the structure strike. In a 2D case diagonal elements of the impedance are equal to zero.

In practice measurements are made in an arbitrary co-ordinate system. Therefore, impedance tensor must be rotated to a proper geologic strike direction prior to further analysis and modelling.

3 EM DATA ACQUISITION

Five Phoenix (300 – 0.0003 Hz) and three NIMS (1- 0.0003 Hz) MT systems operating at low frequency were used in the main survey together with proper magnetic coils, Fluxgates and required electric electrodes. During the first three weeks of September 2004, five channels including two horizontal electric components and two horizontal and the vertical magnetic components were measured at pre-located sites and some new sites. All MT-sites are marked on the location map of Figure 2.

Seven geophysicists, an Iranian (the first author), two Italians and four Russians were involved in the data acquisition, field data processing and preliminary interpretation. Two geologists from Italy provided preliminary information and guidance to the field crews during the campaign. Necessary items for the field campaign for instance note-book PC's, desktop PC's, compasses, hand-held GPS receivers, batteries, cables, mobile phones, 4WD cars and etc. were in service accordingly.

Time domain electromagnetic (TDEM) data at eight sites were measured using Tem-Fast 48 Transmitter-Receiver System. In our case static shift corrections on MT data have been done using TDEM results and the geologic information as the final steps of data processing.

In this study, data within a period range of 0.001-1000 s were analyzed. Overnight MT recording in the range 0.001-1000 Hz for minimum 12 hours per site has been followed by four Phoenix systems whereas the lowest frequency data were collected by two NIMS systems over three-day period. Long time data collection is necessary to recover the proper signals from noise using statistical approaches.

To overcome the noise problem in the area, a remote site was designed on the island of Sardinia, some 500 km away the area of study.

4 MT DATA PROCESSING

Data processing was performed using the single site (SS) and remote reference (RR) robust processing codes of Larsen et al. (1996), and SSMT2000 software (Phoenix Geophysics). As a result some of the noisiest sites/frequencies were excluded from the database. The level of industrial/electrified train noise in the survey area is high, making the remote reference estimation necessary.

The final results of remote reference processing for data from most sites were of a reasonable quality. For some sites very bad electric field data were gathered in either x or y direction, most probably due to the currents directed from various power-lines in the area, geothermal activities, electrified trains or active power-plants. Only one main component of the impedance was used for further analysis for such sites.

5 STATIC SHIFT CORRECTIONS

The static shift of MT apparent resistivity sounding curves is a classic example of the galvanic effect. MT sounding curves are shifted upward when measuring directly over surficial resistive bodies and they are depressed over conductive patches. The physical principles governing electromagnetic (EM) distortions due to near-surface inhomogenities have been understood for several decades and several methods appeared to correct these distortions. Two of these methods are: use of invariant response parameters (like the determinant data) and curve shifting (Jiracek, 1990). Results from TDEM and also detailed known geology were applied for static shift corrections on all data.

6 RESULTS OF THE DIMENSIONALITY ANALYSIS OF DATA

Swift's skew (Swift, 1967), defined as the ratio of the on- and off-diagonal impedance elements, approaches zero when the medium is 1-D or 2-D. Swift's skews are rather small for the majority of sites/frequencies along profiles 1 (Fig. 4).

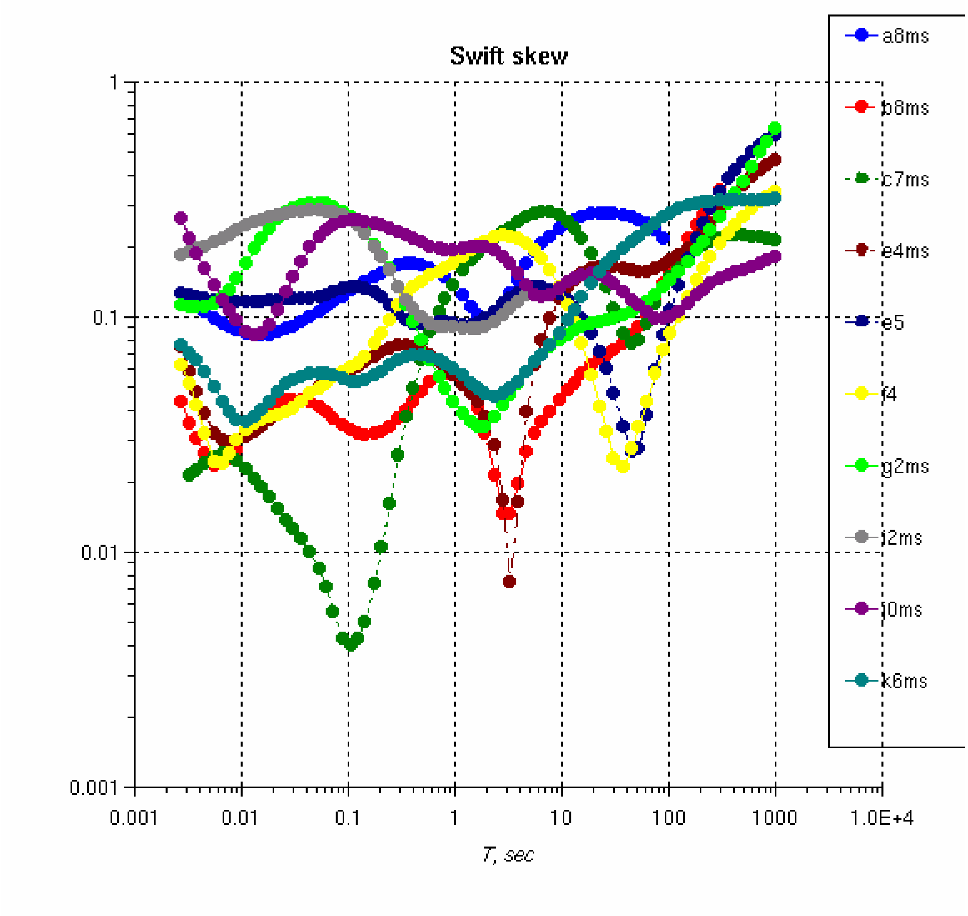

Figure 4. Swift’s skew for sites along profile 1.

7 2D INVERSION, CODES AND RESULTS

The 1D inversion of the data is discussed in Oskooi (2006). 2D modeling has been applied on the data. Models explain the data if their responses fit the measured data within their errors. Generally, the better the fit between measured and predicted data, the better the model resolution.

2D inversion of TE-, TM-, TE+TM- and DET-mode data using a code from Siripunvaraporn and Egbert (2000) were performed. The data were calculated as apparent resistivities and phases. Static shifts were corrected prior to the inversion based upon the geology and TDEM results.

In this paper, subset of Phoenix data along profile 1 were used for the 2D inversion. The profile is in the direction of SW-NE, with receiver spacing of approximately 500 m. The TE and TM responses appear quite uniform over the short periods up to 1 s for most sites suggesting that the surface structure is 1D to a first approximation. At longer periods the TE and TM responses diverge, indicating higher dimensional structure at greater depth. Blocks having widths of the distances between sites were mostly used as model parameters. Most sites exhibit nearly the same conductivity contrast with neighboring sites except that in the southwestern part of profiles the resistivities are increasing with an order of one. Since it is assumed that the earth structure is largely 2D for the purpose of 2D inversion, 3D structure will appear in the data as noise. To avoid probable unrealistic small errors on the data for the 2D approximation an error floor of 5% on the apparent resistivity was defined.

MT data were collected in the period range 0.001 – 1000 s which by taking into account that the average resistivity of the area is extremely low we consider a maximum depth penetration of about 5 km for our models.

Data along proper the profile rotated to the direction of presumed strike of N45W for 2D inversion purpose. Apparent resistivity and phase data exhibit fairly different characteristics in TE- and TM-mode and 2D modeling would therefore be expected to provide a more reasonable approximation of the true subsurface structure.

For 2D modeling purposes corresponding MT-sites were projected on 7 straight lines numbered from 1 to 7 as shown in Fig. 2. In this report we focus on the 2D results of profile 1 which is more informative.

The resistivity models from the inversion of TE-mode and TM-mode data and corresponding apparent resistivity and phase data and model responses are shown in Fig. 5 and 6. Joint 2D inversion of the TE- and TM-mode data is completed in order to derive an overall picture of the subsurface conductivity structure that would explain the data from both polarisations simultaneously. Resistivity model from the joint inversion is shown in Fig. 7 together with corresponding model responses and observed data. The resulting model, data and model responses of the determinant are depicted in Fig. 8. The model is somewhat very similar to the model obtained from the joint inversion.

7.1 2D INVERSION OF DATA USING THE BB' CROSS SECTION AS THE INITIAL AND A PRIOR MODEL

Using an electrical resistivity model (Fig. 9) constructed from the geological cross section of BB' (Fig. 3) as the initial and a priori model. inversion results of various modes of data are shown in Figs. 10 to 13.

The resistivity model from the inversion of TE-mode data and corresponding apparent resistivity and phase data and model responses are shown in Fig. 10. The conductive unit in the NE half of the profile which continues from the surface to about 2 km coincides with the geological cross section of BB' in Fig. 3. There is a sharp transition from this conductor to a more resistive unit all along the profile. To the SW this conductor changes into a resistive unit at the surface down to the 1.5 km. From this depth in SW of the profile, below sites K6, J0 and I2, a conductive unit appears to be extended to deeper levels.

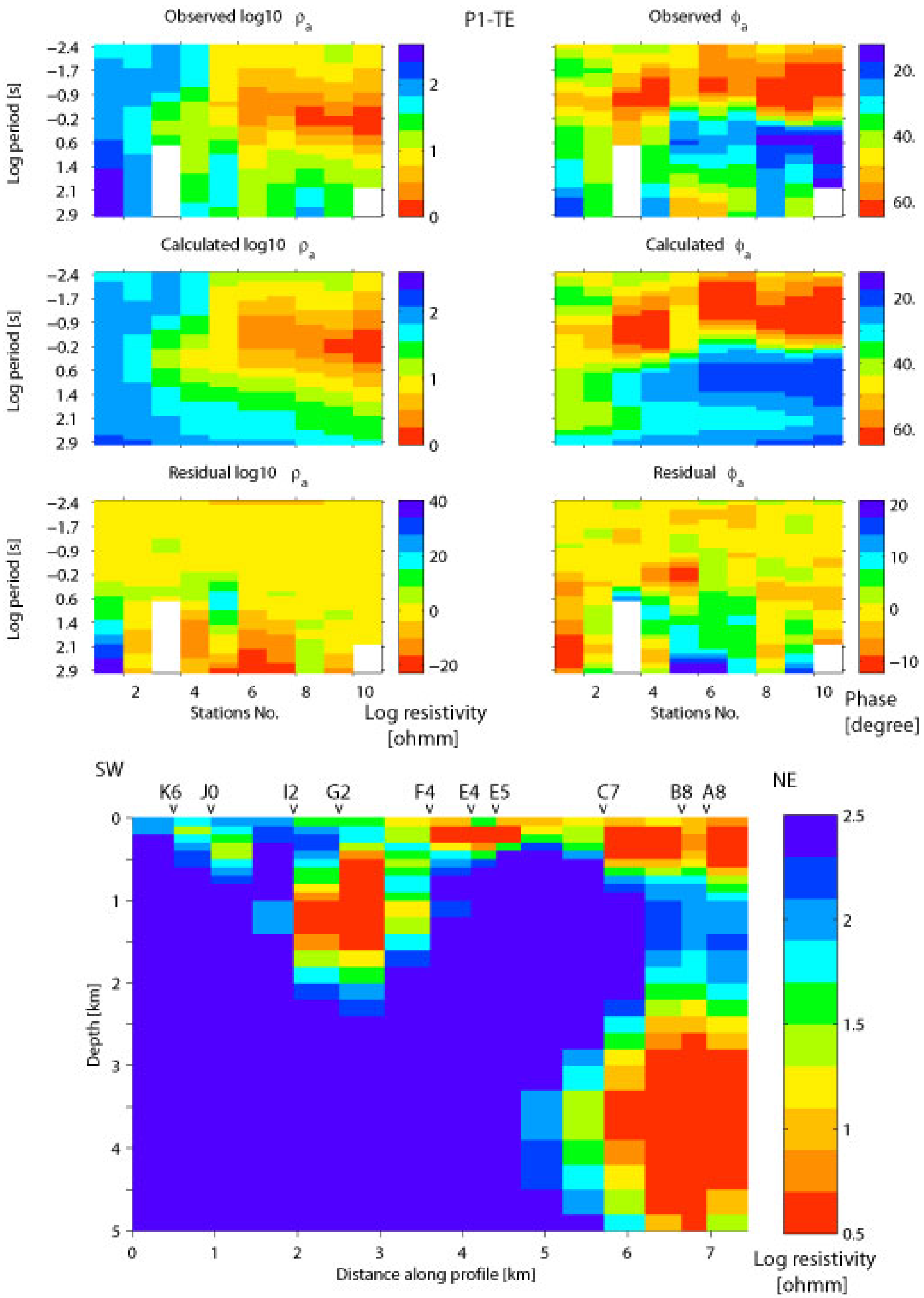

Figure 5. Upper panel shows the data, corresponding model responses and residuals. Lower panel is the 2D inversion model of joint TE-mode data along profile 1.

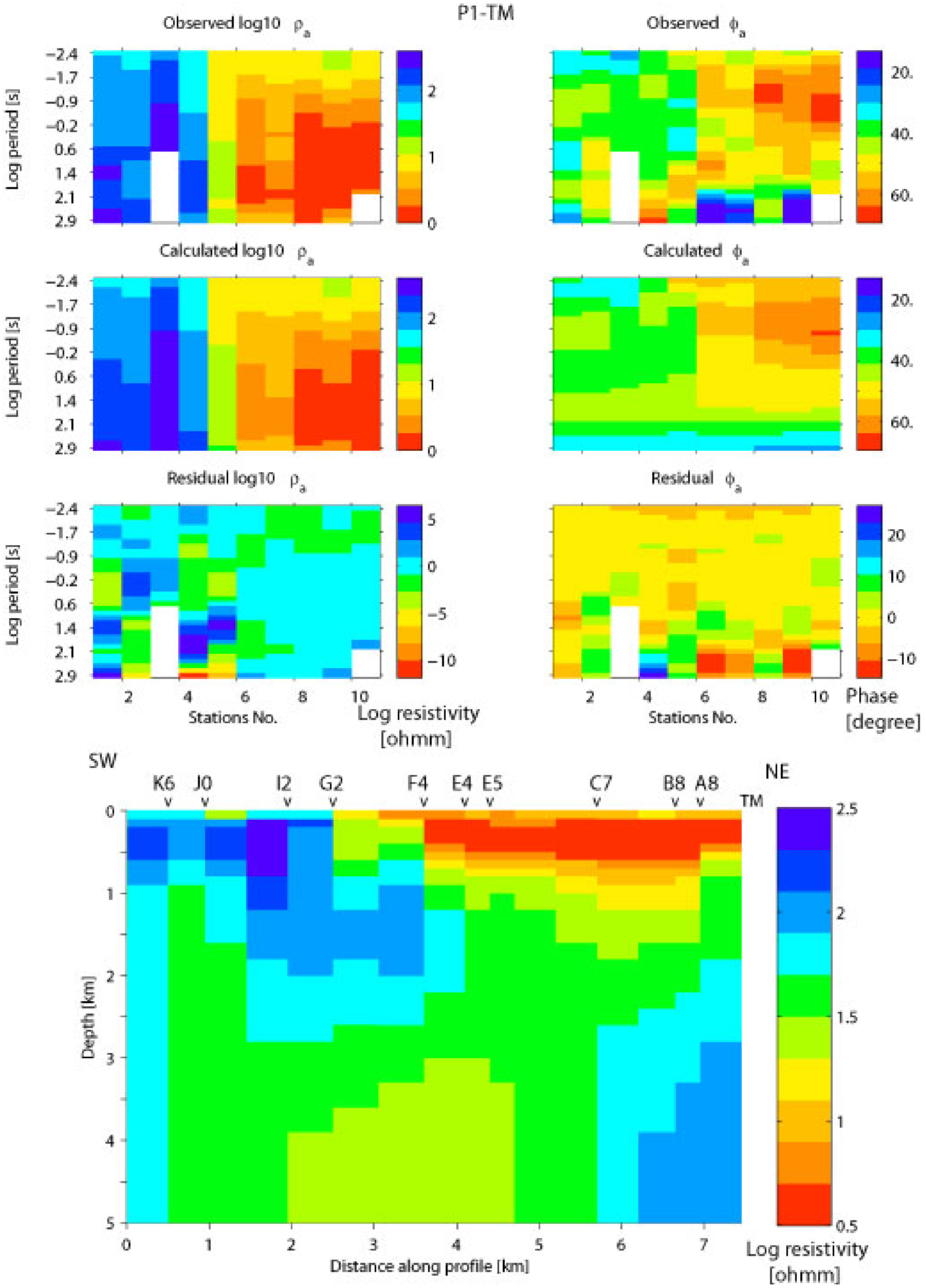

Figure 6. Upper panel shows the data, corresponding model responses and residuals. Lower panel l is the 2D inversion model of joint TM-mode data along profile 1.

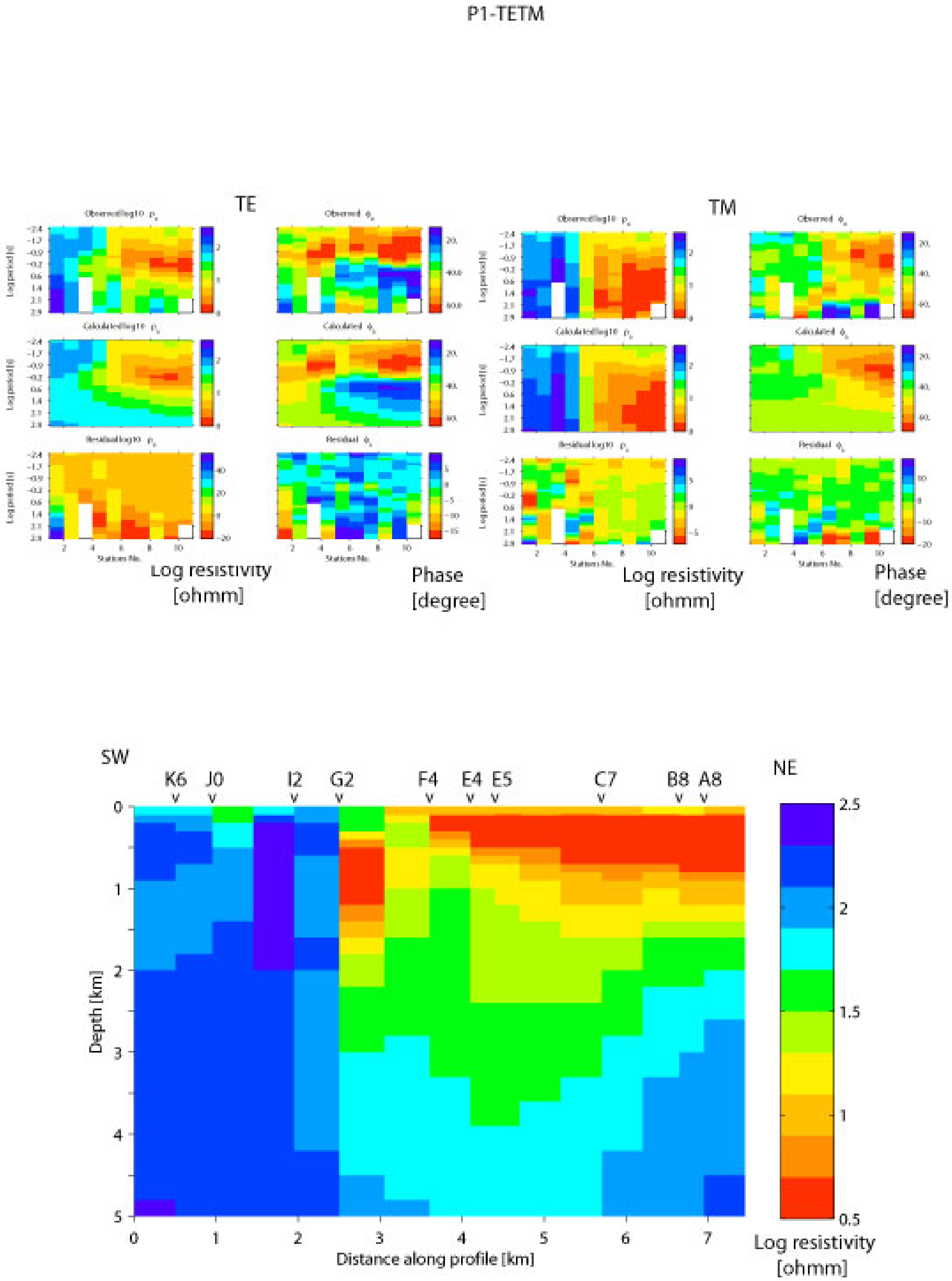

Figure 7. Upper panel shows the data, corresponding model responses and residuals. Lower panel is the 2D inversion model of joint TE- and TM-mode data along profile1.

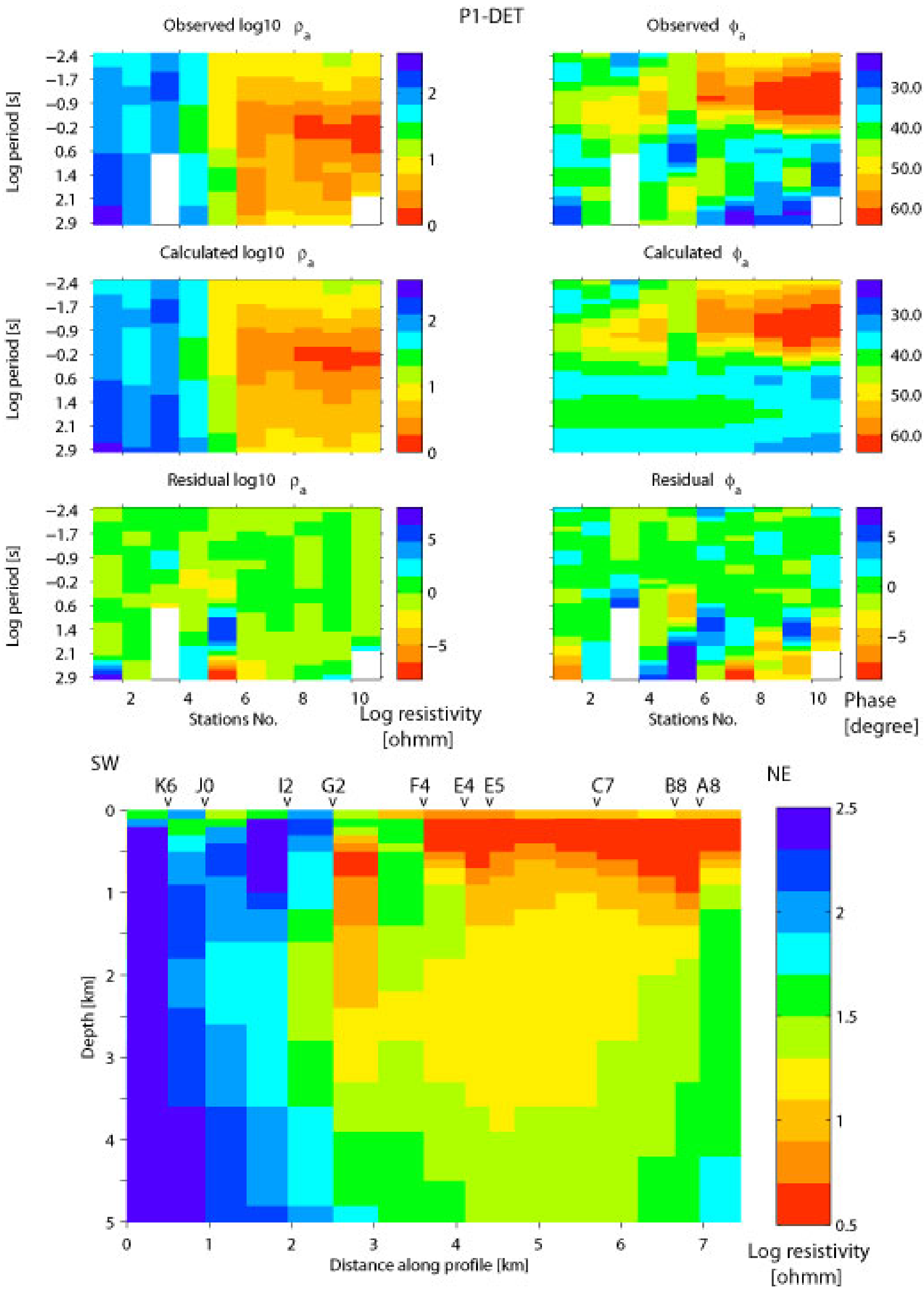

Figure 8. Upper panel shows the data, corresponding model responses and residuals. Lower panel is the 2D inversion model of the determinant data along profile 1.

The resistivity model from the inversion of TM-mode data and corresponding pseudo-sections of the TM-mode apparent resistivity and phase model responses are shown in Fig.11. It shows a fairly good agreement between the observed data and model responses along the profile. The same thick surface conductor in NE of the profile is recognized as well as the TE mode. Then there observed a transition to a resistive unit was observed which is followed by a very conductive unit by depth. Although the deep conductor at this position can be explained by the TM-mode data, it doesn't fit either the results from TE- mode data or the geological cross section. To the SW of the profile a resistive thick layer of 1 km lies on top of a conductive unit which extends down to 2 km where there is a transition to a more resistive structure towards deeper levels.

DET-model and datafit for profile 1 are depicted in Fig. 12. Features in this model are a combination of the TE and TM models, i.e., the inversion of the determinant data could resolve the most common features along profile 1. Apart from the conductor at NE a deep conductor below 3 km in the NE and a shallow conductive unit in SW is recognized by the data.

Resistivity model from the joint inversion of TE+TM along profile 1 is shown in Fig. 13. The main features of the geological model shown in Fig. 3 are resolved by joint inversion. The highly resistive unit in the SW from the top down to 1 km, a very conductive unit at the top starting from the middle of the profile continuing to the far northeast and to the depth of about 2 km and a less conductive basement are considerably match the geology. An isolated conductor below site K6 with 2 km thickness at 1 to 3 km depth is resolved. At about 6 km distance along the MT profile right at the position of a major fault a conductive zone is recognized (compare Fig. 13). The contact zone between the resistive unit and the conductive unit (starting from G2) deepens with a dip angle similar to that of the cross section. This location corresponds to a major fault in the area (Figs. 2 and 3). The model is somewhat very similar to the model obtained from the inversion of the determinant data.

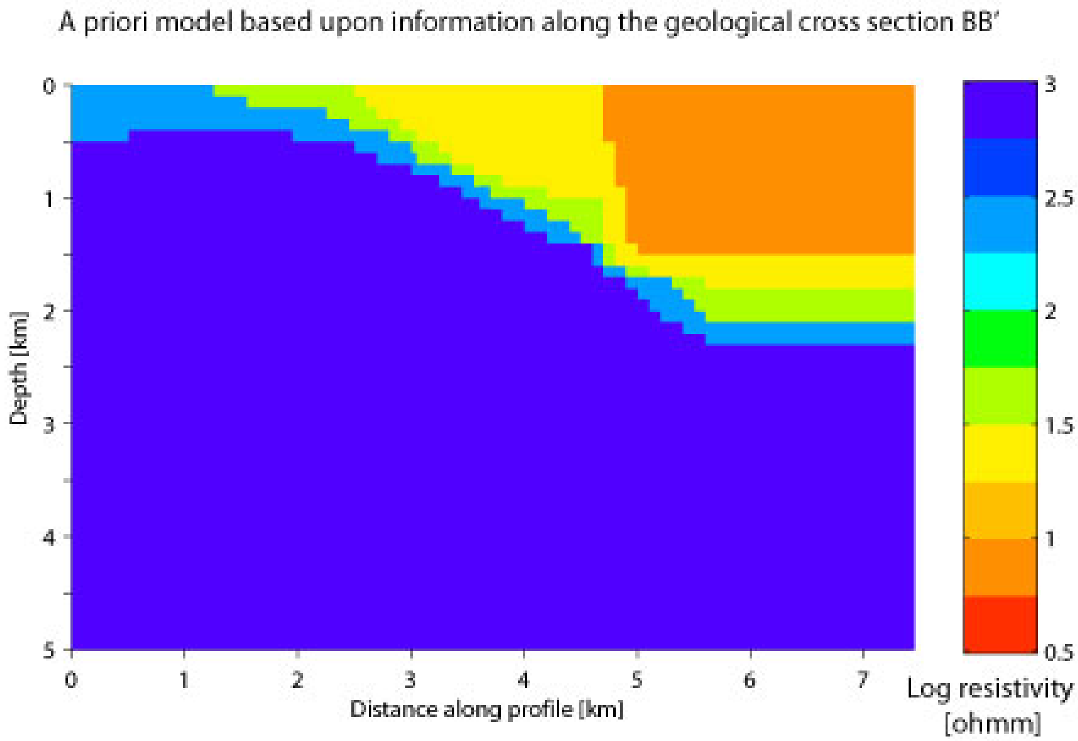

Figure 9. A priori model constructed from the geological cross section of BB'.

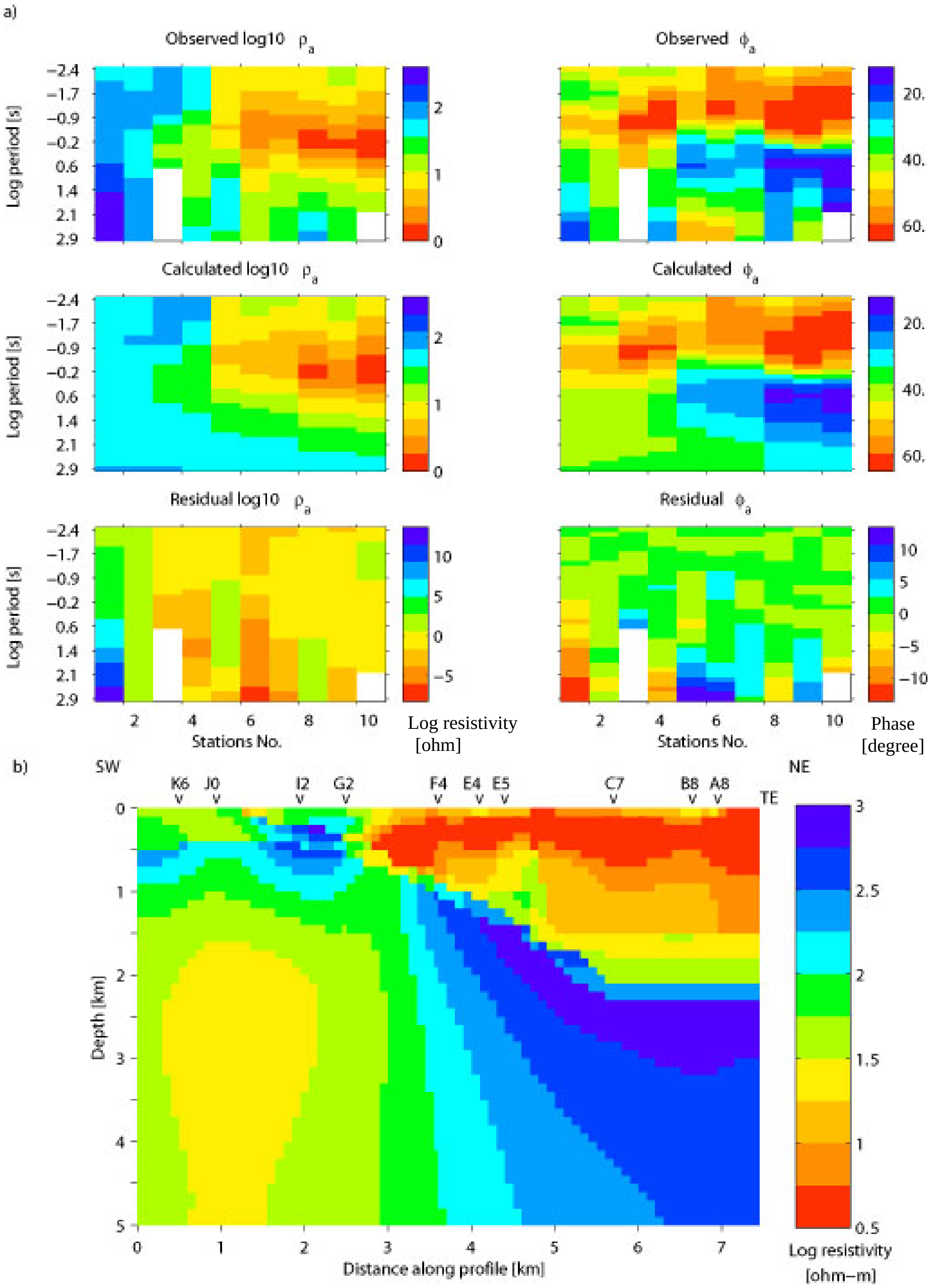

Figure 10. TE-model and datafit for profile 1.

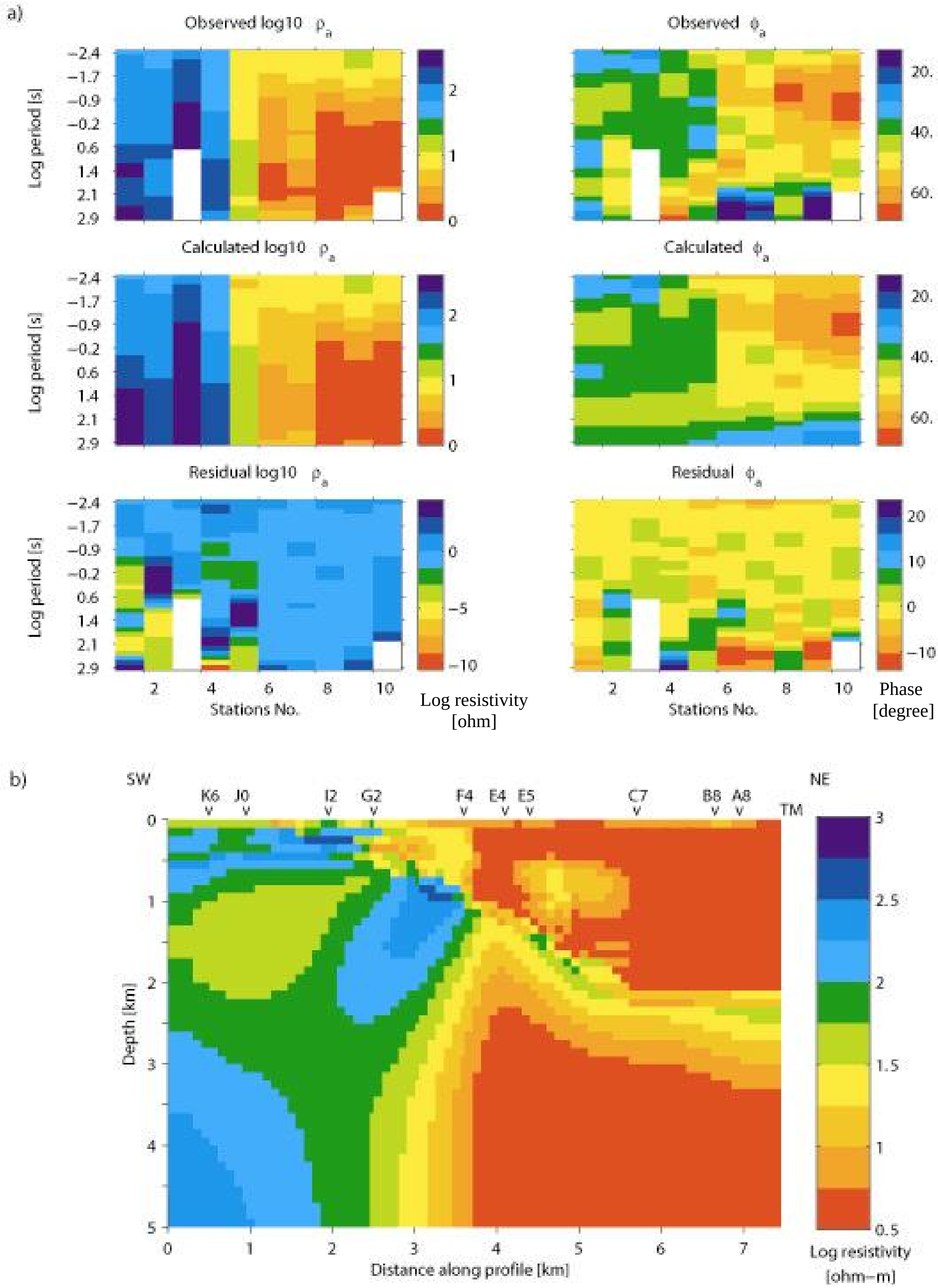

Figure 11. TM-model and datafit for profile 1.

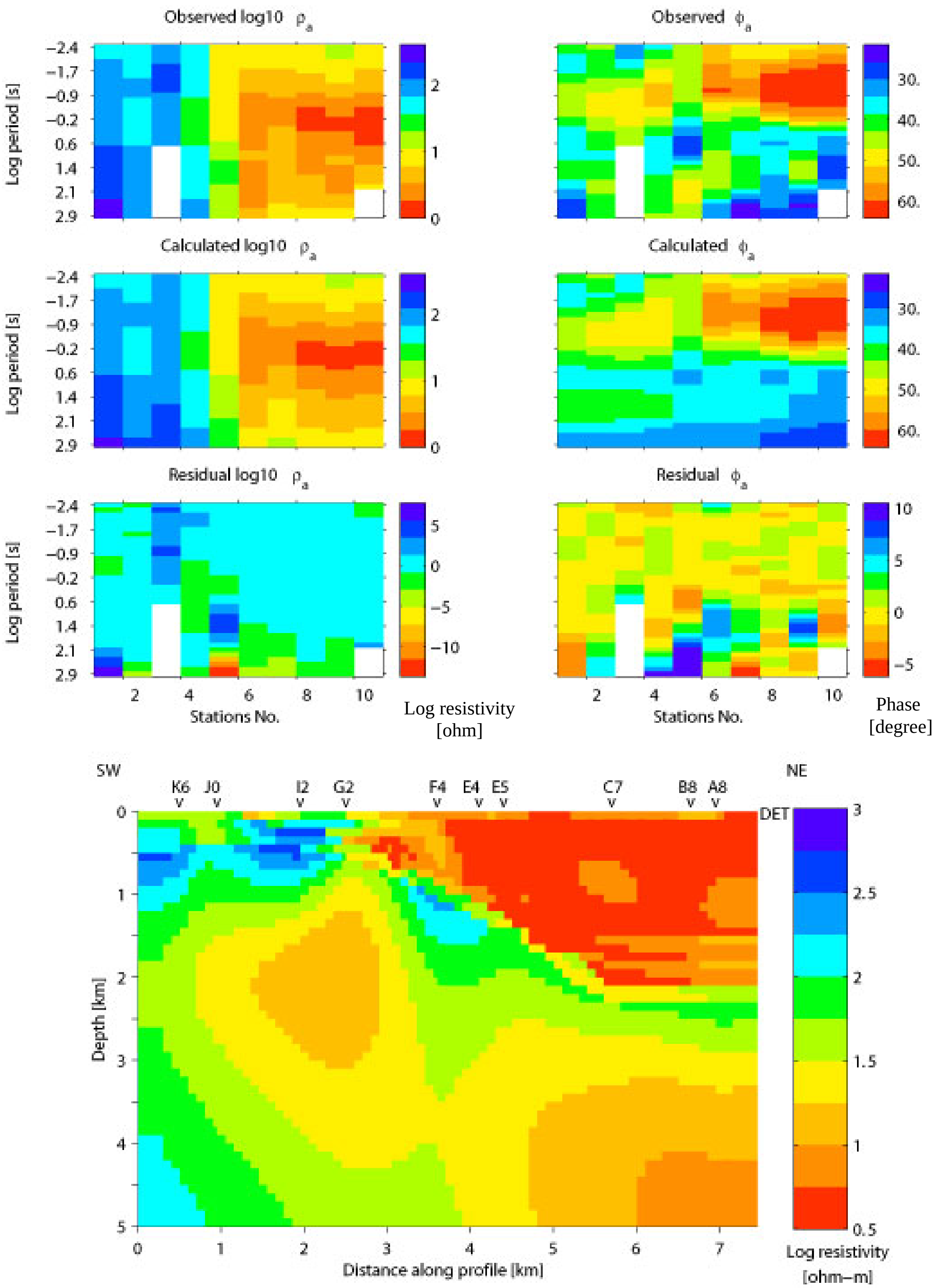

Figure 12. DET-model and datafit for profile 1.

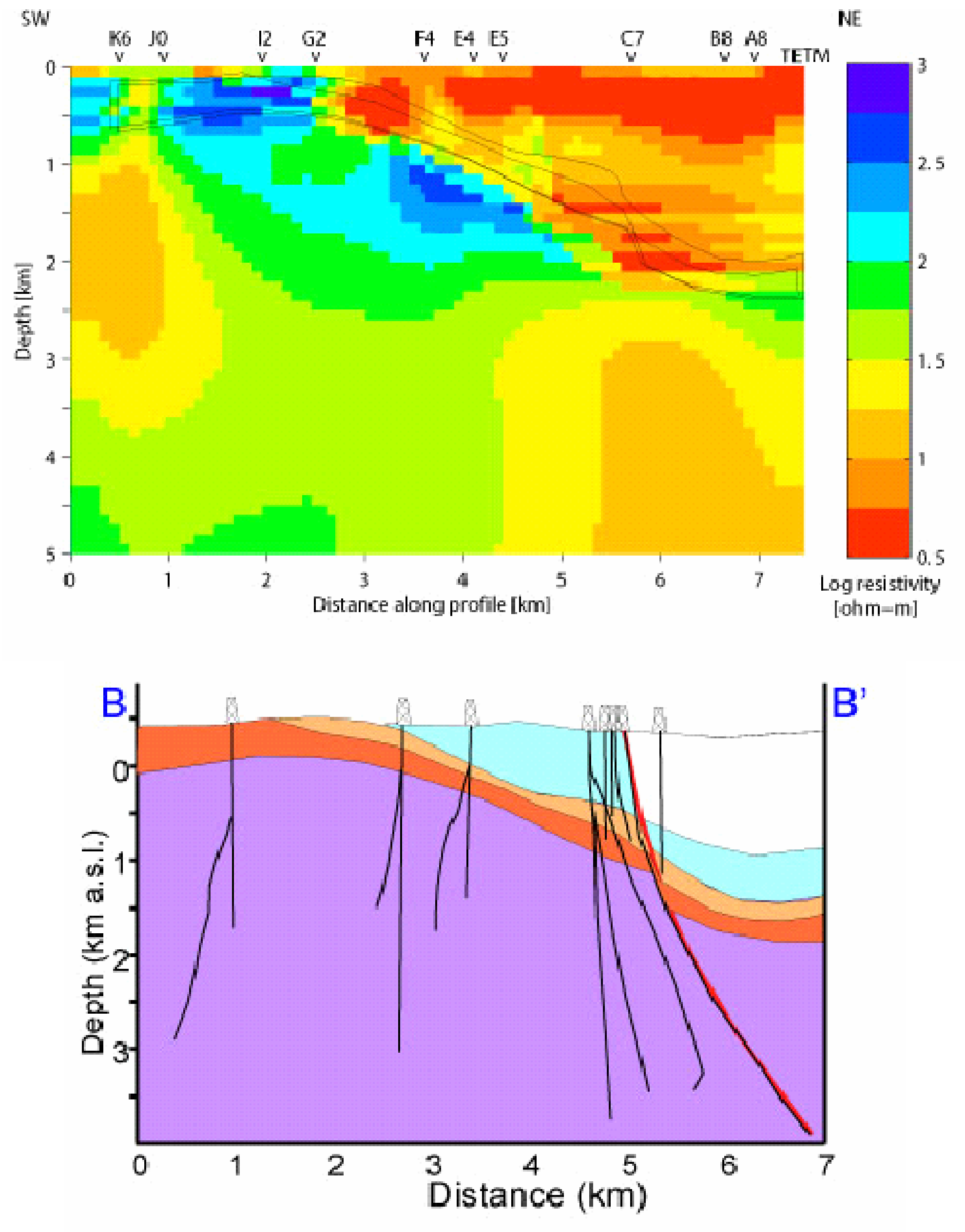

Figure 13. model of the joint inversion of TE+TM and geological cross section of BB'.

8 DISCUSSION AND CONCLUSIONS

2D modelling of the MT data along the selected profiles has revealed remarkable confirmation of the subsurface geology by means of resistivity variations of the upper overlying Neogene cover down to the basement. The final resistivity model of Fig. 13 (TE+TM model of profile 1) shows an electrical resistivity view of the subsurface material from the top to depth of 5 km along the geological section of BB' (shown in Fig. 3). Considering the common geology of the area one expects much higher resistivity by depth (>1000 ohm). Instead our MT investigation resolved the area very conductive. The resistivity models describe the area as generally conductive (0.5-300 ohm) down to a level of 5 km.

2D joint TE- and TM-mode and DET results along profiles 1 properly match the geologic cross section model of BB'. Results of the inversion of data along the other profiles (not shown in this paper) also reflect the geological patterns in the region. Depending on their location the MT profiles show corresponding changes laterally and also by depth. The upper part of the crust towards the northeast consists of a sedimentary sequence. And at the other end (towards the southwest) i.e. where the metamorphic basement formation is close to the surface, large resistivities can be observed.

In the area, a more advanced data acquisition and interpretation was suggested due to a recent MT work in Southern Tuscany (Manzella, 2004). The magnetotelluric surveys performed in this region have provided information on the resistivity structure, which is related to the extent and distribution of free fluids and to the partial melts in the crust. The picture emerging from these MT surveys is that of a resistivity structure that is only partly related to the heat flow regime of the area. A very low resistivity was found below the vapour-dominated geothermal system of Larderello and below areas that have no clear connection to any geothermal system, whereas this reduction of resistivity is less conspicuous below the water-dominated geothermal system of Mt. Amiata (Manzella, 2004).

The current MT results reveal the presence of two major conducting zones beneath the surface in the metamorphic basement (Fig. 13). A shallow conductor in the basement is located at the south-westernmost part of profile 1 beneath sites K6 and J0. It starts at about 1 km and continues down to about 3 km. The deeper conductor is shown as about a two-km wide conductive zone starting at 2.5 km and coinciding with the major fault with an about 45o dip towards northeast (Fig. 13). The deep fault is located at the northeastern quarter of the area crossing the profile 1 close by site E5 (Figs. 2 and 3). These conductive zones representing the probable fluid circulations might be connected at depth to the deep reservoir(s) of the Travale geothermal system. Recognition of the conductive zones in the resistive basement in many sites can clearly be interpreted as the flow of the fluids in the faults and fractures of the metamorphic rocks.

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