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1D interpretation of the Magnetotelluric data from Travale Geothermal Field in Italy

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Abstract

This paper detects the main features of the conductivity structures in the exploited geothermal field of Travale in Italy, where a detailed study was conducted using Magnetotelluric (MT) data in 2004. In this area, the long period natural-field MT method proved very useful for subsurface mapping purpose so that deep resistivity structures were determined properly. Using 1D inversion schemes, MT data were processed and modeled. 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. Analysis of the new MT data-set suggests signatures of a deep geothermal reservoir in the area. The conductive zones which are recognized 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, 1D inversion, Resistivity

1 INTRODUCTION

Geothermal resources are ideal targets for electromagnetic (EM) methods since they produce strong variations in underground electrical resistivity. In thermal areas, the 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 one-dimensional (1D) interpretation and aims at the recognition of the characterization of Larderello-Travale geothermal system in Italy (Figure 1).

MT survey was carried out using high and low frequency MT systems in the Travale area in May-September 2004. The whole field campaign was organized and led by Dr. Behrooz Oskooi (a fellow of the TRIL Programme of the Abdus Salam International Centre for Theoretical Physics) under the supervision of Dr. Adele Manzella (CNR-IGG Electromagnetic Lboratory).

MT processing codes from Larsen et al. (1996), Smirnov (2003), Egbert (1997) and SSMT2000 software (Phoenix Geophysics) were investigated for data sets from high and low frequency systems.

The main faults, geothermal and volcanic areas in Tuscany, Italy, are shown in Figure 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-m below 10 km. At shallower depth the resistivity is around 500 ohm-m. At geothermal fields, where deep conductors associated with geothermal fluids exist, lower resistivities are expected.

Southern Tuscany has been extensively explored by the MT method for more than three decades. MT soundings in the Travale area were performed by Celati et al. (1973). Due to a heavy noise contamination and poor interpretation tools their results did not give a clear picture of subsurface. Later Hutton (1985), Hutton et al. (1985), Schwarz et al. (1985) and Berktold et al. (1985) carried out more MT investigations in the area with the same problem of noise. In those days all measurements were obtained using only single-site processing, although the remote reference technique in MT was introduced by Gamble et al. (1979), it was not very commonly applied by the MT people engaged in that work. Later in 1989 ENEL (the Italian Energy Company) undertook some MT measurements in

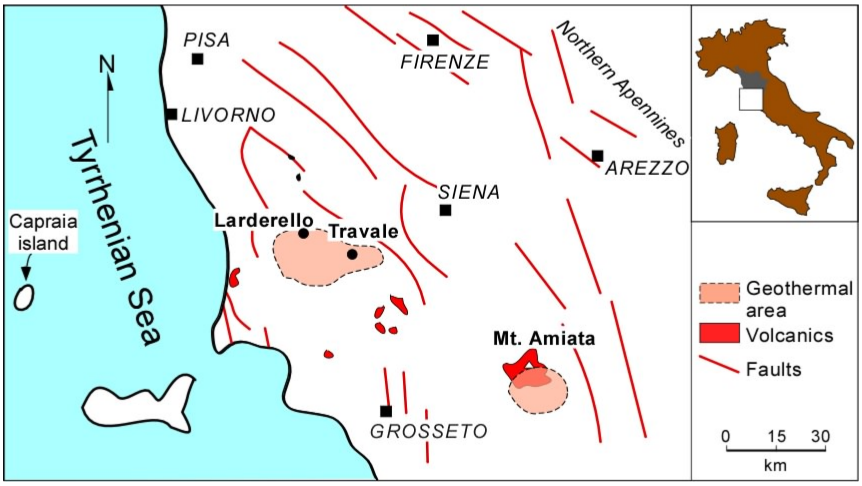

Figure 1. Simplified geological map of area of study.

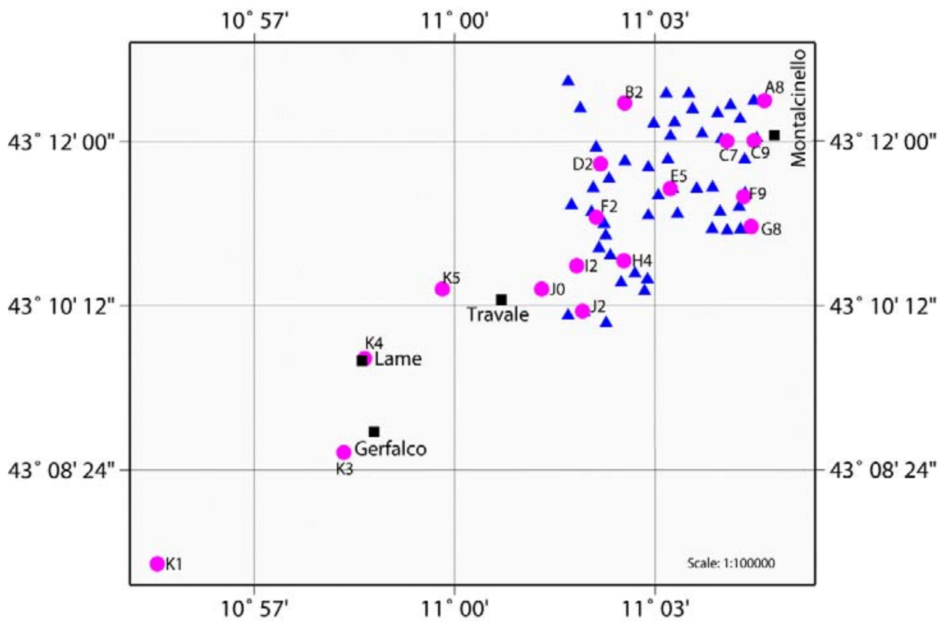

Figure 2. Distribution of MT-sites in the area of study. Sites shown by triangles were measured using Phoenix systems and circles show the sites measured by NIMS systems.

Larderello using local remote references. A remote reference MT data collection in the region was made in 1992 using a remote site at Capraia Island, whose data were reinterpreted by Manzella (2004). The results show that Southern Tuscany is very heterogeneous electrically and the basement has a resistivity of only a few thousand ohm-m below 4 km. This amount of resistivity is much lower than the resistivity of metamorphic formations in other parts of the world.

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 and 1991). Measurements of the horizontal components of the natural electromagnetic field are used to construct the full complex impedance tensor, Z, as a function of frequency,

$$Z = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix}$$

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. Additional information can be obtained if time variations of the vertical magnetic field are recorded simultaneously with the horizontal field components. Parkinson (1985) defines magnetic transfer function (also called tipper vector) which links horizontal and vertical magnetic field components. Induction arrows calculated from the tipper elements point away from the zones of enhanced conductivity and are hence an excellent tool to map the location of anomalous structures (Jones, 1986). Apparent resistivity, ρ_a, and phase, φ, are the desired quantities calculated through the following relations,

$$\rho_{a_i} = \frac{1}{\mu_0 \omega} |Z_i|^2 \qquad , \; i = xx, xy, yx, yy, \; DET$$
$$\varphi_i = \mathrm{phase}(Z_i)$$

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,

$$Z_{DET} = \sqrt{Z_{xx}Z_{yy} - Z_{xy}Z_{yx}}$$

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.

3 EM DATA ACQUISITION

3.1 MT EQUIPMENT AND PERSONNEL

Five Phoenix (300-0.0003 Hz) and three NIMS (1- 0.0003 Hz) MT systems operating in 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. Sites shown by triangles were measured using Phoenix systems and circles show the sites measured by NIMS systems.

Seven geophysicists, an Iranian, two Italians and four from Russia 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. Items necessary 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 used accordingly.

3.2 TDEM DATA ACQUISITIOIN

Time domain electromagnetic (TDEM) data at eight sites were measured using Tem-Fast 48 Transmitter-Receiver System. The single-loop sounding method was chosen for operational considerations and weight minimization. TDEM 1D layered models were converted to pseudo-MT responses by computing the MT responses from TDEM 1D models. TDEM 1D layered models were converted to pseudo-MT responses and compared to corresponding MT measurements for static shift corrections while processing the MT data. Moreover, previous Schlumberger DC and MT resistivity results (Manzella, 2004) and vast geological information would provide a base for static shift correction. In our case static shift corrections on MT data were done using TDEM results and the geologic information as the final steps of data processing.

3.3 LOW FREQUENCY MT DATA ACQUISITION AND QUALITY

In this study, data within a period range of 0.001-1000 s were analyzed. All MT data were processed using modern robust techniques to obtain complete impedance tensors and geomagnetic operators. The vertical magnetic components from various sites are also available and induction arrows were used for dimensionality analysis of the data.

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

Local power plants and geothermal exploiting activities are significant sources of noise for short period MT data. This problem was dealt with by applying remote reference processing technique using corresponding synchronized data from local sites which were simultaneously measured. The Travale area is surrounded by several electrified railways. Electrified railways contaminate the natural MT signals whose effects on the long period MT data in Larderello area have been studied in detail by Larsen et al. (1996). To overcome this problem a remote site was designed on the island of Sardinia, some 500 km away from the area of study. The fifth Phoenix and the third NIMS systems were organized as remote systems on Sardinia. All MT systems were synchronized by precise GPS clocks. MT data are processed either as a single site or using remote reference robust routines depending on the synchronized data availability and also the quality of the remote data. In this report several examples of single site (SS) and remote reference (RR) processing of NIMS's data are shown.

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. For most sites, a comparison of the SS and RR processing show clear effects of possible distortions caused by near field effects. Although the results of different approaches were not in good agreement, they showed to some extent the same trends of the resistivity and phase versus period. Synchronized data from corresponding local sites and a remote site on Sardinia were used as references to remove noise effect for short and long periods, respectively. Processed RR-data were taken for further inversion afterwards.

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.

4.1 MT DATA FROM SARDINIA

Except for a one day interruption the data set covers almost the whole period of survey. Figure 3 shows a part of time series collected in the first days of survey. These data were processed as a single site. Apparent resistivities and phases are shown in Figure 4. Data in the period range 10-1000 s are smooth but periods shorter than 10 s are contaminated by high frequency noise. In practice we need only long periods of the remote site due to the long distance between the remote site and the Travale area. Therefore, our remote reference data processing is reliable.

4.2 EXAMPLES OF SINGLE SITE DATA PROCESSING OF NIMS DATA

Results of single site data processing for four sites of A8, C9, F9 and G8 are shown as Figures 5 to 8. A typical effect of electrified train noise is clearly seen for long periods at almost all sites. This effect is reflected in the data as a steep dip of apparent resistivity curves and phase values close to zero for long periods.

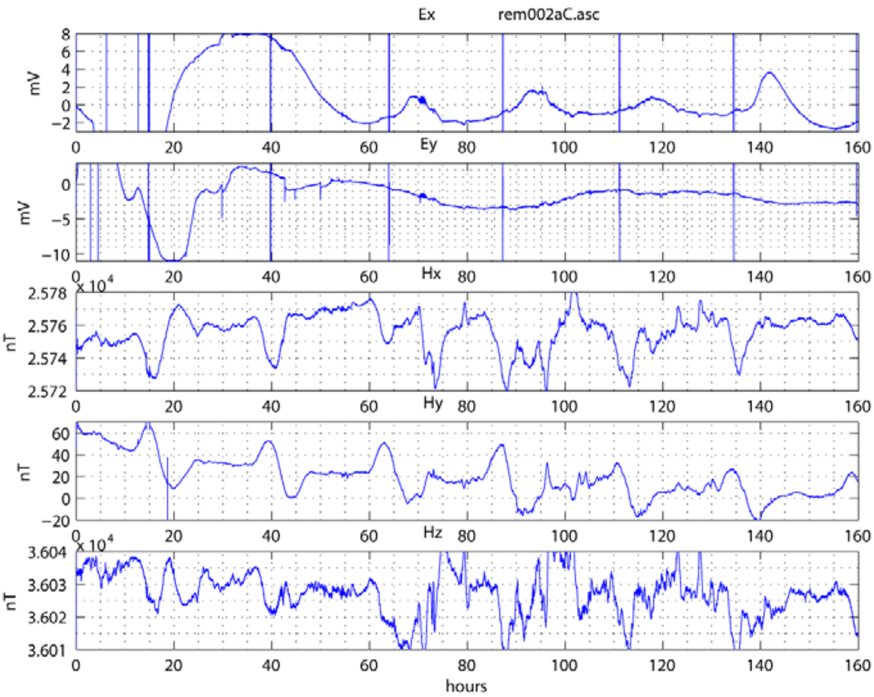

Figure 3. Data from remote site in Sardinia. The first seven days are shown here.

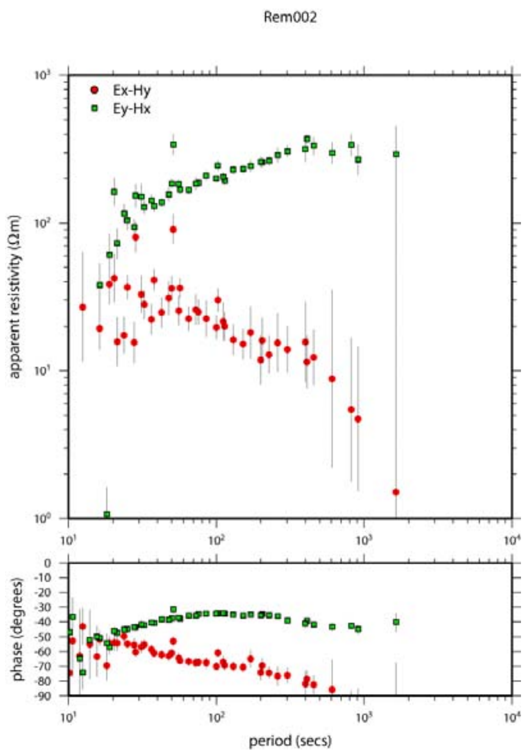

Figure 4. Apparent resistivities and phases calculated from data of the remote site in Sardinia.

4.3 EXAMPLES OF REMOTE REFERENCE DATA PROCESSING NIMS DATA

Results of remote reference data processing for the same four sites of A8, C9, F9 and G8 are shown as Figures 10 to 12. Remote reference processing overcomes the noise effect to a great extent, but for the short period and some of the long period data we deal with a high level of uncertainty about the data.

5 NEAR-SURFACE DISTORTIONS IN EM INDUCTION

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 Phoenix data.

6 INVERSION

1D 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.

The data were calculated as apparent resistivities and phases. Since apparent resistivity data from a few sites showed significant difference between the two polarization curves at high frequencies, the static shift corrections seemed to be crucial. Therefore, static shifts were corrected prior to the inversion based upon the geology and TDEM results.

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.

6.1 1D INVERSION CODE

1D inversion of the determinant (DET) data using a code from Pedersen (2004) for the 1D inversion was performed. The total mean-square error (MSE) of the estimated model, defined as the sum of the standard model variance and the bias variance, is used to define the truncation level of the singular-value decomposition to give a reasonable balance between model resolution and model variance. This balance is determined largely by the data and no further assumptions are necessary except that the bias terms are estimated sufficiently well. This principle has been tested by Pedersen (2004) on the 1D magnetotelluric inverse problem with special emphasis on high-frequency radio magnetotelluric (RMT) data. Simulations clearly demonstrate that the method provides a good balance between resolution and variance. Starting from a homogeneous half-space, the best solution is sought for a fixed set of singular values. The model variance is estimated from the sum of the inverse eigenvalues squared, up to a certain threshold, and the bias variance is estimated from the model projections on the remaining eigenvectors. By varying the threshold, the minimum of the MSE is found for an increasing number of fixed singular values until the number of active singular values becomes greater than or equal to the estimated number.

6.2 RESULTS OF 1D INVERSION

1D inversion of the determinant data (DET) was performed. The determinant provides a useful average of the impedance for all current directions. Furthermore it is unique and independent of the strike direction. Regardless of the true dimensionality 1D inversion of MT data and, in particular, inversion of rotationally invariant data like the determinants, provides an overview of the subsurface conductivity in a feasible sense. Based on the results of 1D inversion, a reasonable starting model and strategy can be constructed for higher order inversions of 2D or 3D.

Examples of 1D models together with the data and calculated model responses are shown in Figures 13 to 20. Data fit and 1D model of NIMS data from site A8 are shown in Figure 13. In this case data have been processed as a single site. Observed data are not fitted showing that the resistivity and phase data are not consistent, therefore, the resulting model of the single-site processed data of A8 cannot be trusted. This is the case for most of the data sites without synchronised remote reference data.

In Figures 14 to 17 data fit and 1D model of NIMS data from sites A8, C9, F9 and G8 are shown. In these cases processing has been done by using data from Sardinia as the remote site. In all four models a shallow conductor and a deep conductor were resolved. Since we have the NIMS data in a limited frequency range so that the short period data, reflecting the near surface, are missing we consider the shallow conductor as an artefact.

Examples of Phoenix data from sites A8, G4 and J0 are also shown in Figures 18 to 20. For these data, processing has been done by using synchronized data from Sardinia and corresponding local sites as the remote sites. Only a shallow conductor can be identified by data from the Phoenix example sites. For most data there is an acceptable level of misfit where for site G4, phase data fit is not satisfactory.

7 DISCUSSION AND CONCLUSIONS

1D modelling of the MT data all over the region has revealed remarkable confirmation of the subsurface geology by means of resistivity variations of the upper overlying Neogene cover down to the basement. The resistivity models show an electrical resistivity view of the subsurface material from the top to a depth of 5 km. Considering the common geology of the area one expects much higher resistivity by depth (>1000 ohm-m). Instead this investigation resolved the area very conductive. The resistivity models describe the area generally conductive (0.5-300 ohm-m) down to the level of 5 km.

A recent MT work (Manzella, 2004) in Southern Tuscany emphasises on lack of clear transition to the possible conductive features in the upper crust suggesting a more advanced data acquisition and interpretation. Conductive units are clear specifications of areas which are affected by geothermal fluid circulations and resolving of conductors at deep levels by MT directly depends their scale.

However, the analysis of the present MT data-set suggests signatures of a deep geothermal reservoir in the area. The conductive zones recognized in the resistive basement at the MT sites can clearly be interpreted as the flow of the fluids in the faults and fractures of the metamorphic rocks.

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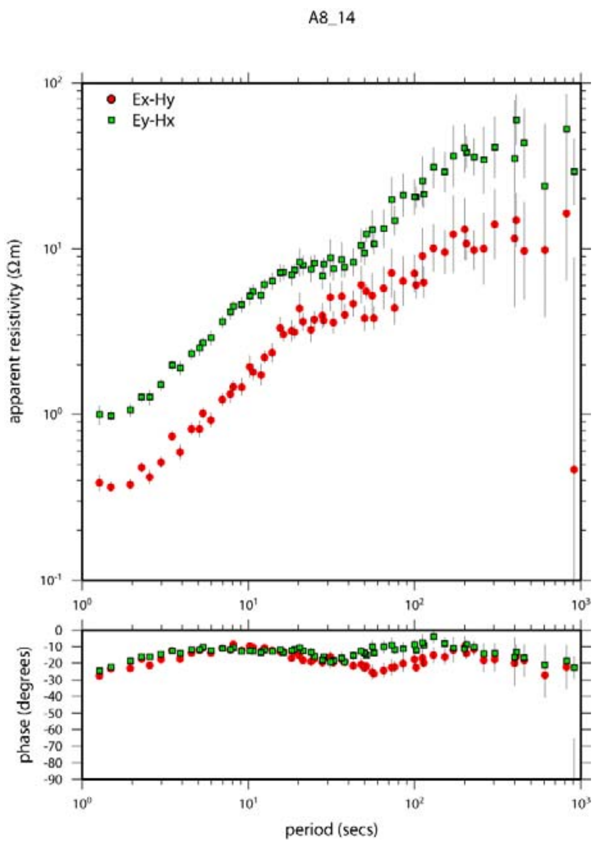

Figure 5. Single site processing results of data from site A8.

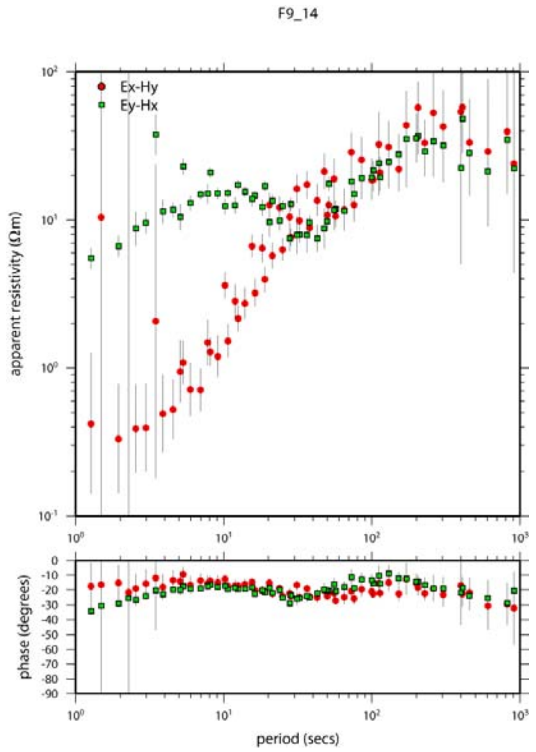

Figure 6. Single site processing results of data from site C9.

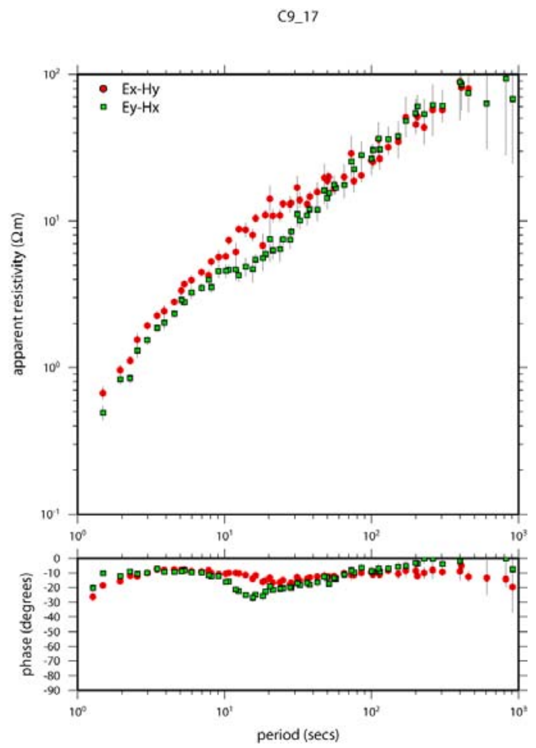

Figure 7. Single site processing results of data from site F9.

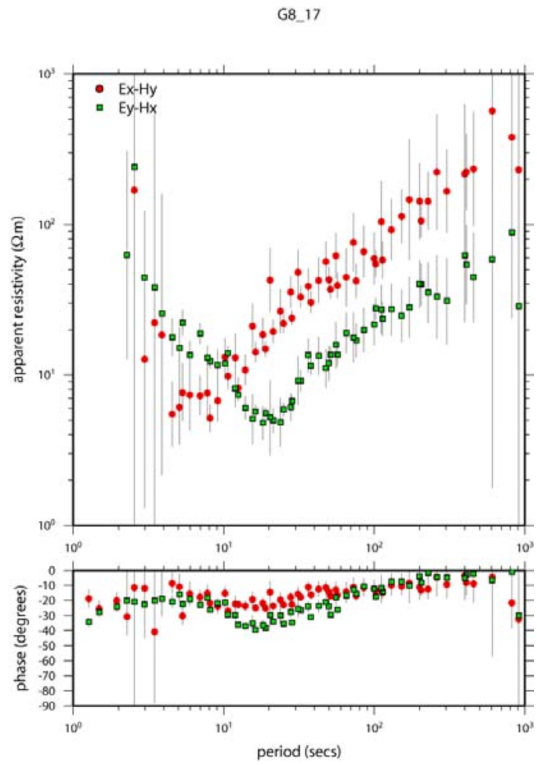

Figure 8. Single site processing results of data from site G8.

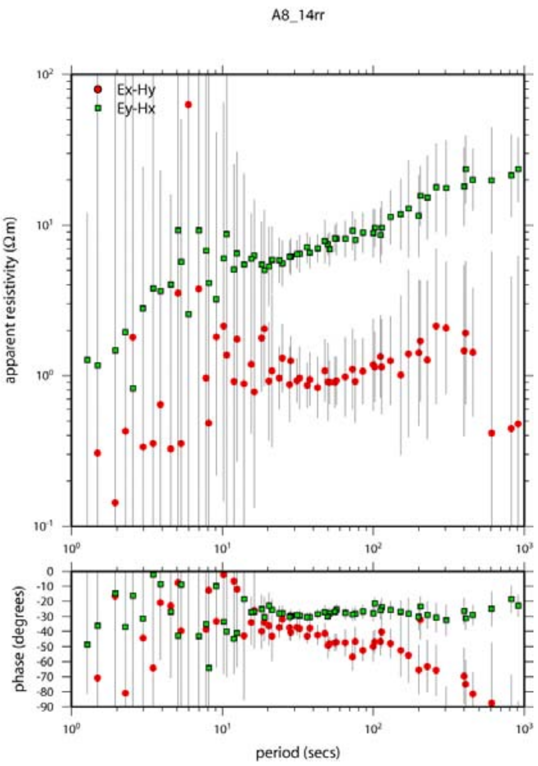

Figure 9. Results from site A8 processed using the remote reference technique.

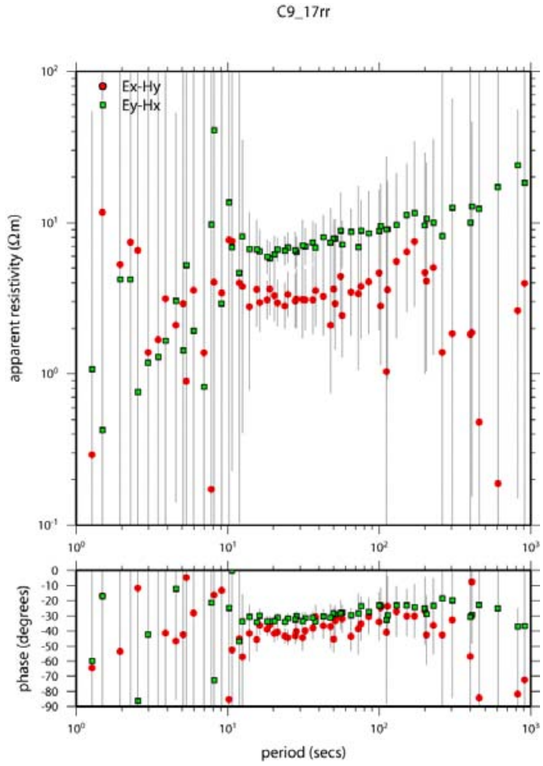

Figure 10. Results from site C9 processed using the remote reference technique.

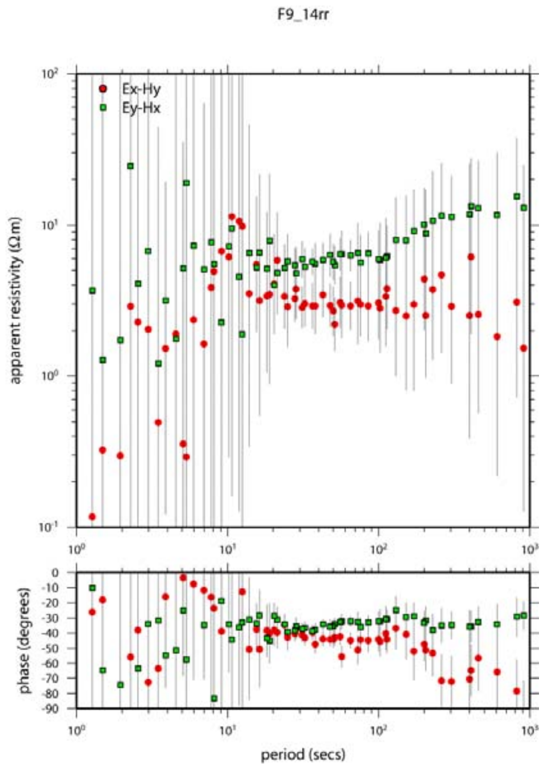

Figure 11. Results from site F9 processed using the remote reference technique.

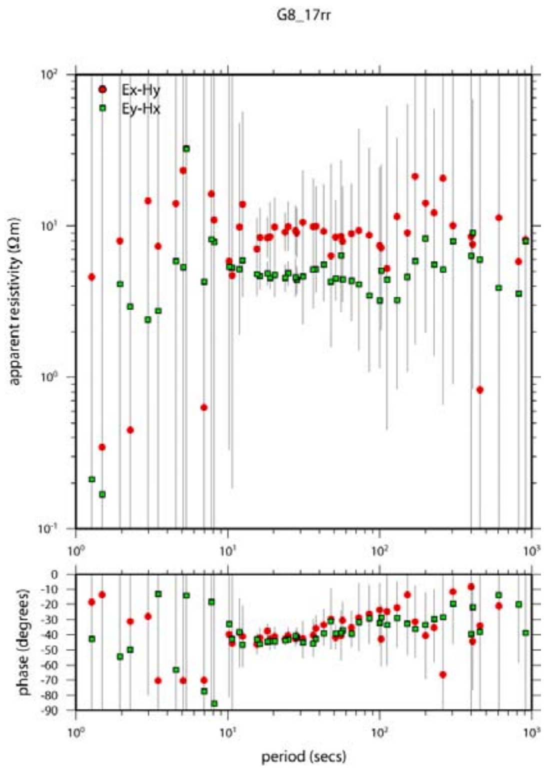

Figure 12. Results from site G8 processed using the remote reference technique.

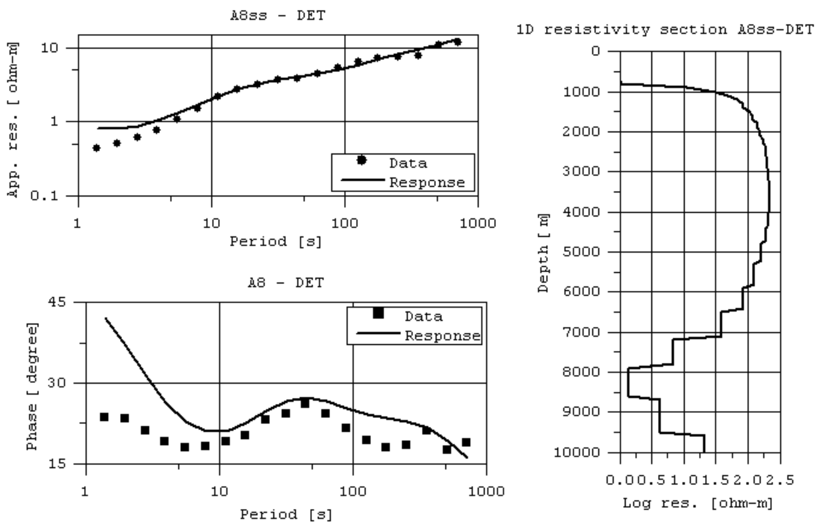

Figure 13. 1D inversion results of single site data from site A8.

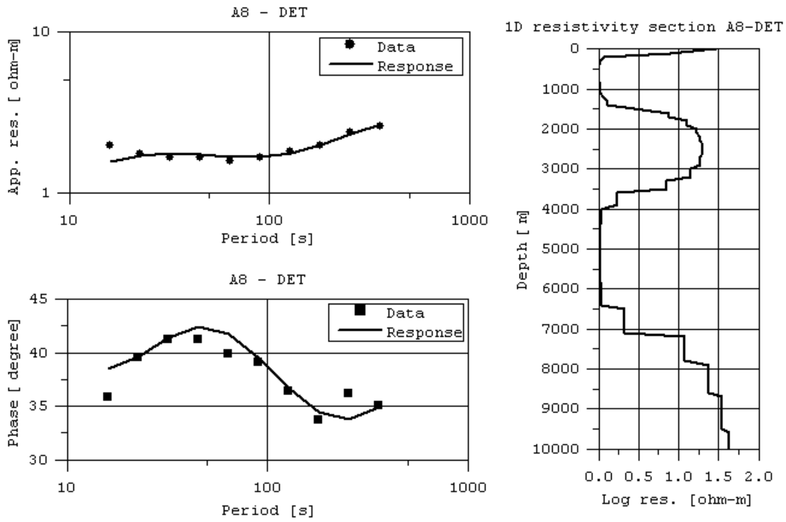

Figure 14. 1D inversion results of remote reference data from site A8.

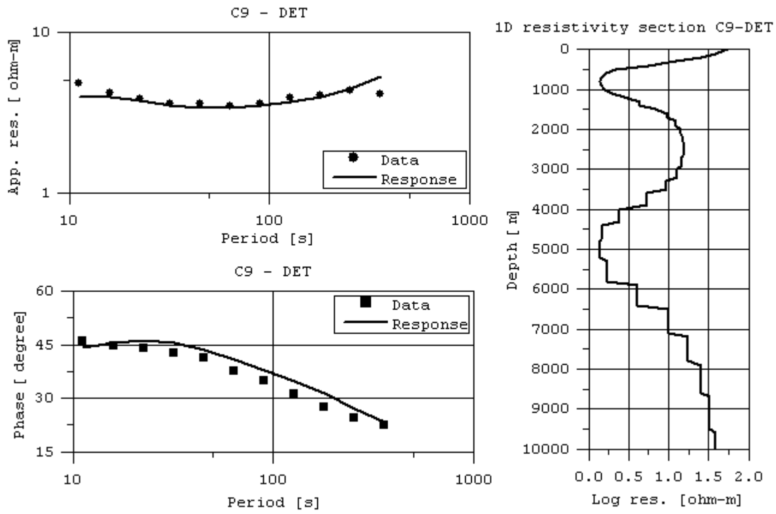

Figure 15. 1D inversion results of remote reference data from site C9.

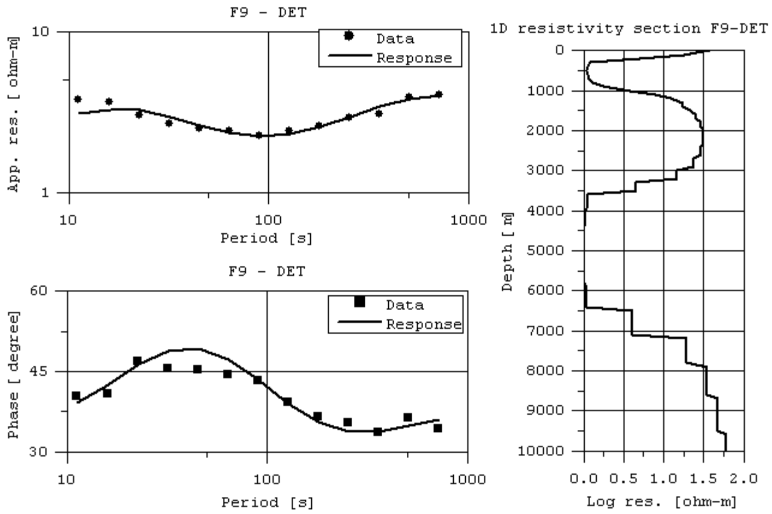

Figure 16. 1D inversion results of remote reference data from site F9.

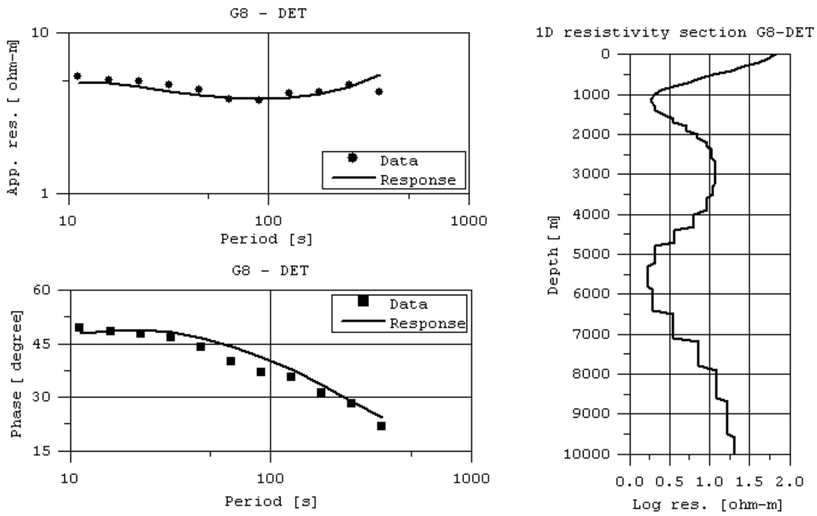

Figure 17. 1D inversion results of remote reference data from site G8.

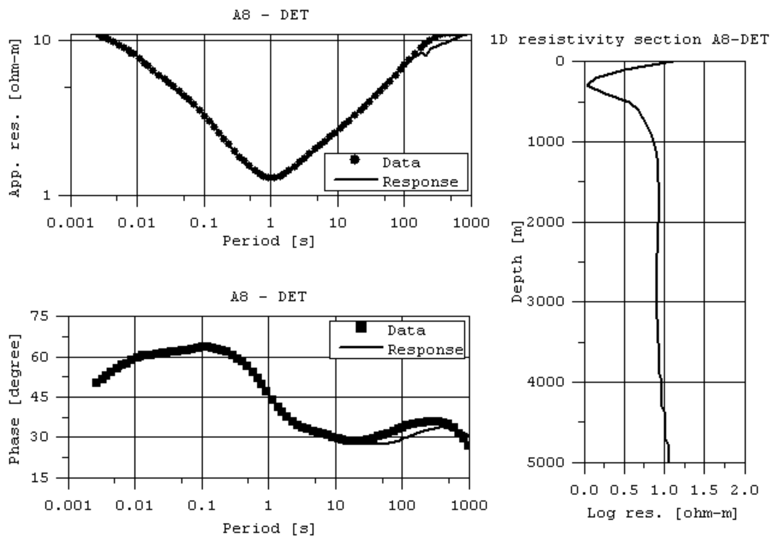

Figure 18. 1D inversion results of remote reference data from site A8 (Phoenix data).

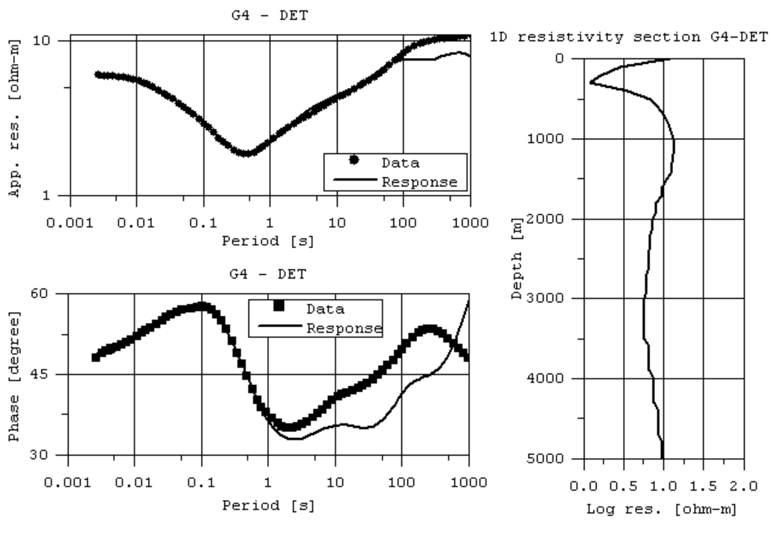

Figure 19. 1D inversion results of remote reference data from site G4 (Phoenix data).

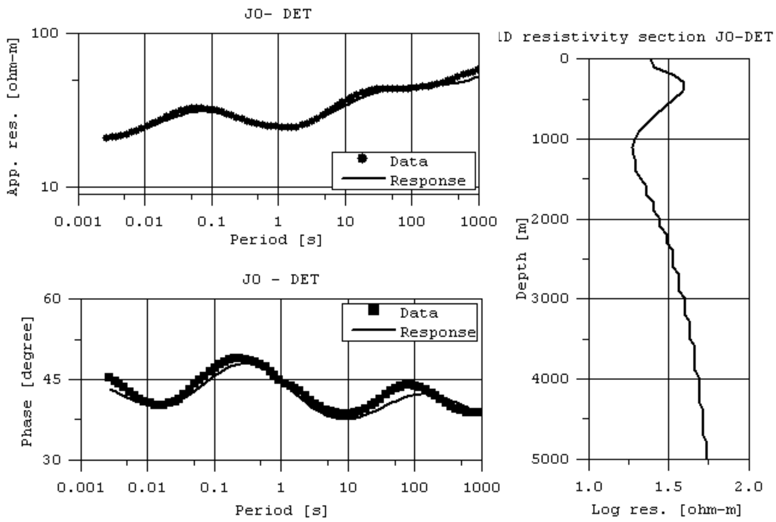

Figure 20. 1D inversion results of remote reference data from site J0 (Phoenix data).