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DEEP FLUID CIRCULATION IN THE TRAVALE GEOTHERMAL AREA AND ITS RELATION WITH TECTONIC STRUCTURE INVESTIGATED BY A MAGNETOTELLURIC SURVEY

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ABSTRACT

The high enthalpy Italian geothermal fields are located in southern Tuscany and are characterized by shallow and deep reservoirs defined by fractures within sedimentary or metamorphic rocks, showing an apparent heterogeneously distributed permeability. The structure of the Travale geothermal area is characterized by NW-trending and NE-dipping normal faults. Heat flow maxima and vertical displacement of isotherms associated with recent normal fault were recognized, and suggested that fluid circulation is not randomly distributed, but correlated to the tectonic setting of the area. In order to get an idea about the geoelectrical structure of the studied area MagnetoTelluric data were collected at 59 sites in the frequency range between 360 and 0.001 Hz. Moreover, a remote system was operated simultaneously with the main survey on Sardinia Island, about 500 km off the survey area, in order to face the low frequency electromagnetic noise affecting the Italian peninsula due to direct current electrified railways.

MT data were processed either as single site or by means of robust routines for remote reference processing, using data from Sardinia or from another local site a few km apart depending on the availability and quality of the synchronized data. Time domain electromagnetic data and geological information provided a base for static shift corrections. Processed data were decomposed, and showed a main NW-SE strike, in accordance to the main tectonic direction of the area.

2D inversion results produced models of resistivity distribution that were related to main lithological changes and the geothermal system. The models provide also a correlation with the main active faults and the seismic features of the area, most probably linked to the geothermal fluid circulation. A preliminary 3D inversion has been carried out using artificial neural network approach.

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.

Our concern, which is followed in the current paper, is the investigation of deep fluid circulation in the Travale geothermal area, Italy (Fig. 1). Travale belongs to the famous geothermal region of Larderello. Here the permeability is usually low and heterogeneously distributed. In particular, two geothermal reservoirs are exploited: a shallow reservoir within cataclastic levels of the carbonate evaporitic rocks of the Tuscan Complex, and a deeper, more extensive reservoir defined by fractures within the metamorphic rocks, at depths of more than 2 km (e.g., Barelli et al., 2000). In the Travale area carbonate units locally outcrop and become recharge areas, so that the shallow reservoir, where present, is usually colder than in Larderello, and mainly the deep reservoir is exploited. In this area the exploration targets are, therefore, mainly located in metamorphic rocks down to 4000 m depth, characterized by very high temperature (up to 400ºC).

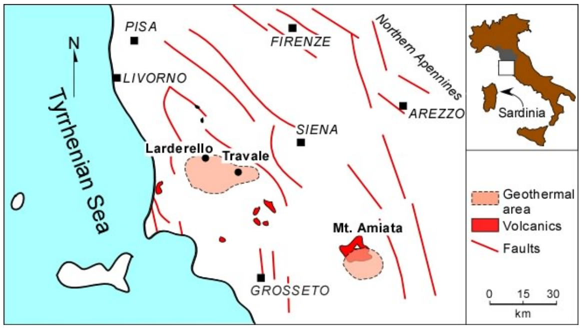

Figure 1. Simplified tectonic map and relative position toward Italy. Sardinia Island is also shown.

Geological setting

In the Larderello region drill-holes within the first 4.5 km of depth encountered sequences of sedimentary, metamorphic and igneous rocks. The geological framework is based on the descriptions reported by Brogi et al. (2003) and Bellani et al. (2004) and reference therein. In this area the following tectono-stratigraphic complexes have been recognized: 1) Miocene-Pliocene and Quaternary sediments, filling extensional tectonic depressions; 2) the Ligurian complex, consisting of Jurassic ophiolite rocks, its sedimentary Jurassic-Cretaceous sedimentary cover, and Creataceous-Oligocene flysch; 3) the Tuscan complex, including sedimentary rocks from Late Triassic-Jurassic evaporitic and carbonate rocks to Late Oligocene-Early Miocene turbidites; and 4) a substratum, principally known through geothermal drillings, composed of two units: the upper is referred to as the Monticiano-Roccastrada Unit, mainly made up of Triassic quartzites and phyllites (Verrucano group), Palaeozoic phyllites and micaschist; the lower one corresponds to the Gneiss Complex. The effect of Apennine orogeny is evident in the upper unit, whereas it was not recorded by the Gneiss complex, which may correspond to part of the Apennine foreland crust.

After the convergent and collisional stages (Late Cretaceous-Early Miocene), which determined the structural development of the Northern Apennines, three extensional tectonic events affected the Larderello region. The first and second events occurred during Miocene, and caused juxtaposition of the Ligurian complex on the Triassic evaporites, on the Verrucano group and on the Palaezoic phyllites along low-angle normal faults. The latest extensional event (Pliocene-Present) is characterised by the development of high-angle normal faults, generally NE dipping.

Surface heat flow values defined maxima (>500 mW/m2) in correspondence of some normal faults in the area (Bellani et al., 2004). This was interpreted as a consequence of the movement of fluids in localized deformation zones, corresponding to main shear zones.

In southern Tuscany extensional tectonic was accompanied by acidic magmatism. In the Larderello region, boreholes often encountered felsic dykes and granitoids, with cooling ages of 2.25-3.80 Ma, which intruded the Paleozoic micaschists and the Gneiss complex. The emplacement of these magmatic bodies caused in some places the superimposition of contact-metamorphic mineral assemblages on previous mineral associations.

Seismic reflection data provide information on the deep structure of the Larderello region. The seismic profiles show a clear distinction between a poorly reflective uppermost crust and a highly reflective mid-lower crust. The top of the reflective crust is marked by a high-amplitude discontinuous reflector, at depths of 3-8 km, with local bright spot features, named K-horizon. The origin of the reflectivity of the K-horizon is considered to be related to the occurrence of localized high fluid pressure within fractured levels, although the fracturing mechanism is still controversial (e.g. Marini and Manzella, 2005). Above the K-horizon another reflective horizon has been recognized, similarly characterized by high amplitude signals. This horizon, named H, is less continuous than K-horizon, and in the Travale area has been recognized at a depth of 2.5-4 km b.s.l. (Bertini et al., 2005).

On the basis of borehole and seismic data Brogi et al. (2003) suggest that the Pliocene to Present high-angle faults are the surface expression of extensional shear zones that tend to flatten at depth. Some of these faults are mineralized. In particular, the Boccheggiano fault (Fig. 2) is characterized by the widespread presence of hydrothermal minerals (i.e. quartz, pyrite, base metals sapphires etc.) indicating that an extensive fluid circulation occurred along this fault.

Intersections between the shear zones and the brittle/ductile transition are correlated with loss of the K-horizon reflectivity, which can be explained with fluid migration from K-horizon along the shear zones (Brogi et al., 2003). Following these authors, the intersections of the shear zones with seismic lines parallel to their strike would correspond to the H-horizon. On the other end, the H-horizon has been also interpreted as productive-fractured levels, usually associated to mineralized breccias and skarn related to a thermometamorphic aureole (Bertini et al., 2005)

The main geological units and a simple geological map of Travale area are shown in Fig. 2. The model along profile AA' of Fig. 2, crossing our area of interest, is shown in Fig. 3. On the base of prior electrical surveys and well-logs (Manzella, 2004 and references therein) lithology may be referred to resistivity variations both laterally and with depth, and corresponding resistivity structure across the area may be defined neglecting fluid circulation. Since this area is exploited by many geothermal wells, fluid circulation is surely present, and the geological model in Fig. 3 can be used to constrain the starting model for 2D inversion.

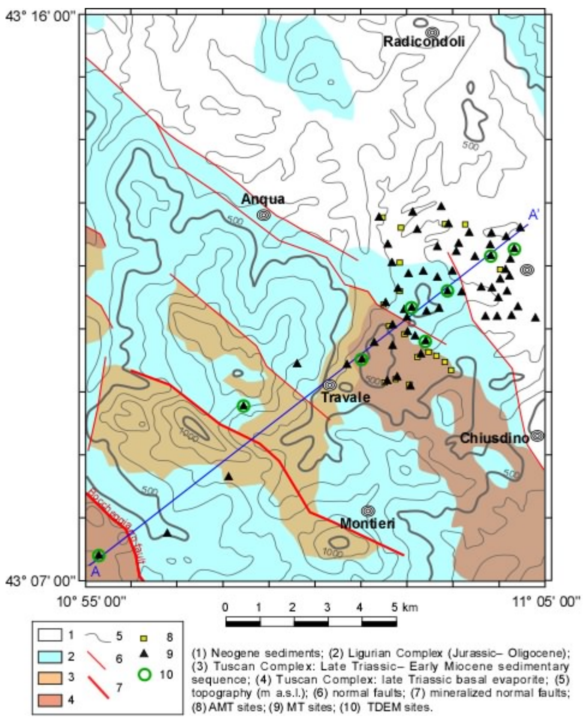

Figure 2. Simplified geological map, showing site location and the main profile AA' (from Brogi et al., 2003, modified). The mineralized fault on the SW corner is the Boccheggiano fault.

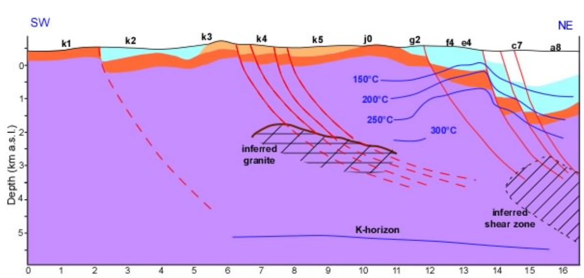

Figure 3. Geological section along AA' profile in Fig. 2 (from Bellani et al. 2004, modified). Colors define the same units of Fig. 2. Purple color refers to the Larderello substratum composed by the Monticiano-Roccastrada unit and the Gneiss Complex (see text for details).

ELECTROMAGNETIC DATA ACQUISITION AND PROCESSING

MT data were acquired in two surveys. Pre-positioning of about 40 sites was done in late May using precise GPS receivers within an acceptable range of error. High frequency MT data using Stratagem system were collected for almost 35% of the proposed sites (frequency range 92 kHz – 10 Hz). Analysis of data regarding quality controls on time series, spectra and transfer functions was carried out. Impedance phases behave naturally for most investigated sites, although a signature of a strong noise as an influence of electrical activities in the area is very critical on data from some sites. On the base of the achieved data quality, some sites were rejected and noisy areas defined.
The rest of the sites were positioned during the main survey, performed in the first three weeks of September 2004. MT data were acquired in 59 sites using Phoenix systems, covering approximately an area of 4 × 4 km^2, although a few sites were added on the SW, aligned along a SW-NE profile, in order to cross some more faults.

Overnight MT recording in the range 360-0.001 Hz for minimum 12 hours per site has been followed by four Phoenix systems. Local power plants and geothermal exploiting activities are significant sources of noise for short period MT data. This problem was dealt by using remote reference processing technique using corresponding synchronized data from local sites, which were simultaneously measured. Moreover, electrified railways contaminate the natural MT signals whose effects on the long period MT data in Larderello region have been studied in detail by Larsen et al. (1996). To overcome this problem a very remote site was designed on the Sardinia Island, some 500 km away from the area of study (Fig. 1). One Phoenix equipment was organized as remote system on Sardinia Island, while precise GPS clocks synchronized all five MT systems.

In order to deal with static shift problems, Time Domain ElectroMagnetic (TDEM) data at eight sites were measured using Tem-Fast 48 Transmitter-Receiver System. Location is shown in Fig. 2. 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. Geological information regarding outcropping units and related resistivity values also provided a base for static shift correction.

Data processing of Phoenix data was performed using Phoenix Geophysics software based on remote reference robust processing method (Jones et al., 1989). The remote reference site used for the processing has been both Sardinia site and another local site. To suppress industrial noise a further manual editing and smoothing of transfer functions was performed. At the end, all results were compared, and the most stable data used for further analysis.

The regional strike of the survey area was calculated by applying a routine from Smirnov (2003) and analyzing the magnitude and phase polar diagrams of impedance tensor (Fig. 4). Polar diagrams ellipses show a round shape at the highest frequencies, defining an almost 1D condition. Relatively stable regional strike estimates defined a principle direction of -45° from magnetic north at most of the sites at the lowest frequencies (< 1Hz), which follows the trend of main faults and basins in the area. Some areas, however, show a 3D structure.

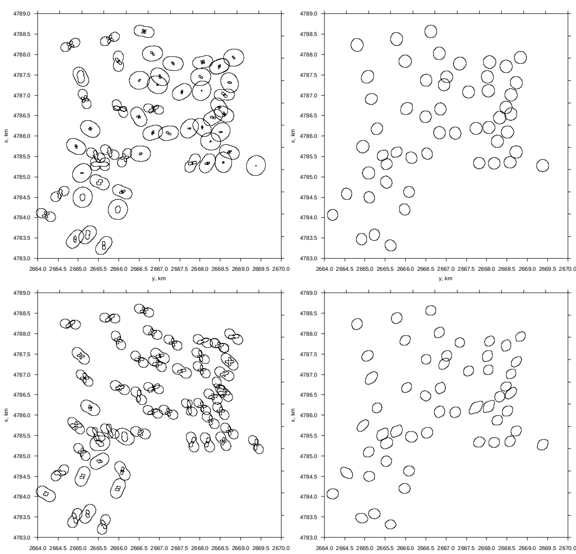

Figure 4. Magnitude (left) and phase (right) polar diagrams of impedance tensor at 22 Hz (top) and 0.02 Hz (bottom). Only sites in the main 3D area are shown. The round shape at high frequency implies an almost-1D structure at shallow depth. At higher depth a N45ºW strike direction is testified by the direction of elongated magnitude polar diagrams on most sites.

During the survey, telluric and magnetic fields were measured in the NS and EW directions. After retrieving the regional strike direction, all data were then rotated in the N45°W direction or decomposed using various algorithms (Swift 1967; La Torraca et al. 1986; Smith 1995). All methods provided similar results and proved that, in order to achieve a correct response, data required rotation before attempting the modeling.

INVERSION

1D inversion of the determinant (DET) data as well as 2D inversion of TE-, TM-, TE+TM- and DET-mode data was performed using various algorithms. Since apparent resistivity data from a few sites showed significant difference between the two polarization curves at high frequencies, decomposition and the static shift corrections seemed to be crucial. Therefore, data were decomposed and then corrected for static shift prior to the inversion. For a maximum period of 1000 s and taking into account that the average resistivity of the area is extremely low, the maximum penetration depth we could achieve was less than 10 km for our models.
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.

In order to get an idea about 3D resistivity distribution in the studied area a neural network inversion (ANN) of MT data was carried out (Spichak and Popova, 2000). For imaging the geoelectric structure of the survey area, the Bostick transformation was applied to the apparent resistivity determinant, calculated at each site for all frequencies. Fig. 5 shows horizontal slices of the resulting volume resistivity image up to a depth of 30 km. In spite of the rather smooth character of the resistivity distribution caused by using resistivity determinant, it is seen that the studied area is generally very conductive (the west and north margins being the most conductive ones). However, it incorporates a deep resistive anomaly in the south-west, where polar diagrams also define a 3D structure. This result will be further refined by using full range 3D Bayesian statistical inversion taking into account all prior information.

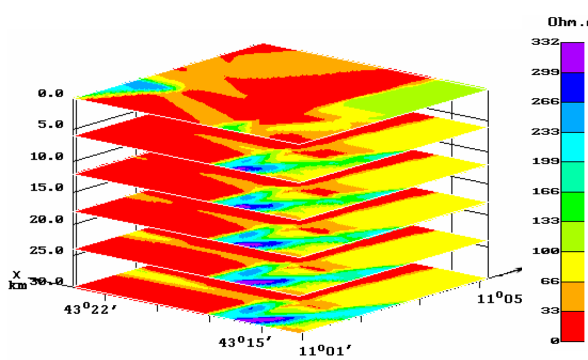

Figure 5. Horizontal slices of 3D resistivity distribution obtained using ANN reconstruction. Only sites in the main 3D area have been considered.

Meanwhile, we studied the geoelectrical structure by 2D inversion using the algorithm of Rodi and Mackie (2001). The profile is in the SW-NE direction, i.e., orthogonal to the main strike direction, with receiver spacing of approximately 500 m in the main area and 2 km outside it. The TE and TM responses appear quite uniform over the short periods up to 1 s for most sites suggesting that the shallow structure is 1D to a first approximation. At longer periods the TE and TM responses diverge, indicating higher dimensional structure at greater depth, as indicated also by polar diagrams (Fig. 4). Most sites exhibit nearly the same shallow conductivity except in the southwestern part of profiles, where shallow resistivities are increased by an order of one.

We used the geological section (Fig. 3) along profile AA' in Fig. 2 to build an a priori model for our 2D inversion. The corresponding results show considerable consistency with the known geology and provide a clear picture, especially down to 2.5 km depth, where more details are known about the structure, particularly in the area exploited for geothermal purposes. The 2D resistivity distribution along profile AA' resulting from inversion is shown in Fig. 6.

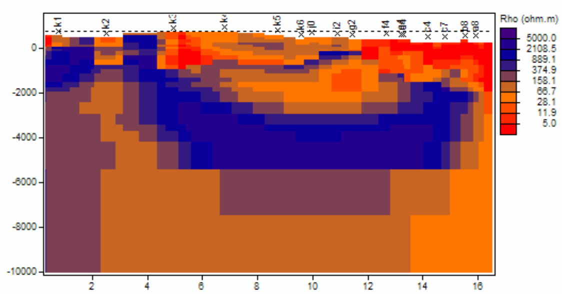

Figure 6. TE+TM-mode 2D inversion model using an a priori model based on the geological section in Fig.3 along profile AA' (SW on the left, NE on the right).

DATA INTERPRETATION

Fig. 7 demonstrates the resistivity cross-section along profile AA' overlapped by the geology (Fig. 3). Inversion has resolved on the SW a high-angle, conductive fault zone-like structure extending from surface down to a broad, deep crustal conductor beneath the Travale area. The top of the deep conductor is coincident with the seismic K-horizon. The outcrop of the high-angle fault corresponds to the location of the Boccheggiano fault, rich of hydrothermal minerals that testify the occurrence of intense fluid circulation. On the base of solely resistivity it is not possible to understand if this fault is still an active pathway for circulation of fluids, as it has surely been in the past, since the metal-bearing minerals themselves may be responsible for a permanent decrease of resistivity. However resistivity data suggest that circulation is or have been very deep, down to a depth of various km, and the fault appears very steep.

The most conspicuous features of the section in Figures. 6-7 is the presence of low resistivity anomalies inside the resistive basement at a depth of 1.5-3 km b.s.l. At the center of the section the resistivity anomaly flattens in correspondence of the faults inferred by reflection seismic data, suggesting an increase of permeability and a pathway for fluids and possible related alteration minerals. This anomaly corresponds to the deep fractured and highly productive zone in the metamorphic rocks, reported at a depth of 1.8 km b.s.l. (Bertani et al., 2005). This deep reservoir is made of sparse fractures whose connection is still not clear, and will be a target for future investigation by means of seismic and MT methods. The anomalies on the central-eastern part of the section show a good correlation with the shallow geothermal reservoir (e.g., Batini et al., 1985).

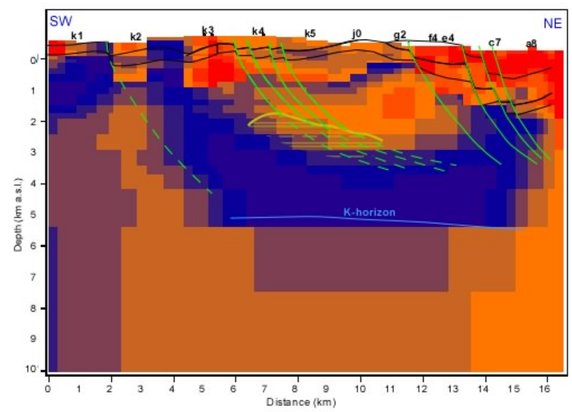

Figure 7. Resistivity cross-section overlapped by the geological model.

CONCLUSIONS

2D and 3D resistivity models of the Travale geothermal field have been constructed. The 2D models show resistivity anomalies that correlate with zones of higher permeability and fluid content representing exploited geothermal reservoirs. Moreover, resistivity appears reduced in correspondence to a fault where fluid circulation is testified by hydrothermal alteration minerals. A deep conductive anomaly is defined at a depth of 6 km, whose features are still to be defined with a broader acquisition net and a more refined 3D modeling.

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REFERENCES

Barelli, A., Bertini, G., Buonasorte, G., Cappetti, G. and Fiordelisi, A. (2000), "Recent deep exploration results at the margins of the Larderello-Travale geothermal system", *Proceedings of the World Geothermal Congress 2000*, 965-970.

Batini, F., Castellucci, P. and Neri G. (1985), "The Travale geothermal field", *Geothermics*,**14**, 623-636.

Bellani, S., Brogi, A., Lazzarotto, A., Liotta, D. and Ranalli, G. (2004), "Heat flow, deep temperatures and extensional structures in the Larderello geothermal field (Italy): constrains on geothermal fluid flow". *Journal of Volcanology and Geothermal Research*, **132**, 15-29.

Bertani, R., Bertini, G., Cappetti, G., Fiordelisi, A. and Marocco, B.M. (2005), "An Update of the Larderello-Travale/Radicondoli Deep Geothermal System", *Proceedings of the World Geothermal Congress 2005*.

Bertini, G., Casini, M., Ciulli, B., Ciuffi, S. and Fiordelisi, A. (2005), "Data Revision and Upgrading of the Structural Model of the Travale Geothermal Field (Italy)", *Proceedings of the World Geothermal Congress 2005*.

Brogi, A, Lazzarotto, A, Liotta, D. and Ranalli, G. (2003), "Extensional shear zones as imaged by reflection seismic lines: the Larderello geothermal field (central Italy)", *Tectonophysics*, **363**, 127-139.

Jones, A.G., Chave, A.D., Auld, D., Bahr, K. and Egbert, G. (1989) " A comparison of techniques for magnetotelluric response function estimation", *Journal of Geophysical Research*, **94**, 14,201-14,213.

Larsen, J.C., Mackie, R.L., Manzella, A., Fiordelisi, A. and Rieven, S. (1996), "Robust smooth magnetotelluric transfer functions", *Geophysical Journal International*, **124**, 801-819.

La Torraca, G.A., Madden, T.R. and Korringa, J. (1986), "An analysis of the magnetotelluric impedance for three dimensional conductivity structures.", *Geophysics*, **51**, 1819-1829.

Manzella, A., (2004), "Resistivity and heterogeneity of Earth crust in an active tectonic region, Southern Tuscany (Italy)", *Annals of Geophysics*, **47**, 107-118.

Marini, L. and Manzella, A. (2005), "Possible seismic signature of the α–β quartz transition in the lithosphere of Southern Tuscany (Italy)", *Journal of Volcanology and Geothermal Research*, **148**, 81-97.

Oskooi, B., Pedersen, L.B., Smirnov, M., Árnason, K., Eysteinsson, H., Manzella, A. and the DGP Working Group (2005), "The deep geothermal structure of the Mid-Atlantic Ridge deduced from MT data in SW Iceland", *Physics of the Earth and Planetary Interiors*, **150**, 183-155.

Rodi, W. and Mackie, R.L. (2001), "Nonlinear conjugate gradients algorithm for 2-D magnetotelluric inversion", *Geophysics*, **66**, 174-187.

Smirnov, M. Yu. (2003), "Magnetotelluric data processing with a robust statistical procedure having a high breakdown point", *Geophysical Journal International,* **152**, 1-7.

Smith, T. (1995), "Understanding telluric distorion matrices", *Geophysical Journal International*, **122**, 219-226.

Spichak, V.V. and Popova, I.V. (2000), "Artificial neural network inversion of MT - data in terms of 3D earth macro – parameters", *Geophysical Journal International*, **42**, 15-26.

Swift, C. M. (1967), "A magnetotelluric investigation of electrical conductivity anomaly in the southwestern United States", *PhD Thesis Massachusetts Institute of Technology, Cambridge, MA.*