MT as a tool for geothermal exploration: a case study from Southern Tuscany

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ABSTRACT

In this paper we will present the results of a study focused on the acquisition, processing and modelling of magnetotelluric (MT) data for the geophysical characterization of two geothermal areas located in the Southern Tuscany. Issues related to the noise characterization of the areas, robust processing, and modelling of the data will be addressed, highlighting also the limitations of such method due to the high cultural EM noise level.

1. INTRODUCTION

In recent years, Electromagnetic (EM) methods have been extensively applied to geothermal exploration (see e.g. Spichak and Manzella, 2009). Such methods may provide – through imaging of the electrical resistivity in the subsurface - useful information pertaining to the geological, rheological and hydraulic conditions of geothermal systems.

Amongst such methods, Magnetotellurics (MT) is based upon the measurement of the fluctuations of the natural electromagnetic (EM) field at the Earth's surface over a wide frequency range (10^{-3} to 10^{4} Hz). Given the diffusive nature of EM field in the Earth, such method allows low frequency measurements to large depths; on the other hand, cultural noise can severely affect the results of MT soundings, and dedicated, robust processing procedures must be implemented.

The aim of this paper is to analyze how MT data can be used to provide a geophysical characterization of two geothermal areas located in the Southern Tuscany. Here Gesto Italia holds three research permits for geothermal exploration and generation of electric power. Mazzolla permit is located in the northern border of the Larderello-Travale geothermal field, while Cinigiano and Montalcino permits are in the vicinity of Mt. Amiata geothermal field (Figure 1). Both these fields are known to be high-grade geothermal systems, as testified by very high values of heat flow (see Figure 1), and are currently exploited for power generation.

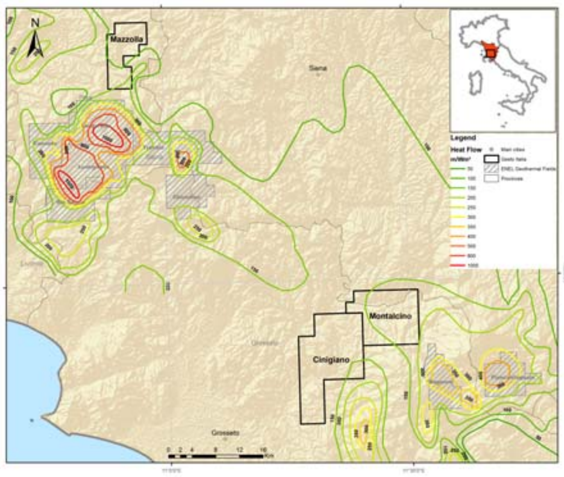

Figure 1: - Location of Mazzolla and Cinigiano-Montalcino research permits (black solid line), superimposed with geothermal fields currently under exploitation (textured grey lines) and heat flow values contours [mW/m^2] (green, yellow, red lines)

The outline of the paper is the following. After a section devoted to the description of the geologic setting of the two areas, we will analyze the various issues pertaining to the acquisition and processing of MT data, focusing in particular on the noise characterization and on the effectiveness of the robust processing algorithms adopted. We will then describe the workflow implemented in order to obtain a full-three dimensional resistivity distribution, using a three dimensional inversion of MT data; finally, we will show how the resistivity estimate from MT data can provide some relevant information about the structural lineaments of the geothermal reservoir, highlighting also the limitations of such method in the studied areas that are affected by very high EM anthropic noise.

2. GEOLOGIC SETTING

The study areas are located in the western-central Italian belt that belongs to the Tyrrhenian-Appennine orogenic system (Eocene-Quaternary age). This system can be considered a "compressional fold trust belt" (Carmignani and Kligfield, 1990) and is constituted by a series of overthrust nappes with a prevalently general eastward vergence.

After the compressional phase, an extensional tectonic phase took place from the Messinian age, opening neogene sedimentary basins that are controlled by NNW-SSE trending normal faults.

In the study area the tectonic-sedimentary sequence can be synthetically described as follow from top to bottom (Brogi, Liotta 2008, Brogi et al., 2003):

- Neogene and Quaternary deposits (continental to marine sediments) filling extensional tectonic depression and unconformably overlying the substratum;
- Ligurian l.s. complex (Ligurian and sub-Ligurian units) includes ophiolitic rocks and pelagic shaly sediments (Jurassic-Oligocene) and overthrusted eastward on the Tuscan Unit;
- Tuscan Unit consists of a variety of sedimentary rocks and includes carbonate and anhydritic formations at the base and terrigenous formations at the top (Upper Trias – Oligocene); this unit is detached from the original substratum at the level of the basal anhydritic formation;
- Metamorphic complex is composed of two metamorphic units (Bertini et al., 1991), the phyllites and micaschists Monticiano-Roccastrada Unit and the lower Gneiss Unit.

ACQUISITION AND PROCESSING OF MT DATA

For this case study two datasets were used comprising 168 MT stations located in Southern Tuscany (114 for Montalcino-Cinigiano and 54 for Mazzolla areas, respectively). For each station, the magnetic and electric time records were acquired using 5-channel ADU-06 Metronix receivers equipped with Pb-$PbCl_2$ non-polarisable electrodes and Metronix MFS-06/MFS-07 coil magnetic sensors. Data were acquired using for sampling frequencies the values 65536, 8192, 2048 and 64 Hz. Those values were defined to cover a broad frequency band (from 0.001 Hz up to 10000 Hz). In particular, for the lowest sampling frequency an overnight acquisition was run lasting 14 hours. As far as the location of the remote station was concerned, after an initial testing phase, such station was positioned 42 km North of the Cinigiano area and 23 km south of the Mazzolla area (see figure 2).

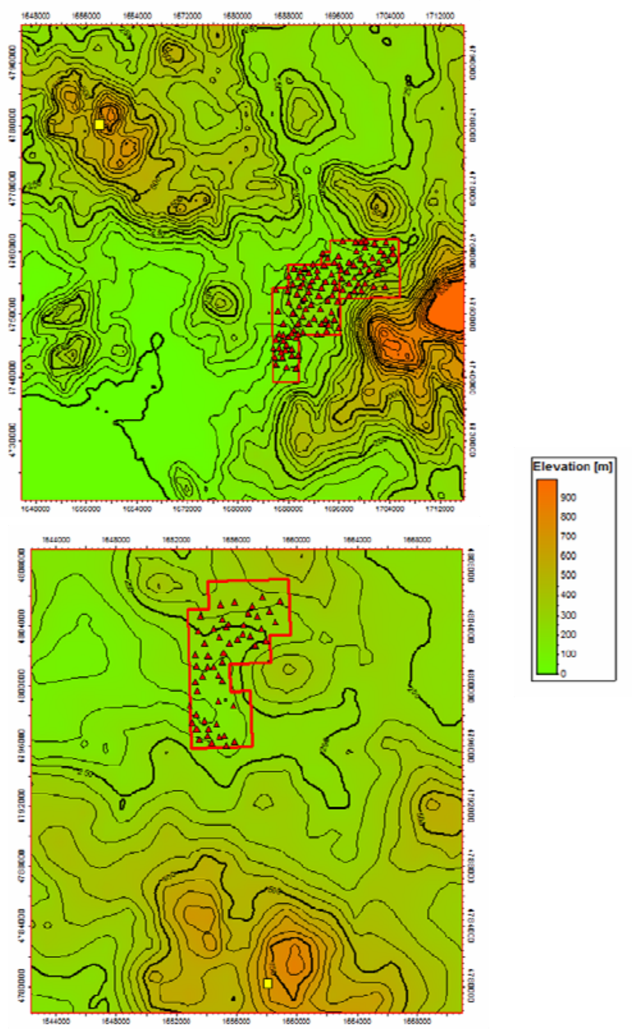

Figure 2: - Location of MT sites (red triangles) for both geothermal areas (red solid line) and remote site position (yellow square). Upper panel: Cinigiano-Montalcino. Lower panel: Mazzolla.

For each site, the full set of time records were used to obtain, over the given frequency band, a reliable estimate for the full magnetotelluric transfer function (both impedance tensor and tipper vector). Since natural magnetotelluric signal is contaminated with "noise" signals produced by near-by environmental, man-made sources (for a comprehensive analysis of the various noise sources for MT data see e.g. Szarka,1988 and Junge, 1996), the remote reference method (Gamble et al., 1979) was adopted within a data analysis workflow. Here two different robust processing algorithms were used, the first based upon an iterative reweighted method on time records corrected for outliers and gaps (Larsen et al., 1996), the second exploiting a bounded influence estimator (Chave and Thompson, 1992).

For both the area surveyed, the data were affected by a number of noise sources. At high frequencies the main sources of EM distortions were power lines and water pumps, while at low frequency data were affected by the presence of a rail network (especially in the northern part of the Cinigiano area) , as well as by the daily variations of source signals. At high frequencies the distortions produced by the various sources on the MT signals were effectively removed by adopting the remote reference method; at low frequencies, in some cases, since the noise level (mainly due to the so-called train effect) was significantly high, its removal produced low data quality results (see figures 3-4)

For the two areas, given the job recording schedule adopted and the noise level, the remote-reference robust processing procedure allowed to obtain – for the sites characterized by the lowest noise level - reliable estimates of the impedance tensor and tipper up to a maximum period of 10 s.

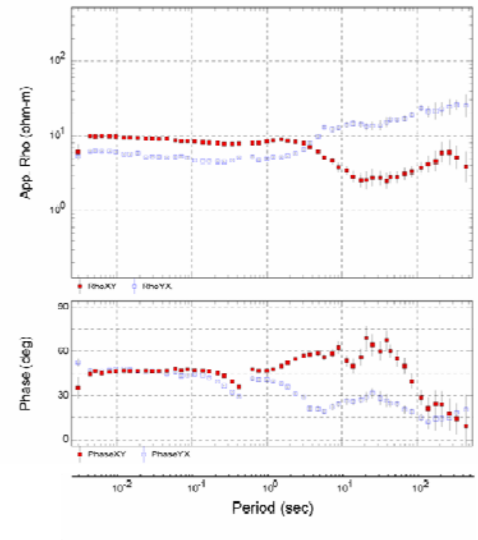

Figure 3: - Apparent resistivity and phase curves as a function of period for one site acquired in the Mazzolla area. Data are rotated to N0°E. Red points indicate XY component, YX is represented by blue points

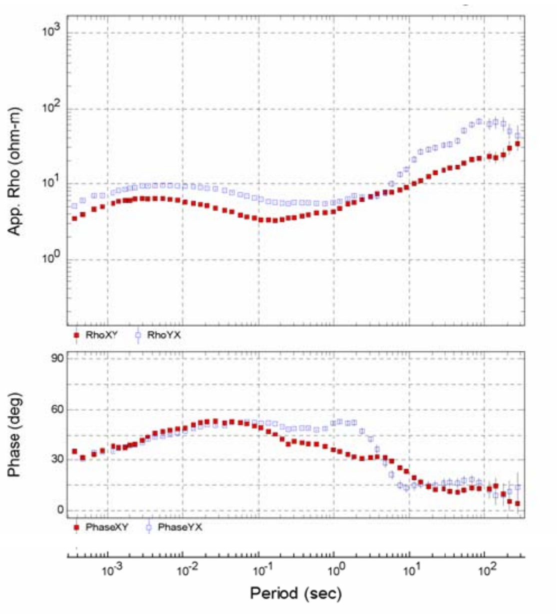

Figure 4: - Apparent resistivity and phase curves as a function of period for one site acquired in the Cinigiano area. Data are rotated to N0°E. Red points indicate XY component, YX is represented by blue points

4 THREE DIMENSIONAL MODELING

For both areas, the processing workflow was the first step to obtain the most reliable resistivity model consistent with the MT data. Hence a series of numerical 3D inversions were carried out using an algorithm based upon the NLCG (Non Linear Conjugate Gradient) method. This was optimized to minimize the so-called objective function, i.e. the sum of the normalized data misfits and a function measuring the smoothness of the model (Mackie and Madden, 1993; Rodi and Mackie, 2001). The horizontal grid chosen for the inversion uniformly covered the area of interest (the so-called core area) and included external padding characterised by a higher spacing. On the other hand the vertical grid was set to be non-uniform, with a base value 1/5 of the estimated shortest period skin depth. As for the initial inversion model, two different choices were adopted:

- A “blind” approach, with an half-.space model, characterized by a constant resistivity value (50 ohm.m)
- A geology-based approach, where the initial resistivity distribution was built using estimated of the tops and basements of different units (flysch, neogene, sandstone and carbonates) and three resistivity values (200 ohm.m for carbonates, 20 ohm.m for flysch, 5 ohm.m for neogene and 40 ohm.m for sandstone).

The model responses were computed over a range of 0.001 to 1000 Hz, with a constant logarithmic spacing. In order to optimize the consistency between the three-dimensional resistivity distribution and MT data, the relative weight was varied between the smoothness of the resistivity distribution and the data misfit (mainly controlled by the so called τ parameter) as well as the relative sharpness between horizontal and vertical directions. Given the significant noise level present in the area, an error floor of 3% was used for the off-diagonal component of the impedance tensor, while for the diagonal components such parameter was set to 10%. Examples of computed *vs*. observed responses are shown in Figure 5 for both areas.

For Cinigiano-Montalcino area, the most stable result (i.e. the most reliable model) was characterized by a global RMS equal to 2.46, while for Mazzolla area the best value for such parameter turned out to be 1.77.

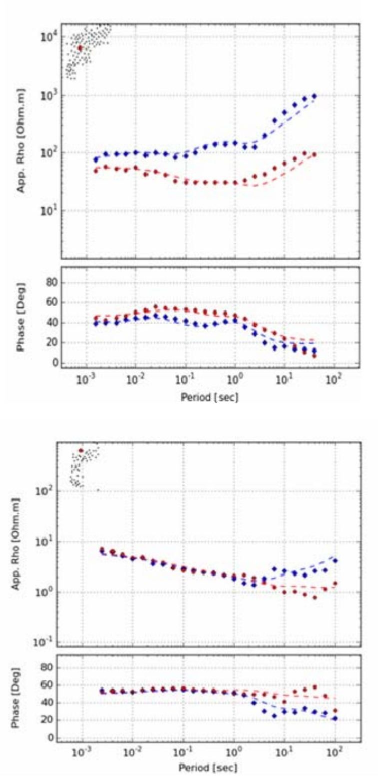

Figure 5. Soundings curves for Cinigiano-Montalcino (top panel) and Mazzolla (bottom panel) areas showing fits between observed (dots) and estimated (dashed lines) 3D model responses.

For both areas, the maximum period where consistency between data and model was optimal was estimated to be 10 s, corresponding to an average skin depth of about 5 km. Given that such quantity is an estimate of an upper limit on the maximum attainable depth, a conservative estimate of the maximum depth at which the resistivity models are reliable turned out to be 2-3 km

A common feature emerging from the inversion and modelling of MT data of both was that the resistivity distribution obtained from the inversion of MT data did not significantly depend upon the choice of the initial model, while the models obtained from the initial geology based distribution displayed sharper contrasts.

For the Montalcino-Cinigiano area, the inversion of MT data highlighted the occurrence of a resistive anomaly in the SE portion of the survey area already at 750 m depth and the presence of a thick conductive basin in the central part of the survey area consistent with established geological data (see figure 6).

For Mazzolla area, the main features characterizing the three-dimensional resistivity distribution obtained from the inversion of MT data were the occurrence of thick conductive body in the NE portion of the survey area and the presence of a resistive body already at 1.0 km depth in the central part of the survey area (see figure 7). It’s worth noticing that at depths greater than 1.5 km, the resistivity model displayed in the NE and SW portions of the survey area show resistive anomalies which however can be probably explained by the lack of soundings in those parts of survey area.

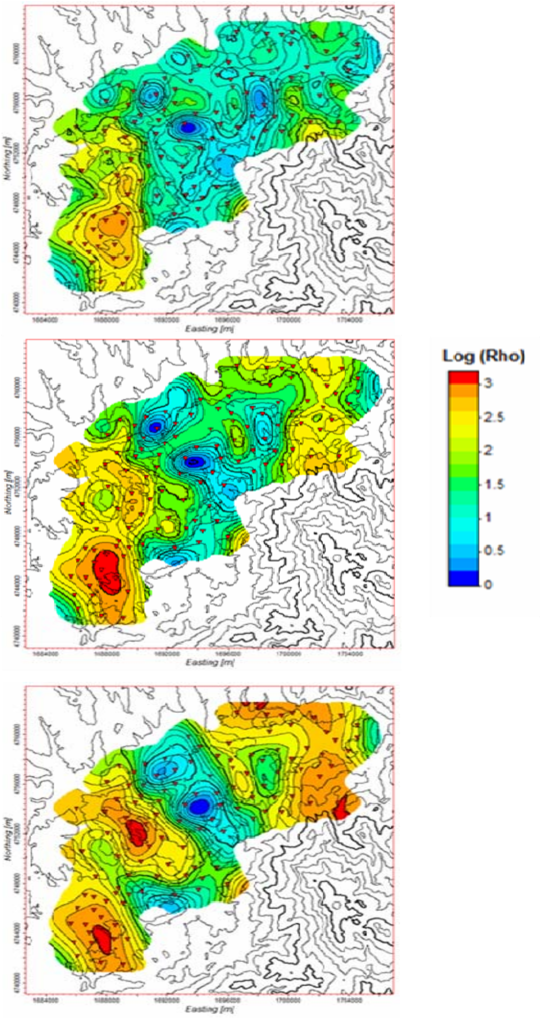

Figure 6:Resistivity maps at different depths for the Cinigiano-Montalcino area: 1000m (top panel), 1500m (middle panel), 2000m (bottom panel)

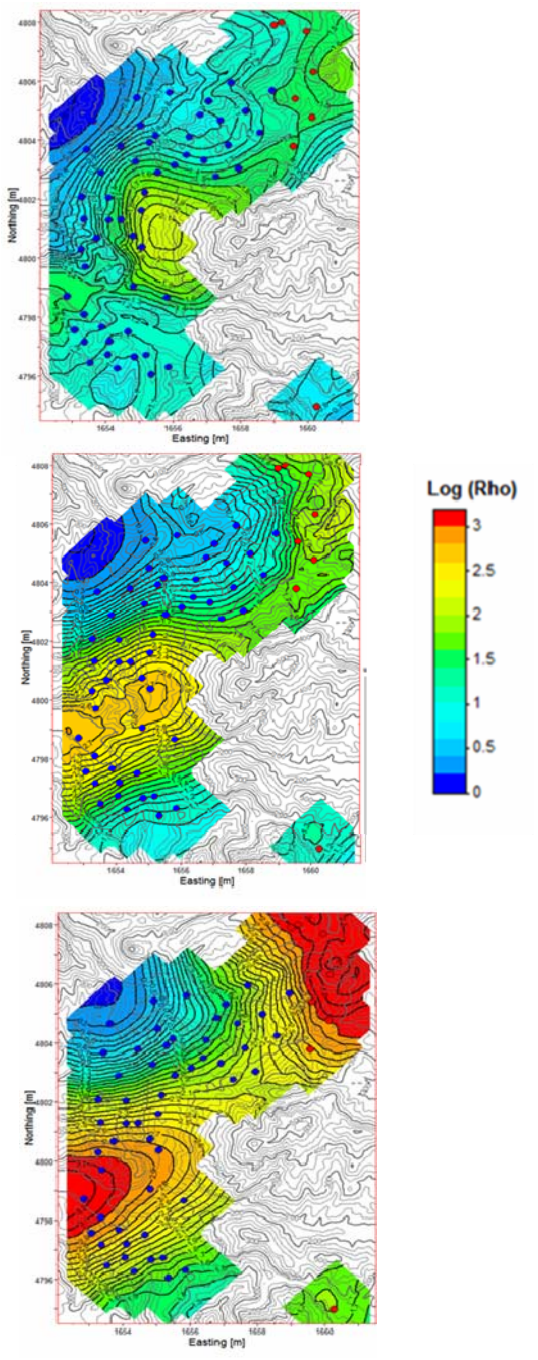

Figure 7:Resistivity maps at different depths for the Mazzolla area: 1000m (top panel), 1500m (middle panel), 2000m (bottom panel)

5. CONCLUSIONS

In this paper we have addressed – using a case study from Southern Tuscany – issues related to the use of MT data for the geophysical characterization of geothermal systems. The analysis was focused in particular on the quality of MT sounding data, which significantly depends upon the high level of cultural EM noise present in such areas (partly due to the development in the last ten years of the high-speed railway network),. This was the main constraint on the reliability of the resistivity models at depth. Hence, taking into account such limiting factors, we analysed the geophysical features – relevant for of the resistivity models obtained from a full, three-dimensional inversion of MT data.

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