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Gesto Italia Activities in the Exploration of Italian Geothermal Resources Preliminary Results

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ABSTRACT

Geothermal exploration activities of GESTO Italia in the past two years resulted in awards of four geothermal research permits in south Tuscany, Italy. The four areas cover a total area of 289 km^2; Mazzolla (52.5 km^2) is located in the vicinity of Larderello geothermal field while the remaining three areas are in the neighborhoods of Monte Amiata geothermal field, Cinigiano (141.20 km^2), Montalcino (65.74 km^2) and Montenero (30.19 km^2).

MT and gravity data have been jointly used in order to provide a geophysical characterization of the geothermal areas under exploration. The acquisition and processing of MT data have been mainly focused on the noise characterization and on the effectiveness of the robust processing algorithms adopted. A full three-dimensional resistivity distribution has been defined by using a three dimensional inversion of MT data that provided relevant information about the structural lineaments of the geothermal reservoir. The MT survey highlighted also the limitations of such method in the studied areas that are affected by very high EM anthropic noise.

For two of the studied areas (Cinigiano and Montalcino), the results of the resistivity modelling have been used to update a geologic model that was assessed through the full three-dimensional modelling of gravimetric data.

1. INTRODUCTION

In Italy, since 2009 Gesto has four concessions for development of geothermal projects varying from 5 to 20 MW. Gesto was the first company to apply for geothermal concessions in the Tuscan region (Italy) following new legislation promulgated in February 2010 that opened the Italian Geothermal market to the private sector.

The four concessions (Figure 1) cover a total area of 289 km^2 and were granted to Gesto in 2011 and 2012 by the regional government and the Italian Central Government. The four concessions, Cinigiano (141.20 km^2), Montalcino (65.74 km^2), Mazzolla (52.50 km^2) and Montenero (30.19 km^2) are close to two proven, high-grade geothermal systems, the Larderello-Travale and Monte Amiata geothermal fields (Baldi et al. 1995). These fields have been developed since 1913 (the first geothermal project in the world was built on the Larderello field) and today have a combined total of 772 MW of installed geothermal capacity.

All of the concessions held by Gesto are in an advanced stage of exploration. Surface exploration is either complete or in the final stage of completion. Proximity to the developed Larderello-Travale and Monte Amiata geothermal fields has allowed Gesto to estimate the resource potential of the concessions based on the known characteristics of the existing operating fields and the abundance of data regarding the geology/subsurface conditions in the area.

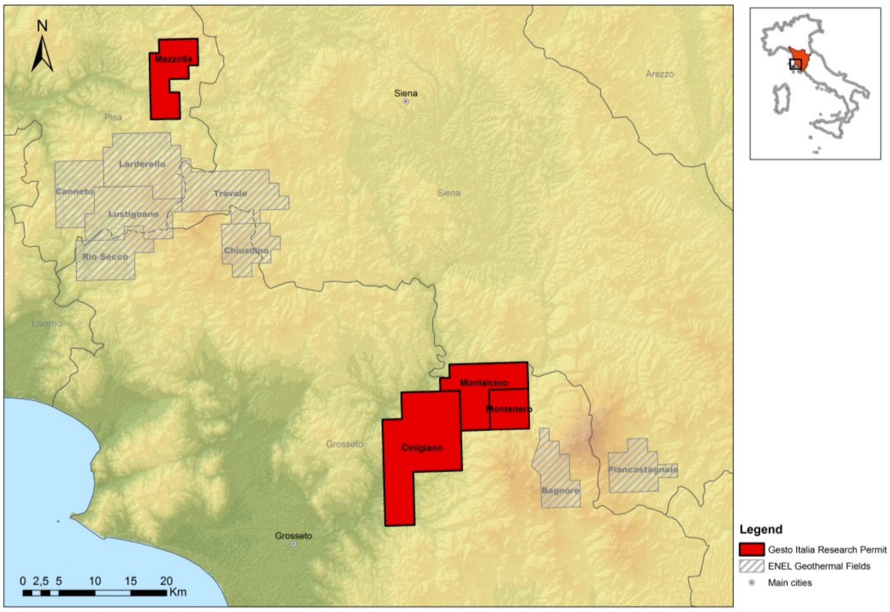

Figure 1: Gesto's Italian research permits.

The detailed resource evaluation undertaken by Gesto to identify and evaluate the potential reservoirs includes:

- Detailed structural geological studies and analysis of the extensive literature on geology and geothermal exploration that exists for the region;
- Analysis of gradient wells and several deep wells made during geothermal exploration of Italian geothermal fields;
- Analysis of raw data from existing seismic lines that cross Gesto's concession;
- Magnetotelluric ("MT"): Acquisition and 3D modeling of subsurface conditions utilizing a dense grid of 168 MT stations within the concession areas;
- Gravity Modeling: Acquisition of Gravity Bouguer Data (D=2.67 g/cm3) with 1x1 km resolution and integration with selected MT profiles.
- Reprocessing of existing seismic profiles and planning of new lines to be acquired.

In past years, geophysical electromagnetic 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 104 Hz). Given the diffusive nature of EM field in the Earth, such a 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.

This paper contains an analysis of how MT data can be used to provide a geophysical characterization of two geothermal areas located in Southern Tuscany, focusing in particular on the noise characterization and on the effectiveness of the robust processing algorithms adopted. We will also 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, also highlighting the limitations of this method in the studied areas that are affected by very high EM anthropic noise.

2. GEOLOGIC SETTING

The concessions areas are located in the western-central part of the 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 successions of overthrust nappes with a prevalently general vergence to the east.

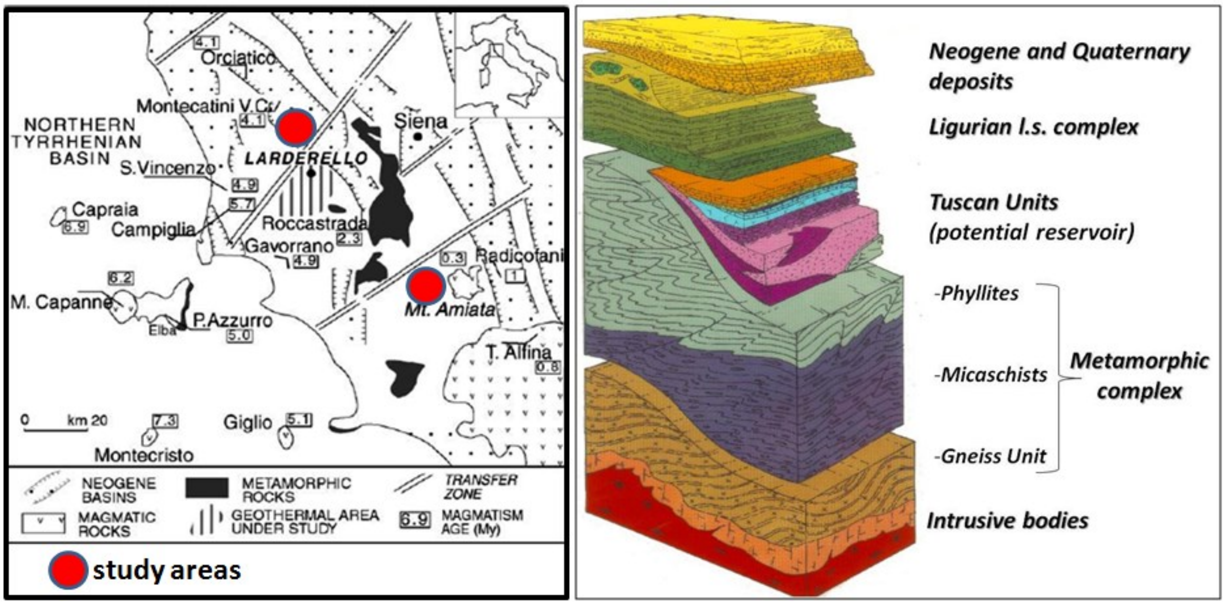

Figure 2: Structural setting of the western-central Italian belt (from Brogi et al. 2003) (on the left). Tectonic-sedimentary sequence in the study areas (from Bertini et al. 1991) (on the right).

Following 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 (Brogi, Liotta 2008, Brogi et al., 2003).

In the study area the tectonic-sedimentary sequence can be synthetically described as follows from top to bottom:

- Neogene and Quaternary deposits represented by continental to marine sediments (Late Miocene to Pliocene and Quaternary) filling extensional tectonic depressions and lying unconformably over the substratum. This basins elongated NW-SE direction is filled by neo-autochthonous sediments;

- Ligurian l.s. complex (corresponding to Ligurian and sub-Ligurian units) consisting of ophiolitic rocks and pelagic 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; The Tuscan Unit is also affected by tectonic extension which locally superimposes directly Ligurian units on the metamorphic formations.
- Metamorphic complex is composed of two metamorphic units (Bertini et al., 1991), the phyllites and micaschists Monticiano-Roccastrada Unit and the lower Gneiss Unit. The two units are separated by a mylonitic horizon linked to the orogenic phase (Elter & Pandeli, 1990).
- The Gneiss Unit and the underlying intrusive bodies have been drilled only in the fields of the Larderello-Travale geothermal system.

2. GEOPHYSICAL FEATURES

In order to provide a geophysical characterization of the geothermal areas under exploration and to contribute to the definition of the structural lineaments of the reservoir formations, both magnetotelluric (MT) and gravity methodologies have been jointly used. Carbonate lithologies of the geothermal reservoir allow detection of as a denser and more resistive substratum.

2.1 MT data Acquisition and Processing

In the study areas, 168 MT station have been acquired (54 in Mazzolla and 114 in Montalcino-Cinigiano, respectively) on an irregular 2D grid, with a station spacing range of 0.5-2.0 km. For each station, the magnetic and electric time records were acquired using 5-channel ADU-06 Metronix receivers equipped with Pb-PbCl2 non-polarisable electrodes and Metronix MFS-06/MFS-07 coil magnetic sensors. Data were acquired in a broad frequency band from 0.001 up to 10000 Hz, using sampling frequencies values of 65536, 8192, 2048 and 64 Hz. For the lowest sampling frequency, an overnight acquisition was run lasting 14 hours (Buonasorte et al., 2013).

A remote station was positioned, after preliminary tests, about 40 km north-west of the Cinigiano area and about 20 km south of the Mazzolla area (Figure 3).

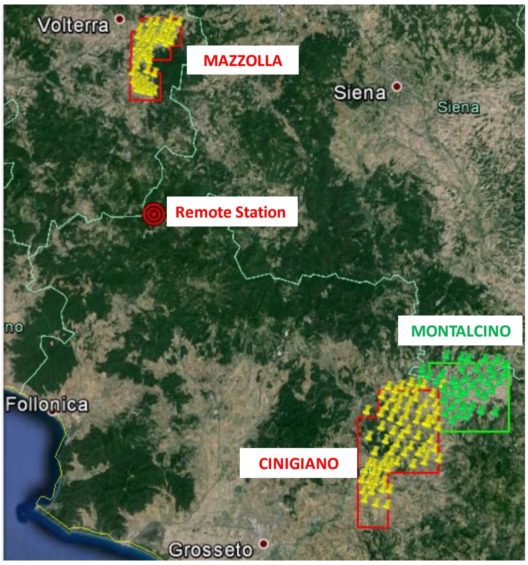

Figure 3: Location of MT sites in the three geothermal areas and remote site position.

Anthropic EM sources affect the natural magnetotelluric signals that result to be contaminated with "noise" signals produced by nearby environmental sources largely present in all of the study areas. At high frequencies the main sources of EM distortions are due to power lines and water pumps, while at low frequency data are mainly affected by the presence of a rail network (train effect) especially in the northern part of the Cinigiano area, as well as by the daily variations of source signals.

Therefore, the remote reference method (Gamble et al., 1979) was adopted within a data analysis workflow. 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, 2004).

The distortions produced at high frequencies 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.

For all the study areas, the remote-reference robust processing procedure allowed for reliable estimates of the impedance tensor and tipper up to period range of 1-4 s. Only in few cases can data be reliability extended to 10 s (Figure 4).

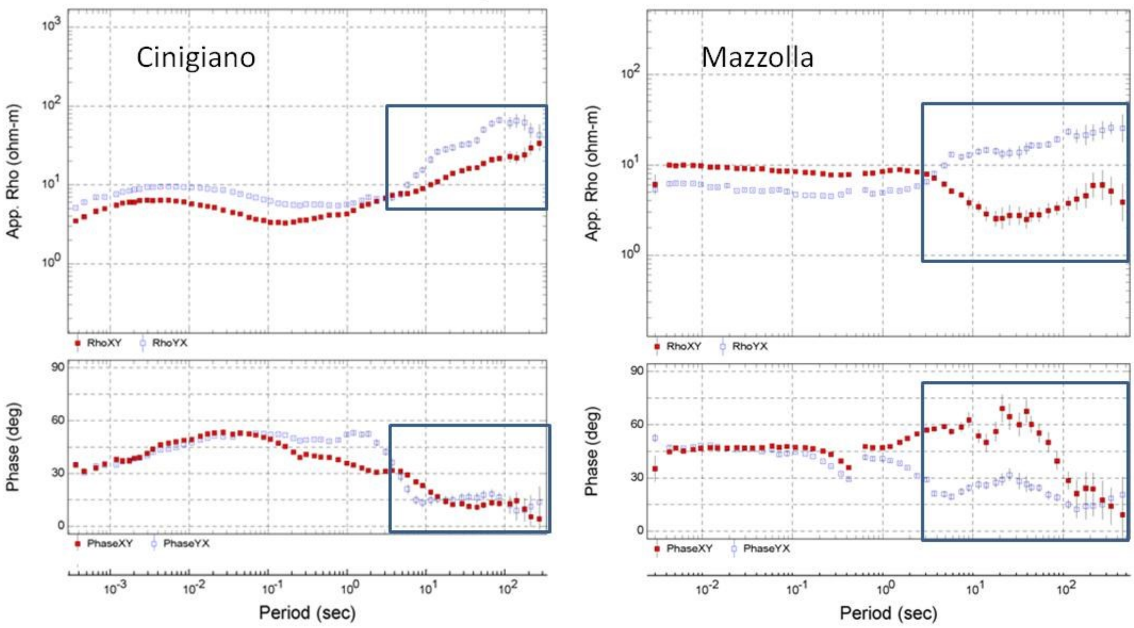

Figure 4: Apparent resistivity and phase curves as a function of period for one site acquired in the Cinigiano (left) and Mazzolla (right) areas. For periods > 2-4 s Rho and Phase are affected by noise, mainly for the component (blue points).

2.2 3D MT Modelling

A series of numerical 3D inversions were carried out using an algorithm based upon the "Non Linear Conjugate Gradient" method (NLCG), optimized to minimize the so-called objective function (Mackie and Madden, 1993; Rodi and Mackie, 2001).

The 3D grid parameters chosen for the inversions were as follows (Figure 5):

- core area with uniform horizontal spacing of 300 m
- external padding area characterised by higher and increasing spacing
- non-uniform vertical grid with a base spacing = 1/5 of the smallest estimated skin depth

For the wide Cinigiano-Montalcino (figure 5) the total xyz grid dimension was 240x246x65 km.

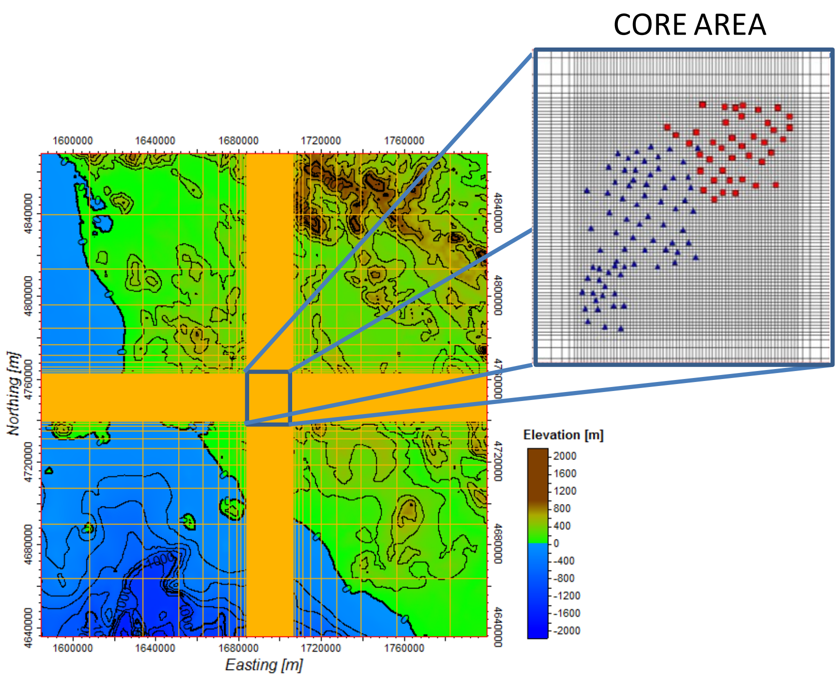

Figure 5: 3D horizontal grid adopted for the Cinigiano-Montalcino area.

For the a-priori inversion model two different choices were adopted:

- A "blind" approach, with a homogeneous half-space model having constant resistivity value of 50 ohm.m;
- A geology-based approach, where the initial resistivity distribution was built using expected resistivity and thickness values of the geological formations present in the area (Figure 6).

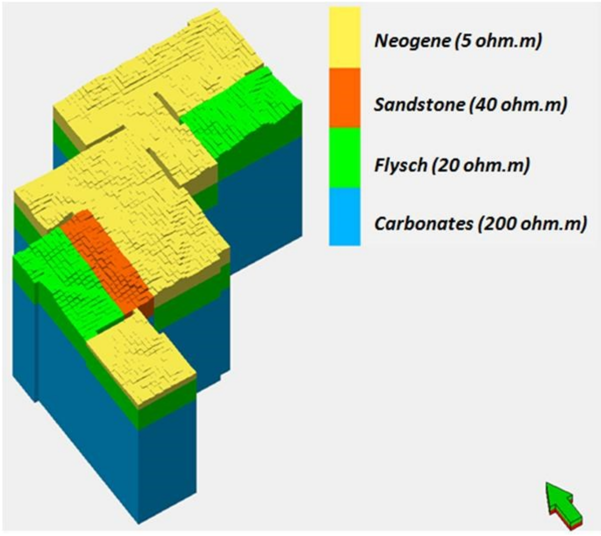

Figure 6: Geology-based a-priori model for the Cinigiano-Montalcino area.

For the 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 the Mazzolla area the best value for such parameter turned out to be 1.77. Furthermore, for all the areas the chosen a-priori model did not significantly affect final data fitting (Figure 7).

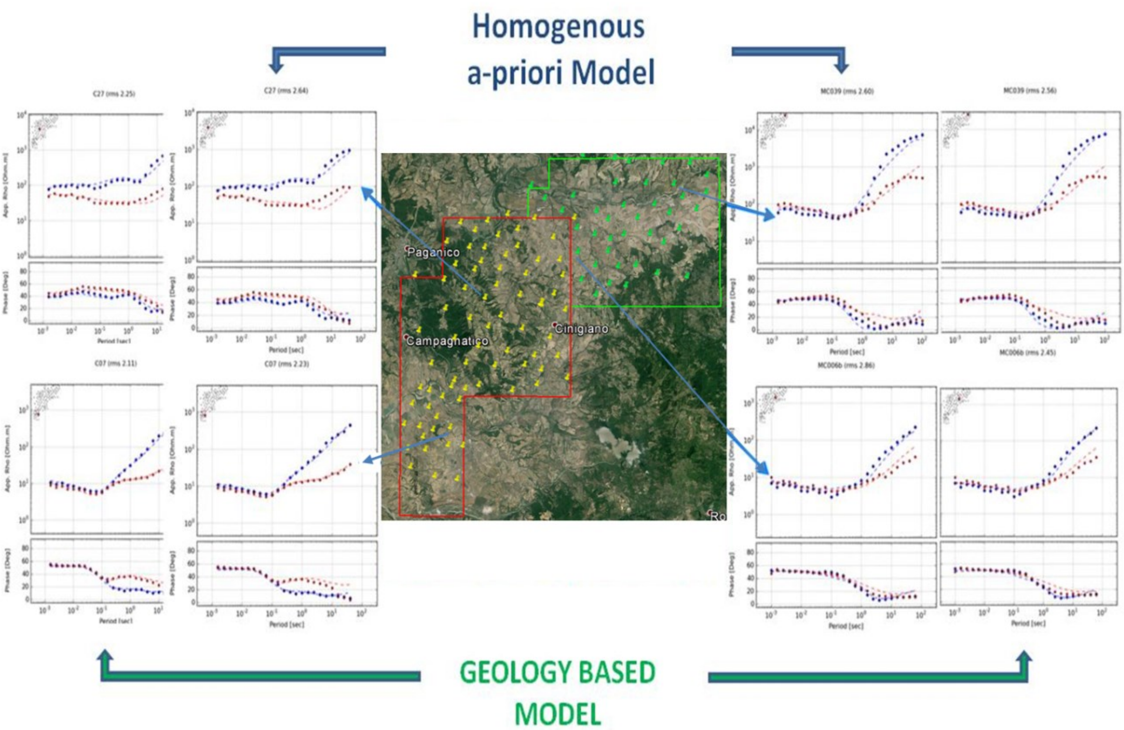

Figure 7: Examples of MT soundings curves for Cinigiano-Montalcino area showing fits between observed (dots) and estimated (dashed lines) values obtained with different a-priori model.

As mentioned, the maximum period of good consistency between data and model was estimated to be averagely 2-4 s and only in some case 10 s, corresponding to a maximum skin depth of 4 km. Given this, a conservative estimate of the maximum depth at which the resistivity models are reliable turned out to be 2-2.5 km

The main results of the models obtained by the 3D inversions can be summarized as follows:

- For Mazzolla area, the main feature of the 3D resistivity distribution is the occurrence of thick conductive body in the NE portion of the survey area and the presence of a resistive body at 1.0 km depth in the central part of the survey area (Figure 8 and 9).

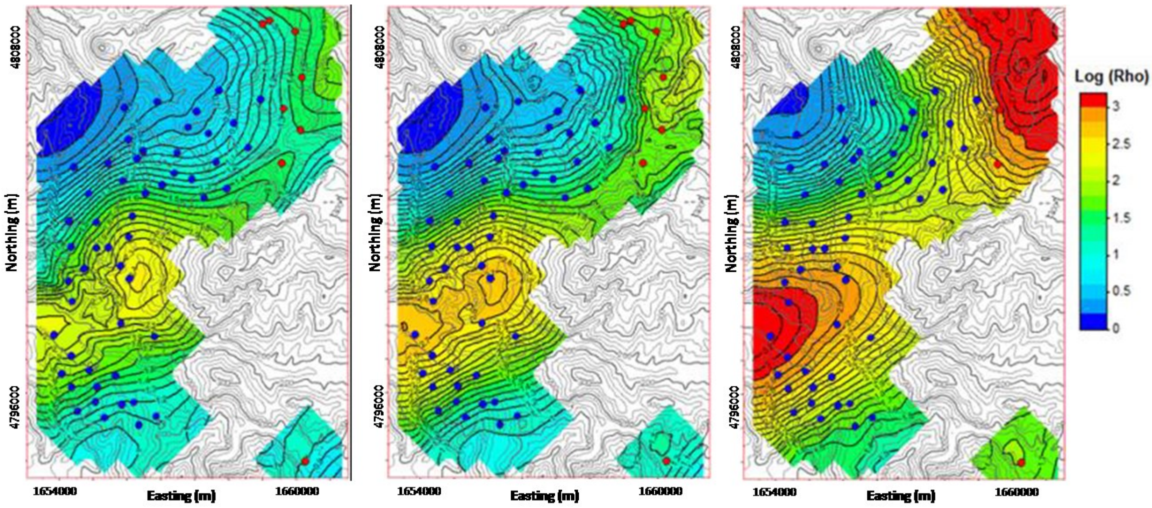

Figure 8: Resistivity maps at different depths for the Mazzolla area (from left to right 1000 m, 2000 m and 3000 m rsl).

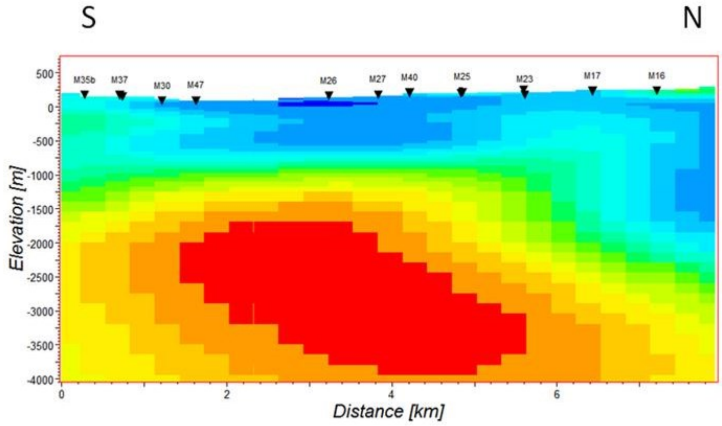

Figure 9: Resistivity S-N cross-section for the Mazzolla area.

- 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 at 750 m depth and the presence of a thick conductive basin in the central part of the survey area (Figure 10 and 11).

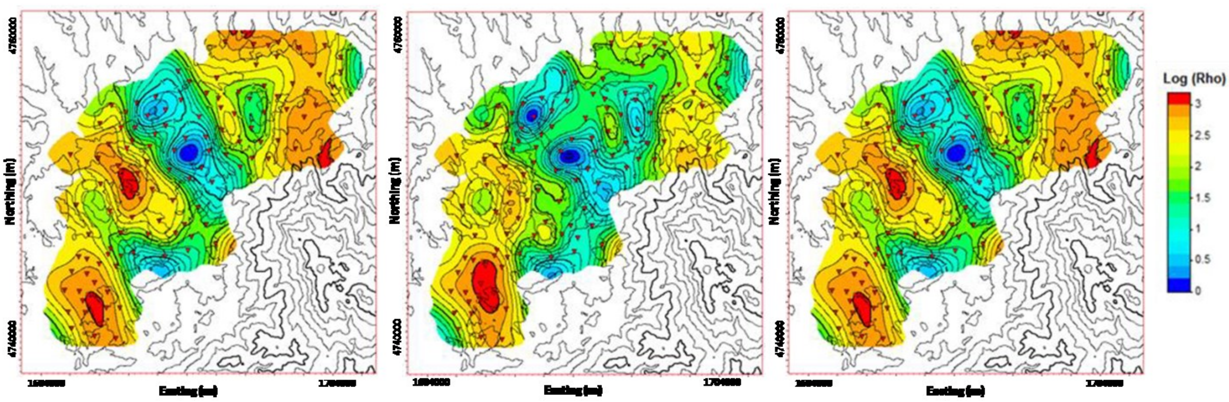

Figure 10: Resistivity maps at different depths for the Cinigiano-Montalcino area (from left to right 1000 m, 2000 m and 3000 m rsl).

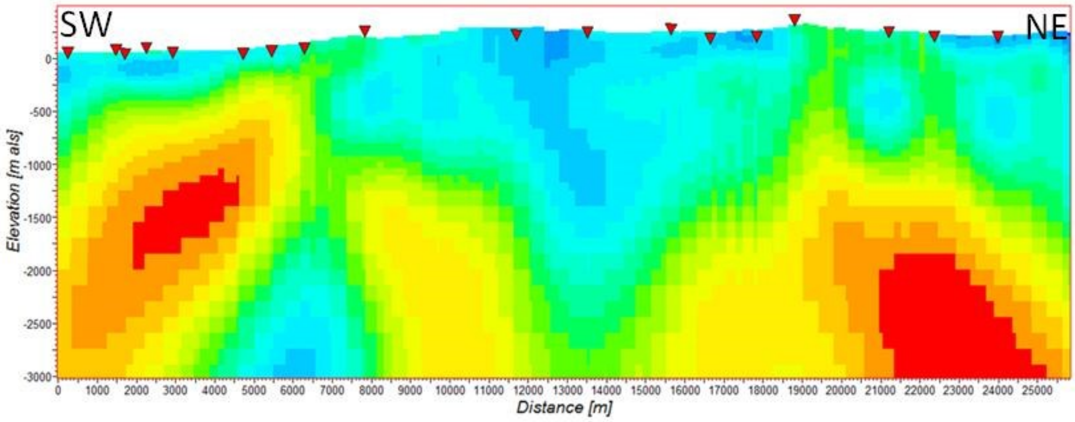

Figure 11: Resistivity SW-NE cross-section for the Cinigiano-Montalcino area.

Both in the Mazzolla and Cinigiano-Montalcino area, the resistive substratum has been interpreted as the expression of carbonate formations. So, the good definition of the top of this resistivity marker given by the 3D MT data inversion provided is also used as a reliable reconstruction of the reservoir lineament.

2.3 Gravity Data Processing

In order to check the structural lineaments defined by MT data and in this way reduce the interpretative ambiguity due to the utilization of a single methodology, available gravity data was processed and modelled. The input data set was provided by Trieste University, which has licence to extract digital data from the Gravity Map of Italy.

Specifically, the Bouguer anomaly data, computed with a reduction density of 2.67 g/cm^3, was provided with a "virtual" station density of 1/km^2 for a wide area of about 110000 km^2, extending from Mazzolla to Cinigiano-Montalcino areas. The Bouguer maps were modeled for both the areas (Figure12), providing suitable gravity images.

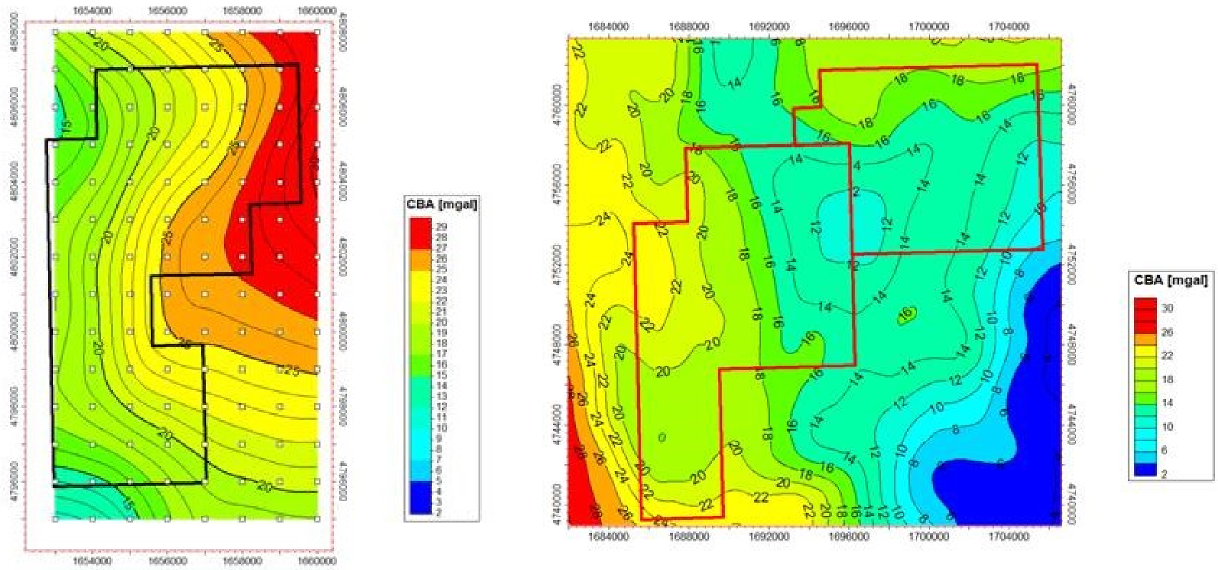

Figure 12: Bouguer anomaly Map (d=2.67 g/cm3). Mazzolla area (left) and Cinigiano area (right).

Three-dimensional inversions of gravity data were carried out using an algorithm optimized for minimizing the objective function (Li and Oldenburg 1996, 1998), starting with an a-priori model based on a preliminary geological and density characterization, as well as MT data inversions (Figure 13).

In particular, the results of the MT resistivity model were used to constrain the geological/density a-priori model, mainly for what concerns the depth of the carbonate reservoir that is characterized by values of resistivity and density much higher than those of the cover formations. In this way, an integrated modeling has been performed in order to verify the coherency between resistivity/density variations and to constrain the reconstruction of the reservoir top. For all the study areas, a substantial agreement has been pointed out between the structural lineaments evidenced by the 3D resistivity and density models (Figure 14).

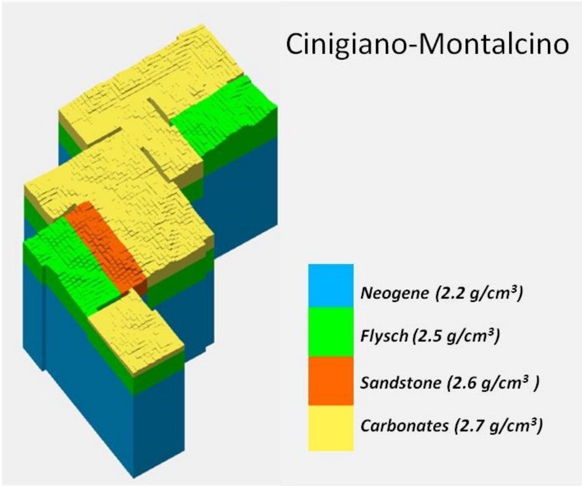

Figure 13: A-priori geological/density model used for the 3D gravity inversion of the Cinigiano-Montalcino area.

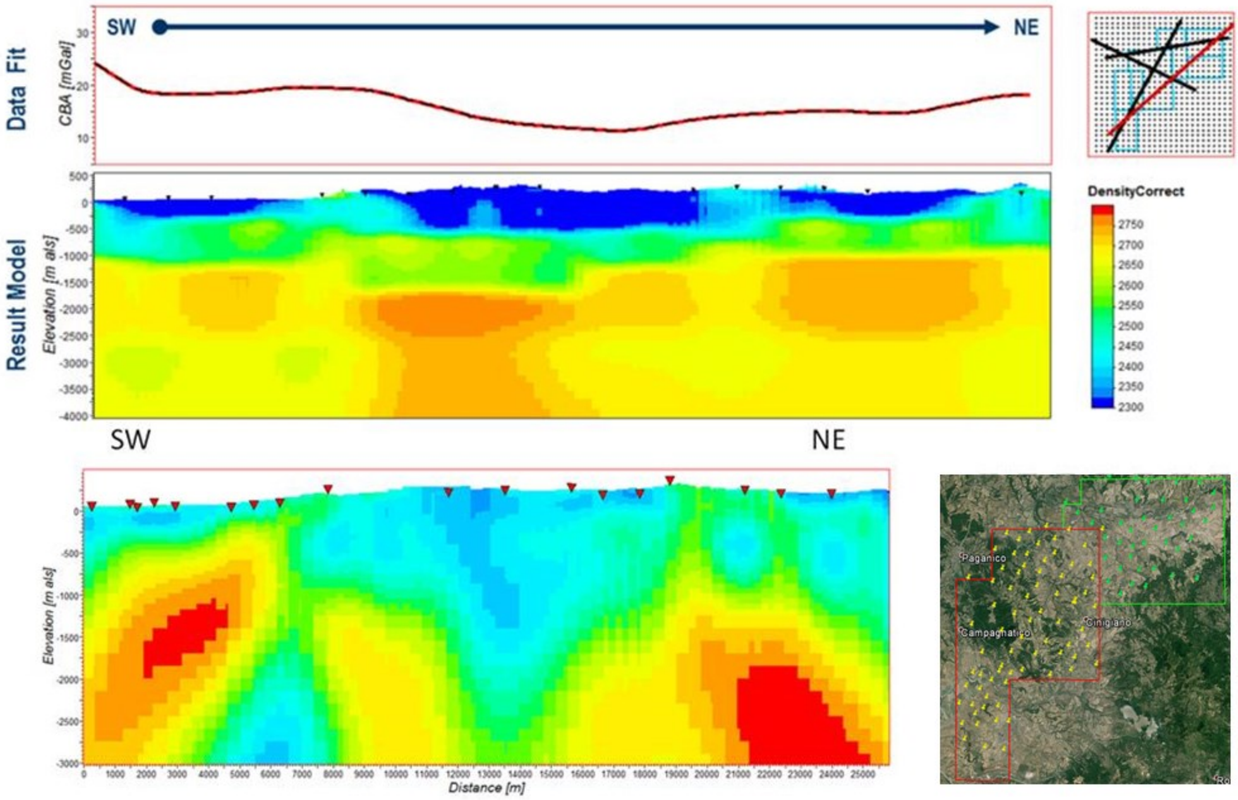

Figure 14 - Comparison between density (upper) and resistivity (lower) sections extracted by the respective 3D models in the Cinigiano-Montalcino area.

Of course, some differences can be noted between the two models, which are the consequence of the diverse petro-physical characteristics evidenced by the respective model inversions. Furthermore, the gravity seems to be strongly influenced by the geologically constrained a-priori model. Nevertheless, a reliable map of the reservoir top has been defined for all the areas and this is a first and important tool for planning the successive deep exploration phase.

2.4 Seismic Data Processing

With the aim to integrate the geophysical data set in these areas, Gesto purchased the raw data of about 80 km of two seismic profiles (CROP_3 and CROP_18) acquired between 1986 and 1999 for scientific studies of the deep crust (Brogi et al., 2005, Scrocca et al. 2003). These profiles (Figure 15) go across the Cinigiano area and have been reprocessed in order to focus the shallower seismic markers that can be possible targets of geothermal interest. For this reason, the re-processing has been centered on the first 6 seconds of the total recorded time (Figure 16); data interpretation is still in progress.

Furthermore, to complete the seismic data coverage, the acquisition of a new survey has been planned in the Cinigiano area along a profile oriented NNE-SSW.

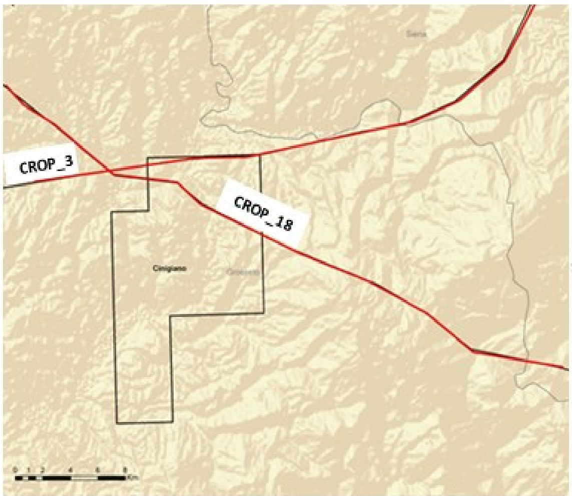

Figure 15 - Location map of Crop_3 and Crop_18 seismic lines.

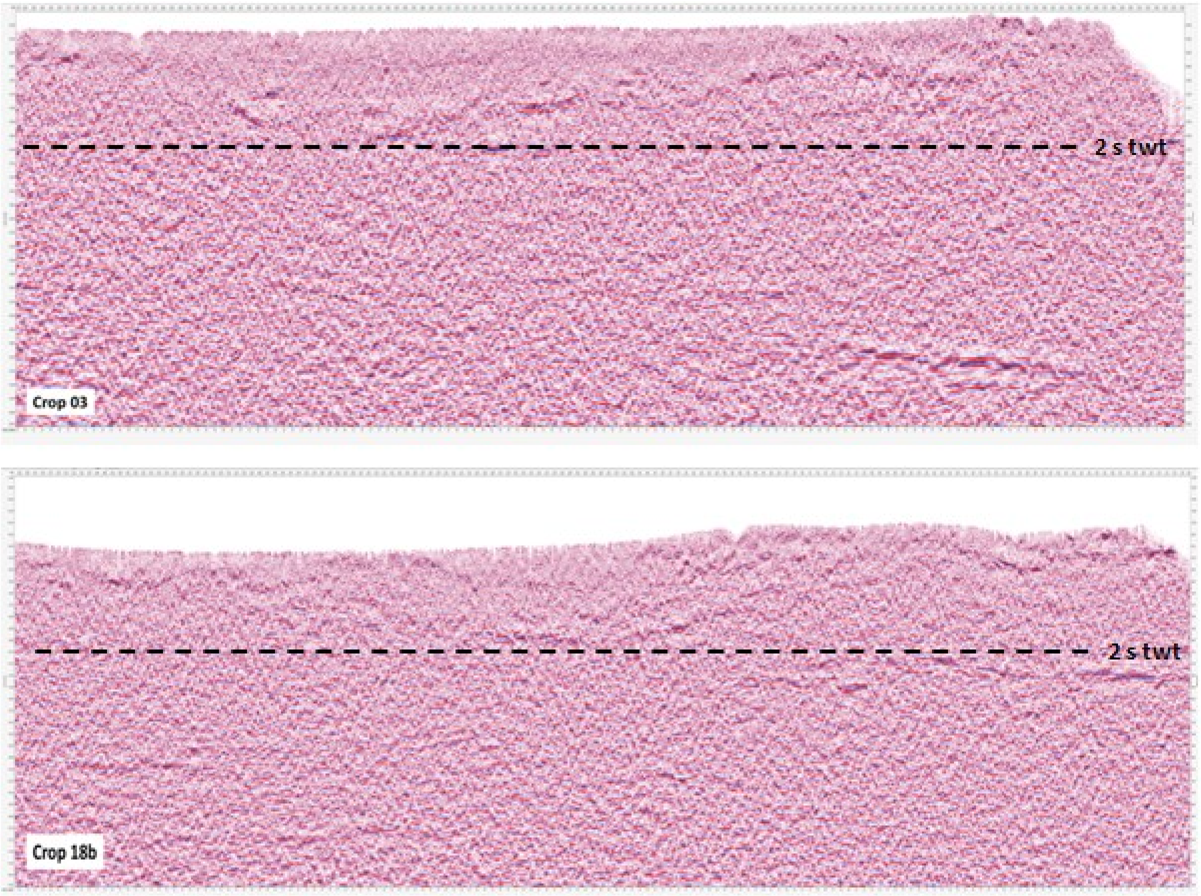

Figure 16 - Final stacks of Crop_3 and Crop_18 re-processed data. Shallower reflectors (within the first 2 s twt) are more evident and continuous. Total vertical scale is 6 s twt.

3 CONCLUSIONS

The geophysical methodologies were applied with the aim of helping to define the structural lineaments of the reservoir formations in the south Tuscany region where Gesto has their concessions areas. The main conclusion can be summarized as follows:

- MT method is undoubtedly a valid method for the electrical resistivity imaging, but the data quality significantly depends upon the high level of cultural EM noise present in the surveyed areas that limits the reliability of the resistivity 3D models at depth (period > 1s).

- In order to increase the reliability of such method in high cultural noise areas some key factors are an appropriate location of the remote station, longer observation times and the improvement of robust processing.
- The results of the MT resistivity model have been used to constrain the geological model, mainly for the depth of the carbonate top, which has been used as an a-priori model for the 3D gravity modelling.
- The 3D gravity model is in substantial agreement with the resistivity model, but seems to be influenced by the geologically constrained a-priori model.
- The top of the reservoir formations defined by means of an integrated interpretation of density and resistivity 3D models is quite reliable and can be used as an important tool for the deep exploration phase.

All of the above mentioned data will be integrated with forthcoming results from the interpretation of the reprocessed and new seismic lines in order to validate the location of sites for deep exploration wells that have already been individuated based on a preliminary logistic and environmental scouting.

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