Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

Electrical resistivity at the Travale geothermal field (Italy)

Adele Manzella[1], Carlo Ungarelli[1] , Giovanni Ruggieri[1], Chiara Giolito[1] and Adolfo Fiordelisi[2]

[1]CNR - Istituto di Geoscienze e Georisorse, Pisa, Italy

[2]Enel Green Power, Pisa, Italy

manzella@igg.cnr.it, ungarelli@igg.cnr.it, ruggieri@igg.cnr.it, giolito@igg.cnr.it, adolfo.fiordelisi@enel.it

Keywords: Travale, electrical resistivity, magnetotelluric.

ABSTRACT

Electromagnetic methods have been tested in the Travale geothermal field (Italy), a high-enthalpy field where the geothermal reservoir is located at a depth of 2-4 km in metamorphic and magmatic rocks, characterized by a high degree of heterogeneity and anisotropy and by the presence of superheated steam.

In order to determine whether magnetotelluric method is capable to define different reservoir features, and in particular a steam-dominated system, magnetotelluric (MT) data were collected during different surveys. After detailed robust analysis of these very noisy data, we have carried out 1D, 2D and 3D forward and inverse modeling in order to establish the resistivity data distribution at depth, its robustness and the sensitivity of MT data to different features. Resistivity log data, zones of high temperatures and productive fractures from drillholes measurements, a bright-spot type horizon identified in seismic profiles and estimated resistivity values of the lower crust and mantle were considered. The results have shown at the depth of the exploited geothermal reservoir a significant reduction in electrical resistivity whose large volume embrace but cannot be restricted to productive fractures from drillholes measurements and the bright-spot type horizon.

The observed reduction in resistivity may be interpreted taking into account the lithology and heterogeneities of reservoir rocks, their alteration and/or to the presence of a liquid phase within a fracture net sufficiently interconnected to produce electrolytic conduction. Since this last hypothesis is in disagreement with the known physical characteristics of the Travale geothermal fluid (superheated dry steam), a study on cores and cuttings was carried out in order to identify the types and abundance of primary and alteration minerals and to compare these data with resistivity values. An inverse correlation between resistivity of the encountered formation and phyllosilicates amounts has been observed. However, the quantity of phyllosilicates and their effect on resistivity may account only for the small variation observed in the resistivity logs, but not for the main resistivity anomaly defined by magnetotelluric data in the area. We conclude that lithology and conductive minerals appears to be not the main cause of resistivity reduction, and that the natural state of fluids in the microfractures remains an important matter that needs further investigation.

1. INTRODUCTION

Geophysical surveys exploiting electromagnetic induction methods are widely used in geothermal exploration. These surveys enable the distribution of electrical resistivity in the subsurface to be mapped, and provide complementary information (e.g., with respect to seismic surveys) for the characterization of the geological, rheological as well as hydraulic conditions of geothermal systems. The Travale geothermal field (Italy) represents a significant test site for assessing the robustness of such methods. Travale is a high-enthalpy system characterized by exploration targets located in metamorphic and magmatic rocks up to a depth of 4000 m, by a high degree of heterogeneity and anisotropy and by the presence of superheated steam.

Previous studies (Manzella, 2004) highlighted a significant reduction in resistivity in the geothermal areas in Tuscany. MT data collected in Travale share the same feature: at the depth of the geothermal reservoir these data are consistent with a significant reduction in electrical resistivity. However, a complete understanding of such a reduction is lacking. The geothermal fluid exploited in Travale is a dry superheated steam and thus does not lead to a decrease in resistivity. Fluid-rock interaction does not seem to have produced wide-scale alterations, also because the Travale geothermal reservoir shows a very low permeability caused by a few main fractures. However, detailed information on microfractures and their effect on permeability is lacking.

In geothermal systems, anomalous resistivity variations generally depend on a wide range of factors such as lithology and fluid distribution. These are in turn controlled by temperature, pressure and tectonic processes (Spichak and Manzella, 2008). Thus, such issues require the development of a multidisciplinary, integrated approach that brings together geological and geophysical data and aims at understanding the key factors determining resistivity variations. Such an approach would then be able to link these factors to the lithological properties of the reservoir rock, to the type and distribution of alterations and to the nature of the geothermal fluid.

In this paper, we address the capability of electromagnetic induction methods, such as MT, to define different reservoir features, and in particular the ones pertaining to the Travale geothermal field. In the next section we describe the key features of the MT data processing. In Section 3 we present the modeling procedure applied to the MT data and the results obtained and in Section 4 we attempt to interpret these results also in view of a mineralogical analysis. In the final section we discuss the results and draw some conclusions.

2. PROCESSING AND ANALYSIS OF MT DATA

For this study we used a MT dataset comprising 101 sites, collected during different surveys from 1992 to 2007. Over 66 sites, broad-band data were collected using Phoenix systems in 1992 (Fiordelisi et al., 1995) and 2004 (Manzella et al., 2006). 35 additional sites were surveyed in 2006 and 2007, where low-frequency data (4 -10^{-3} Hz) were acquired using LEMI and NIMS receivers over 20 sites and high-frequency (0.1-10^{3} Hz) data were recorded using a Stratagem system. Given the presence of various noise sources, a remote reference processing technique (Gamble et al., 1979) was adopted for low-frequency data using synchronized magnetic time series both from sites at a distance of a few kilometers and from far remote location (both the island of Sardinia and the isle of Capraia).

We used the data set as described in Manzella et al. (2006), and reprocessed the old MT data acquired in 1992 (Larsen et al., 1996) with an improved version of the original data processing code. We then analyzed the set of low frequency MT data collected over 20 stations in the Travale area and one remote site located on Capraia, covering the frequency range 10^{-3}-10^{-1} Hz. For such dataset, the total observation time ranged from 7 to 12 days with an effective sampling frequency of 4 Hz. For each site, data were processed using the algorithm described in Larsen et al. (1996) adopting three different methods to compute the impedance tensor: the least-squares single site, the local remote (i.e. correlating electric and magnetic channels of couples from local sites with synchronized data) and the remote reference method (i.e. using the synchronized MT data from Capraia). In order to extract the most reliable estimates for the impedance tensor, different frequency bands for each station were analyzed by choosing different values for the decimation factor and for the number of samples in each segment of data (for a description of the data processing algorithm used see Larsen et al., 1996). The optimal bands were identified making a trade-off between maximizing the coherency between electric and magnetic channels and the statistical robustness, i.e. with a sufficiently high number of data segments and a sufficiently high signal-to-noise ratio between the pre-processed time series and the residuals. This procedure enabled us to extract the most reliable estimates of the impedance tensor over multiple frequency bands and entailed detailed analyses of the various features of the magnetic and electric time series for each station.

The main outcome of this analysis was that for the Travale area, in the low frequency band, the recorded electric and magnetic data were in fact a superposition of both the MT signal and a wide range of noisy signals. Thus, the accuracy and reliability of the transfer function estimates turned out to be highly dependent on the strength, spectral properties and relative weights of the various correlated and uncorrelated noise sources. A preprocessing of the data (removal of outliers, large periodic variations, frequency spikes) enabled us to remove some effects associated with the presence of noise in some frequency bands. These features are shown in Fig. 1, where the estimates of the apparent resistivity ρ_{axy} and phase ϕ_{xy} as a function of the period at Site 14 are compared to the corresponding estimates obtained using a different processing algorithm (Egbert and Booker, 1986).

In some of the sites surveyed, the measured electric and magnetic time series were affected by uncorrelated and correlated noise signals of comparable strengths. The corresponding estimates of the transfer function tensor obtained using the least-squares, single site and local remote reference methods turned out to be both biased and distorted. When we used the remote reference method both those effects were reduced. In Fig. 2, for Site 4, the estimate of the apparent resistivity ρ_{axy} computed using the single-site, least squares method is compared with the corresponding estimate obtained using the remote reference method. For periods between 40 and 400 s the presence of strongly correlated and uncorrelated noisy signals produced both a significant distortion and a downward bias on the apparent resistivity.

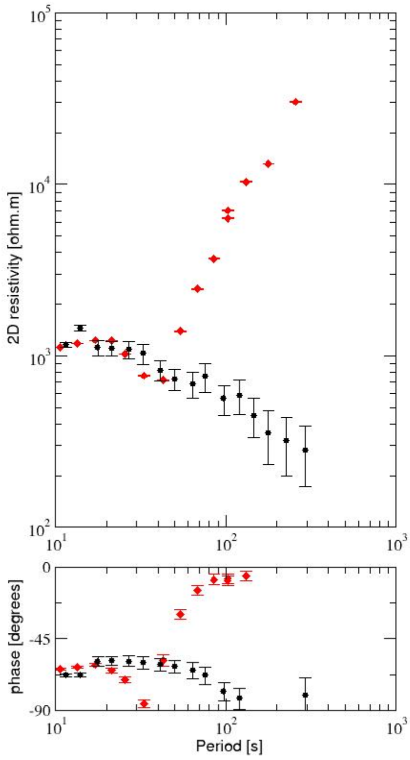

Figure 1: Comparison between single site, least squares estimates of the apparent resistivity ρ_{axy} and phase ϕ_{xy} - as a function of the period, obtained using the robust processing algorithm of Larsen et al. (1996) (black circles) and the processing algorithm developed by Egbert and Booker (1986) (red diamonds). Applying Egbert and Booker's algorithm, for periods longer than 40 s, the presence of a correlated noise signal distorts the apparent resistivity curve and drives the corresponding phase to zero.

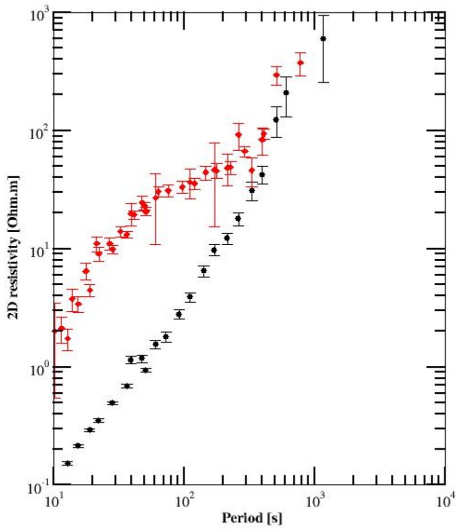

Figure 2: Comparison between single site, least squares (black circles) and remote reference (red diamonds) method estimates of the apparent resistivity ρ_{ayx} - as a function of the period. The remote reference method enabled us - for periods between 40 and 400 s - to remove the distortion and the bias caused by the presence of strongly correlated and uncorrelated noisy signals at the site.

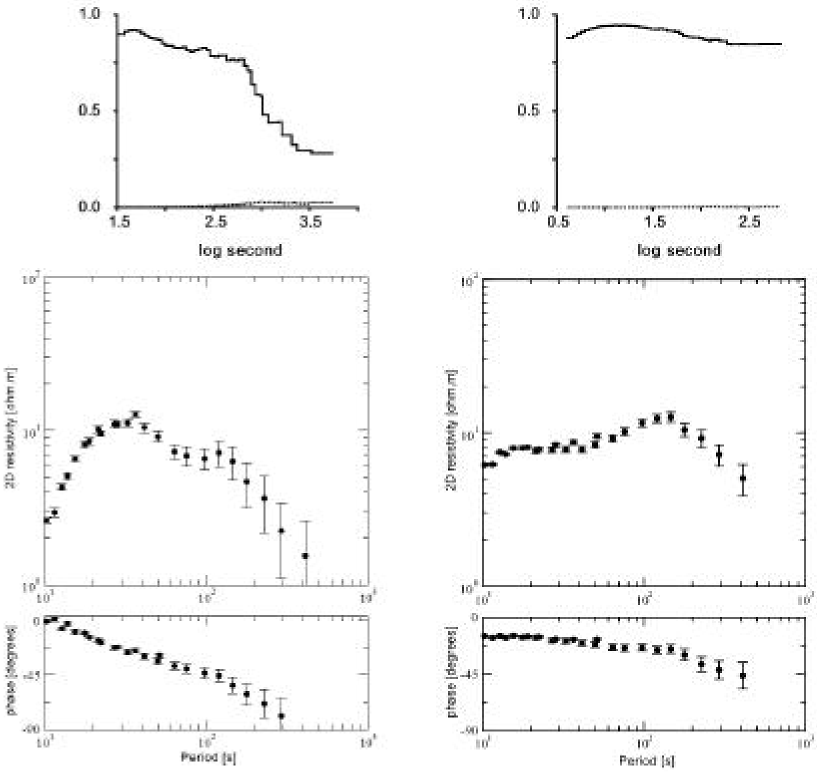

Figure 3: Main features of the long period MT data analysis for Travale. Here we consider the results from Site 9, showing low coherency, and Site 19, showing high coherency. The total observation time was 170 and 279 hours, respectively. Top-left: the coherence (between Ex and By) as a function of the logarithm of the period for Site 9. Bottom left: the best estimate of the apparent resistivity and phase as a function of the period for Site 9. Top-right: the coherence (between Ex and By) as a function of the logarithm of the period for Site 19. Bottom right: the best estimate of the apparent resistivity and phase as a function of the period for Site 19.

On the other hand, the correlation of the electric time series with the magnetic ones measured at the remote location removed these effects.

The main features of this analysis of long-period MT data can be summarized as follows. For most of the sites, electric and magnetic data were characterized by a cross-spectrum where the highest coherence was reached for frequencies in the range of 10^{-1}-$3x10^{-3}$ Hz (0.8-0.9), while - in the best cases – for frequencies less than 3×10^{-3} Hz the optimal value for the coherence ranged between 0.6-0.7. In some sites, magnetic and electric channels had a maximum coherence along parallel directions, thus highlighting the presence of a polarized EM signal (acting as a noise source for the MT signal). In this case, in the computation of the transfer function tensor, the electric fields were further rotated along the polarization direction and the direction perpendicular to it. However, in some cases, the electric signal turned out to be strongly polarized, thus lowering the accuracy of the transfer function tensor. In addition, given the slightly lower optimal coherence and the smaller number of good data segments (relative to higher frequency bands), in the low-frequency regime the estimates of the transfer function tensor were affected by significant statistical uncertainties.

The main characteristics of the data analysis are outlined in Fig. 3, where we show some examples of magnetic and electric pre-processed data from different sites, (characterized by different optimal coherencies) and the corresponding estimates of apparent resistivity and phase. The outcome of the full analysis of the complete set of MT data provided us - for each site - with an estimate of the impedance tensor over a frequency band corresponding to a range of penetration depths. These estimates were further processed by carrying out a single value decomposition (La Torraca et al., 1986) of the impedance tensor that enabled us to compute the maximum and minimum apparent resistivities.

We therefore estimated the strike direction by applying different methods: the Swift algorithm (Swift, 1967); using the direction of principal electric and magnetic fields obtained by La Torraca decomposition; using the tipper for each site whose data included a vertical component of the magnetic field. The results showed a relatively consistent estimate, at the regional level, for the strike that allowed us to define a principle direction of about N45°W degrees from magnetic north at most of the sites at the lowest frequencies (< 1Hz). This direction follows the trend of the main faults and basins in the Travale area. We also computed the amount of skew, finding low values on most sites, with the exception of those sites that were the most contaminated by noise. Since the typical skew values were below 0.4, we were able to approximate the area under study using two-dimensional (2D) geometry. However, given the complex geological structure of this area, our 2D interpretation can only be considered partially appropriate. As demonstrated by Ledo et al. (2002), for MT data pertaining to 3D structures the removal of near-surface galvanic distortions in any 2D interpretation is paramount in order to reduce the error sources in the 2D as well as the 3D interpretation. Applying La Torraca decomposition, most of the MT sounding curves showed a typical feature of 2D structures, i.e. a clear distinction between the TM and TE curves.

To eliminate the problem of static shift, MT data were compared with the geoelectrical data available in the area. For this study we used Schlumberger VES and a few TDEM data to correct for such effect. For those sites where VES and TDEM data were not available and the TM and TE curves showed a significant shift, we attempted to model the data without any preliminary static shift correction, including the static shift as a parameter to be determined by the 2D inversion. However, this approach yielded models that were not very consistent with the known geological features of the area. We therefore adopted a more empirical approach taking into account the geological unit outcropping below the MT sites. We looked at the apparent resistivity curves and chose the one characterized by the most probable correct position: on all sites at least one curve showed a shallow resistivity similar to the values from the same geological units in other sites. The “incorrect” curve was then shifted over the “correct” one. However, this procedure was only carried out for 15 sites out of 101.

3. MODELING OF MT DATA

The whole MT dataset from the Travale area was modeled using 2D (Rodi and Mackie, 2001) and 3D (Mackie et al., 1994) codes provided by WinGLink commercial software. In order to build the various models, we used the geological and seismic information available regarding the bottom of the Neogene sediments, the bottom of the Ligurian and Tuscan Nappes, the top of metamorphic units and the position of productive fractures in the wells and of the main seismic reflectors. Using resistivity log results and SEV data and on the basis of previous MT studies carried out in Tuscany (see e.g. Manzella, 2004), we estimated the following average values for resistivity: Neogene sediments 5-10 ohm.m, Ligurian-Tuscan Nappes 20 ohm.m with the exception of anhydrites with a resistivity of hundreds of ohm.m, metamorphic units and granites 1000 ohm.m (metamorphic and granitic units show the same resistivity on the resistivity logs). We used these data to define the distribution of resistivity below our target area, which was used both in the 2D and 3D forward models and in the a-priori models of 2D inversions.

We used both 2D inversions and 2D and 3D forward modeling extensively in order to define the most robust features of the resistivity distribution, and to distinguish between the regional and the local effects. We first carried out 2D and 3D forward modeling of a medium where only the lithological discontinuities were taken into account. We then compared the apparent synthetic resistivity and phase curves with the corresponding estimates previously obtained from the robust processing of MT data. We tested various hypotheses, assuming that metamorphic and granitic units maintain a resistivity value of 1000 ohm.m for the whole crustal thickness and a reduction of resistivity to 10 ohm.m in the mantle. Alternatively we assumed that a main regional seismic horizon (K) roughly defines the transition to the lower crust, and that temperature, if not partial melts, produce a resistivity decrease from 1000 to 100 ohm.m in the lower crust. For both classes of models the forward computations provided synthetic data that were not consistent with the experimental data. We therefore considered a model where a shallow conductive anomaly was located in the carbonatic units. Although in this case the fit improved, the synthetic and experimental data were still inconsistent.

The results of a 2D inversion obtained using the high-frequency data showed that the corresponding model was consistent with the experimental data only by assuming the presence of highly-conductive units (i.e with a resistivity of 1 ohm.m) both at the bottom of the Neogenic sedimentary basin - whose shallow resistivity values of 5-10 ohm.m were also confirmed by SEV data - and at their contact with Flysch formations. These anomalies are probably linked to the presence of faults bordering the basin and behaving like main fluid-filled or clayey units. This hypothesis was exploited in the 3D forward computations, where the bottom units of the sedimentary basin were modeled using low resistivity values.

The outcome of this analysis showed that consistency with experimental data required the presence of a deep low resistivity anomaly at the metamorphic basement. A range of values for these low resistivity anomalies was then tested in the 3D forward model in order to assess the minimum extension of this anomaly compatible with the experimental data. First we considered a class of models characterized by a low resistivity anomaly located either in a volume defined by the occurrence of productive fractures in the well, or at the depth of the phyllite and contact-metamorphic rocks. However, even assuming very low resistivity values these models did not fit the experimental data.

These computations provided strong evidence that neither the resistivity of the lithological units nor the presence of an upper and a lower reservoir limited to the currently productive fractures could explain the conductive anomaly highlighted by the MT data. Thus, we enlarged the anomaly in order to find a model that was reasonably consistent with the experimental data. In this case we analyzed a deep conductive body of about 60 km^3 in volume. We found that the consistency between the model and the MT data improved when a relatively conductive lower crust and a conductive mantle were both present. Indeed a resistivity decrease at these depths is not surprising, given both the increasing temperature and the presence of melt phases in an active tectonic region such as southern Tuscany. However, the conductive lower crust and mantle were not sufficient to explain the main conductive anomalies.

2D inversion computations were then carried out in order to constrain the location of the 3D low resistivity deep anomaly. The models were computed along five parallel profiles oriented NE-SW, i.e., orthogonal to the main strike direction of the area (Fig. 4). Different boundary conditions and inversion parameters were used in the inversions; the robustness of the results was also checked in detail. We computed 2D inversions of TE-, TM-, TE+TM data, and checked which features were really required by the data and were not bias effects produced by inversion. Sensitivity maps of inversions were also checked. Here we show only TE+TM inversions (Fig. 4), since they show the most robust results. RMS values of the TE-TM inversions shown were 1.1, 1.5, 6.0, 13.5 and 8.8 for Profiles 1, 2, 3, 4, and 5, respectively, using an error floor of 2% for resistivity and 1% for phase. The difference between the experimental and computed responses can be explained both in terms of genuine 3D effects and as due to low data quality. The main discrepancies were found in the south-west sector of the area under study, where the geothermal field is less exploited and less information is available.

The 2D and 3D modeling of MT data provided a robust evidence for a geometrically complex low resistivity anomaly at the depth of the exploited geothermal reservoir, which is not limited to the currently exploited productive fractures, but extends also to larger volumes. A further outcome of such analysis was that while productive fractures can not be identified solely on the ground of the resistivity distribution provided by MT data modeling, there exists a correlation between the number of productive fractures and resistivity values (see Fig. 5). Such issue certainly deserves further work (i.e. a more detailed three-dimensional model) in order to establish whether MT data modeling might provide useful information regarding areas of enhanced productivity.

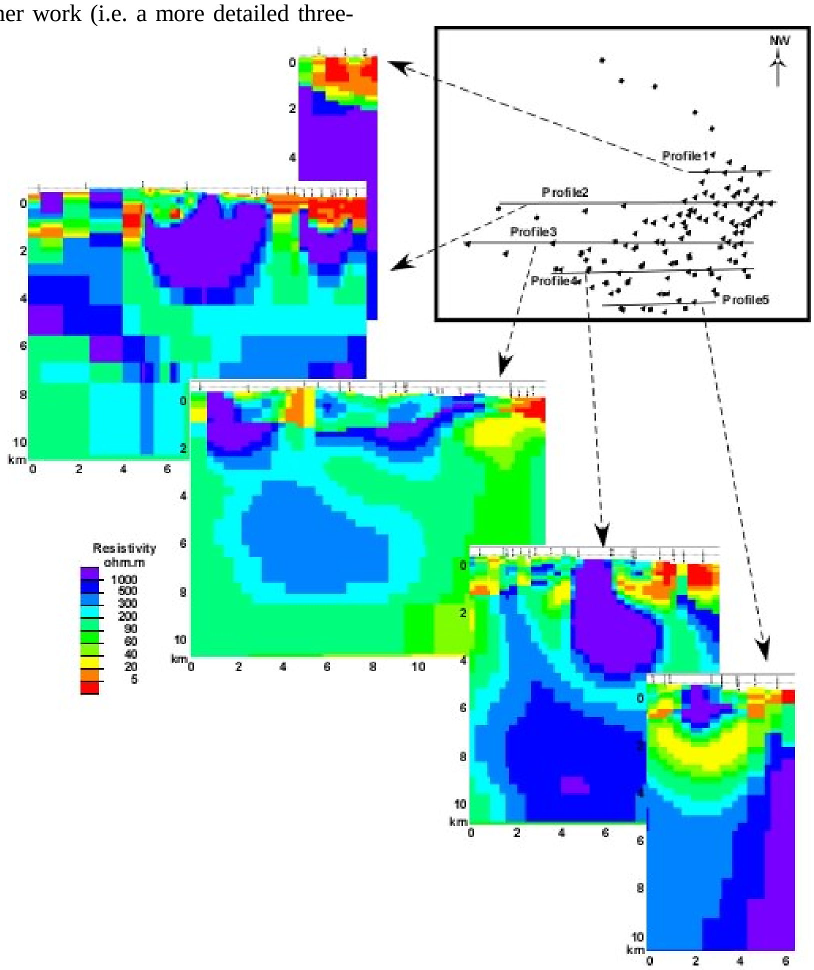

Figure 4: Resistivity models obtained from 2D MT data inversions carried out along five parallel profiles orthogonal to the main strike direction. Top-right: the direction of the profiles with respect to site location. Distances are in km.

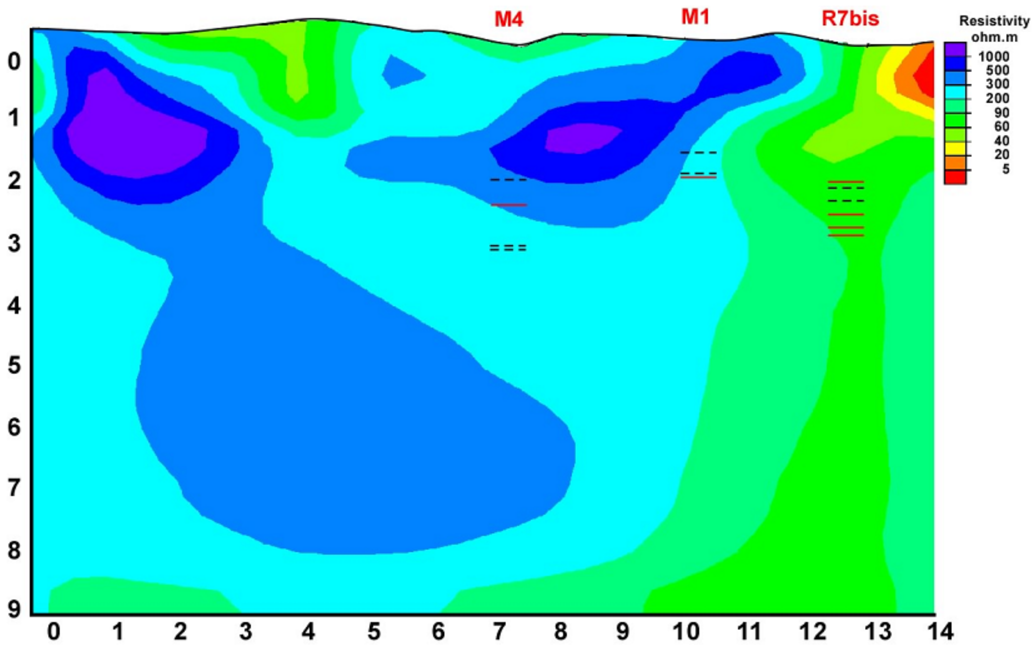

Figure 5: Two-dimensional resistivity map for the profile 3. The projected depths of productive (red-solid lines) and non-productive (black-dashed lines) fractures crossed by three deep wells located at close distance are also shown. Distances and depths are in km.

4. INTERPRETATION

In order to further investigate the nature and properties of such resistivity anomaly, MT data modeling results were compared with the mineralogical analysis on samples from two wells located in the Travale area, for which resistivity logs are available. In particular, the mineralogical studies of the cuttings of the two geothermal wells were carried out in order to compare the types, abundance and distribution of primary and alteration minerals with the resistivity values defined by MT data and resistivity logs.

The resistivity logs showed values generally higher than 1000 ohm.m (Fiordelisi et al., 2009). On the other hand, for thin fractured levels inside reservoir formations (contact metamorphic rocks and phyllitic units) resistivity showed values as low as few ohm.m (see e.g. Fig. 6). Since the resistivity logs are locally disturbed (e.g due to the presence of productive fractures filled by conductive drilling fluids), the single resistivity values at the corresponding depths may be too specific and not representative. Therefore, at each well the average resistivity values of each lithological unit for the occurring depth range was compared with: a) the average relative XRD intensity (I%) of the highest peak of specific minerals (Fig. 6), the variation of the I% would, in fact, reflect the increase or decrease of the minerals; and b) the average mineral content of the samples belonging to the same lithological unit (Fig. 7), computed following the method of Leoni et al. (1989). The phases constituting the analyzed rocks turned out to be characterised by relatively high-resistivity values. Among these phases, phyllosilicates (i.e chlorite, muscovite/illite, kaolinite) are comparatively less resistive than other minerals (i.e. quartz, carbonates). In particular, both the XRD I% of chlorite and muscovite (Fig. 6) and the total abundance of phyllosilicate (Fig. 7) showed a correlation with the average resistivity of the corresponding unit. Therefore phyllosilicate abundances, related either to primary mineralogical compositions or to secondary alteration processes, may explain the resistivity reduction observed in the resistivity logs and related to limited and thin layers.

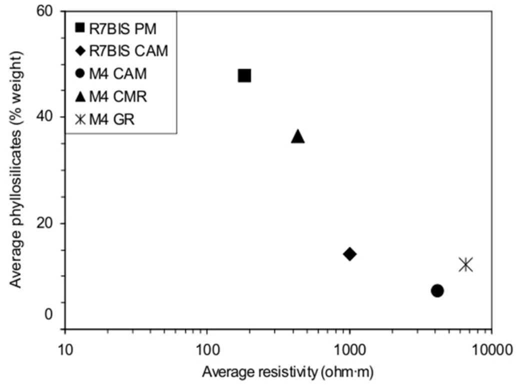

Figure 7: Average total phyllosilicate (i.e. chlorite + muscovite/illite + kaolinite) content versus average resistivity of the main lithological units in R7BIS and M4 wells. CAM = Carbonate-anhydrite Member; PM = Phyllite Member; CMR = contact-metamorphic rocks; GR = granite.

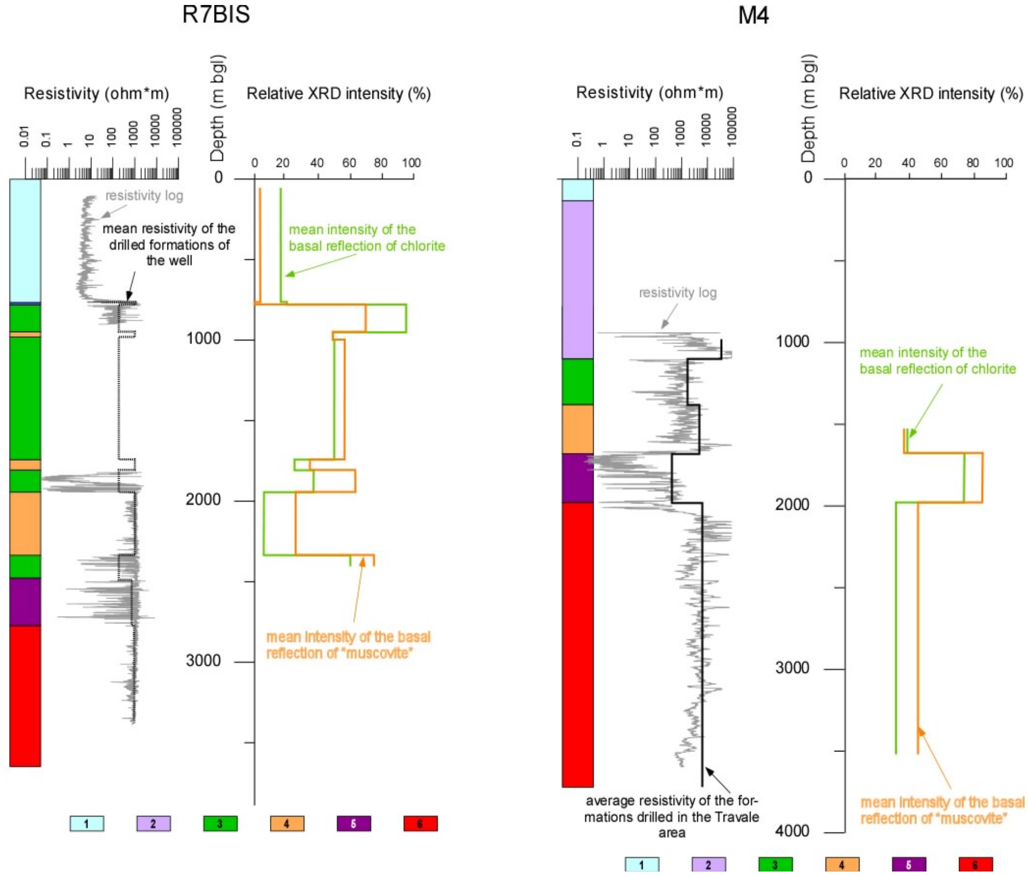

Figure 6: Relative X-ray diffraction intensity (%) of the basal reflection of chlorite and muscovite-type, well stratigraphy and resistivity in M4 and R7BIS wells. Drill-hole lithostratigraphy: 1) Ligurian Units; 2) "Scisti policromi" and/or Anhydrites of the Tuscan Complex; 3) Phyllite Member (PM) of the Phyllitic Quartzitic Complex; 4) Carbonate-anhydritic Member (CAM) of the Phyllitic Quartzitic Complex; 5) Micaschists and contact-metamorphic rocks (CMR) and 6: Granite (GR).

Hydrothermal alteration play an important role in the contact-metamorphic rocks, where fracturation processes allows the development of the intense hydrothermal flow responsible for the formation of interconnected phyllosilicates. The mineralogical analysis highlighted that the primary and alteration conductive minerals appears to be confined in relatively thin layers, thus accounting only for very localized resistivity anomalies. Below the metamorphic contact and in the granite there was no evidence of a pervasive conductive alteration that could justify the presence of a strong resistivity reduction predicted by MT data modeling. Hence, in order to explain large-scale low resistivity anomalies, a possible scenario could rely upon the occurrence of interconnected fluid in the geothermal reservoir.

Within vapor-dominated geothermal systems, both interstitial and adsorbed water can be present in the reservoir, since local temperature and pressure conditions within micro-fractures and small pores can be quite different from their average values observed at much larger scales. In particular, brines often display high concentrations of dissolved salts and ions; the latter enhance the electrical current flow in the reservoir rocks, therefore yielding a strong resistivity decrease. Experimental data on Monteverdi samples showed the occurrence of small fractions (0.2%) of adsorbed liquid water inside the pore network of the rocks (Bertani et al., 1999). Adsorption was also advocated for the existence of a liquid phase inside the pore network of the rocks and as a possible explaination for the long exploitation life of the Larderello reservoirs (Bertani et al., 1996). Furthermore, the study of fluid inclusions have shown that there was circulation within the reservoir of high-salinity fluids that were trapped in minerals often along healed micro-fractures in the Larderello geothermal area (Valori et al., 1992; Cathelineau et al., 1994; Boiron et al., 2007; Giolito et al., 2008). The occurrence of brines was also suggested by Truesdell et al. (1989) who took into account the chemical properties and the temperature of the exploited fluid. It is worth noticing that the presence of a brine as a liquid fluid inside the pore network of the rocks or adsorbed water was never highlighted by production tests in the Travale deep reservoir: it is presented here as an interesting hypothesis for the observed resistivity anomaly.

5. DISCUSSION

There are a number of issues concerning the nature and properties of the Travale geothermal field that still need addressing, namely the origin of the constituents of geothermal fluids, the lowest boundary of the deep reservoir, and the physical and hydraulic properties of the rocks. In terms of a detailed reconstruction of subsurface geology, MT surveys cannot compete with active seismic methods but they may provide important and complementary information related to fluid circulation and temperature distribution.

In this paper we have outlined the occurrence of a geometrically complex low resistivity anomaly in the geothermal reservoir. The key outcome of our analysis is that even in a steam dominated system hosted in crystalline rocks, such as Travale, resistivity distribution is clearly perturbed by the geothermal system. The main issue is then to identify the causes of this anomaly, which could be related not only to current but also to past fluid circulation, as well as to the tectonic and rheological conditions. In the Travale geothermal system there is no evidence either of a strong lithological change or a pervasive alteration whose mineralogy could explain the strong resistivity decrease (Manzella et al., 2009). This opens up the possibility of exploring a hypothetical scenario where the geothermal reservoir could contain an adsorbed fluid phase while the exploited fluid has the character of a dry steam. To this end, we have started to analyze the behavior of geothermal fluids at different scales in more detail, i.e., inside the main productive fractures and in microfractures where the capillary pressure may drive different effects.

The key aims of our planned study (the preliminary results of which are presented in this paper) are both to assess resistivity changes in crystalline rocks affected by the circulation of geothermal fluids also in a vapor phase, and to identify the origin of such changes. Given that crystalline rocks represent the most common scenario for Enhanced Geothermal Systems (EGS), the results of our study could have a wide range of applications. Furthermore, some of the results could be useful for exploration studies concerning sedimentary rocks where, similar to crystalline rocks, the mechanisms for electrical conduction are not primarily associated with surface effects and clay alteration minerals. A complete, self-consistent model describing geothermal fluid circulation requires multidisciplinary data integration and the simulation of the physics of the rocks. This would then provide key information regarding the origin of the field, its evolution and the possible duration of the geothermal resource.

ACKNOWLEDGEMENTS

This work has been funded by the I-GET Project (518378) co-funded by European Commission under the 6th FP.

REFERENCES

Bertani, R., Parisi, L., Perini R., Tarquini B.: High temperature adsorption measurements, Proceedings 21st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, USA, (1996), Report number: SGP-TR-151-71.

Bertani, R., Parisi, L., Perini, R., Tarquini B.: High temperature measurements of water adsorption in geothermal rocks, Geothermics, 17, (1999), 166-183.

Boiron, M.C., Cathelineau, M., Ruggieri, G., Jeanningros, A., Gianelli, G., Banks, D.A.: Active contact metamorphism and CO2–CH4 fluid production in the Larderello geothermal field (Italy) at depths between 2.3 and 4 km, Chemical Geology, 237, (2007), 303–328.

Cathelineau, M., Marignac, C., Boiron, M.C., Gianellli, G., Puxeddu, M.: Evidence for Li-rich brines and early magmatic fluid-rock interaction in the Larderello geothermal system, Geochimica et Cosmochimica Acta, 58 (3), (1994), 1083-1099.

Egbert, G.D., Booker, J.R.: Robust estimation of geomagnetic transfer functions, Geophysical Journal of the Royal Astronomical Society, 87, (1986), 173-194.

Fiordelisi, A., Mackie, R.L., Madden, T., Manzella, A., Rieven, S.: Application of the magnetotelluric method using a remote-remote reference system for characterizing deep geothermal systems, Proceedings, World Geothermal Congress, Florence, Italy, (1995) , 893-898.

Fiordelisi, A., Perticone, I., Spinelli, E. : Geophysical Logs and petrophysical characterization in the Travale test site (Italy), (2009), submitted to Geothermics.

Gamble, T.D., Goubau, W.M., Clarke, J.: Magnetotellurics with a remote magnetic reference, Geophysics, 44, (1979), 53–68.

Giolito, C., Ruggieri G., Manzella, A., Gianelli, G.: Resistivity reduction in the vapour-dominated field of Travale (Italy), Proceedings, 70th Conference of the European Association of Geoscientists and Engineers, Workshop 9, Geosciences for Geothermal Exploration: An Integrated Approach, Rome, Italy, (2008), 50-51.

Larsen, J.C., Mackie, R., Manzella, A., Fiordelisi, A., Rieven, S.: Robust Smooth magnetotelluric transfer functions, Geophysical Journal International, 124, (1996), 801–819.

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

Ledo, J., Queralt, P., Martì, A., Jones, G.: Two-dimensional interpretation of three-dimensional magnetotelluric data: an example of limitations and resolution, Geophysical Journal International, 150, (2002), 127–139.

Leoni, L., Sartori, F., Saitta, M.: Analisi mineralogica quantitativa di rocce e sedimenti pelitici mediante combinazione di dati diffrattometrici e dati chimici, Rendiconti della Società Italiana di Mineralogia e Petrologia, 43, (1989), 743-756.

Mackie, R.L., Smith, J.T., Madden, T.R.: Three-dimensional electromagnetic modeling using finite difference equations: the magnetotelluric example, Radio Science, 29, (1994), 923-935.

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

Manzella, A., Spichak, V. , Pushkarev, P., Sileva, D., Oskooi, B., Ruggieri, G., Sizov, Y. : Deep fluid circulation in the Travale geothermal area and its relation with tectonic structure investigated by a MagnetoTelluric survey, Proceedings, 31st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, USA, (2006), report number: SGP-TR-179.

Manzella, A., Giolito, C., Ruggieri, G., Ungarelli, C.: Electrical resistivity data and their relation to geological features at the Travale geothermal field (Italy), (2009), submitted to Geothermics.

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

Spichak, V., Manzella, A.,: Electromagnetic sounding of geothermal zones., Journal of Applied Geophysics (2008), in press.

Swift, JR.: A magnetotelluric investigation of an electrical conductivity anomaly in the southwestern United States, PhD Thesis, (1967), MIT, Boston.

Truesdell, A.H., Haizlip, J.R., Armannsson, H., D'Amore, F.: Origin and transport of chloride in superheated geothermal steam, Geothermics, 18, (1989), 295-304.

Valori, A., Cathelineau, M., Marignac, C.: Early fluid migration in a deep part of the Larderello geothermal field: a fluid inclusion study of the granite sill fromwell Monteverdi, Journal of Volcanology and Geothermal Research, 51, (1992), 115–131.