Imaging the deep structures of the Larderello geothermal field (Italy) by electrical resistivity measurements: the IMAGE experiment

Alessandro Santilano [1-3], Adele Manzella [1], Enzo Rizzo [2], Valeria Giampaolo [2], Luigi Capozzoli [2], Alberto Godio [3-1]

[1] CNR, Institute of Geosciences and Earth Resources (IGG), Pisa (Italy)

[2] CNR, Institute of Methodologies for Environmental Analysis (IMAA), Potenza (Italy)

[3] Politecnico di Torino, Department of Environment, Land and Infrastructure Engineering, (DIATI), Torino (Italy)

alessandro.santilano@igg.cnr.it

Keywords: Larderello, Resistivity, Magnetotellurics, Electrical Resistivity Tomography.

ABSTRACT

We are developing an integrated method for exploring deep geothermal systems based on electrical resistivity surveys. The test site is the Larderello geothermal field (Italy).

Despite the amount of geological and geophysical data acquired in the frame of previous exploration projects in the area, several critical issues are still matter of debate, e.g., permeability distribution in the hydrothermal reservoir and the presence of fluids at supercritical condition at depth.

We have recently carried out a new broadband magnetotelluric (MT) survey in the western sector of the Larderello field. MT soundings (22) were acquired using a remote site in Capraia Island (Tuscan Archipelago) as Remote Reference measurements; this was necessary to overcome the anthropic electromagnetic noise affecting the data.

We have designed an experimental high resolution Surface-Hole Deep Electrical Resistivity Tomography (SHDERT), in order to constrain the resistivity response at the depth of the hydrothermal reservoir hosted in the crystalline units. A deep geothermal well kindly provided by Enel GP and located in the central sector of the MT survey area, was used for the experiment.

The design of the in-hole experiment and the preliminary results of the MT survey are hereby presented. The experiment represents a challenge and an opportunity for the applied geophysics.

1. INTRODUCTION

The Larderello geothermal field is the most ancient in exploitation in the world for power production since 1913, with an actual installed capacity of 795 MWe (Bertani, 2015). It is located in southern Tuscany (Italy), in the inner part of the Northern Appennine belt.

The southern Tuscany is characterized by a reduced lithosphere thickness and late Miocene to recent magmatism resulting in a huge geothermal anomaly. Several authors described in details the geological and geophysical features of the system (Gianelli et al., 1997; Manzella et al., 1998; Dini et al., 2005; Bertini et al., 2006 and reference therein). The shallow igneous intrusions, feeding the Larderello field, have been cored in deep wells. A vapour-dominated system is exploited to depth over 3500 m, with temperatures exceeding 350°C, from two different reservoirs: i) Mesozoic limestone and anhydrite dolostone, ii) metamorphic rocks locally intruded by igneous bodies. The occurrence of deep-seated fluids at supercritical conditions is suggested by geophysical evidences close to the seismic marker called “K-horizon” (Gianelli, 2008).

Previous MT studies were carried out in southern Tuscany in the frame of exploration and research projects (Fiordelisi et al. 1998; Manzella, 2004; Manzella et al., 2006). Despite of the lithological features of the reservoirs and the vapour state of the geothermal fluids, low resistivity anomalies have been recognized.

A re-analysis of old MT data acquired by Enel in the ’90 was proposed by Santilano et al. (2015a) integrating geological and geophysical data and imaging the low resistivity anomalies at depth below the Larderello field.

More recently, we have carried out a new broadband magnetotelluric (MT) survey in the south-western sector of the Larderello field (Fig. 1). This area is characterized by some prominent features of the geothermal system: i) the occurrence at shallow depth of the K-horizon, ii) very high temperature and pressure, higher than 400°C and 240 bar at 3000 m. b.g.l., measured in the San Pompeo 2 well (Batini et al., 1983).

Furthermore, we acquired a high resolution Surface-Hole Deep Electrical Resistivity Tomography (SHDERT). The experiment was properly designed in order to face extreme condition at depth characterising the geothermal well. The in-hole electrical cable was equipped with flexible steel electrodes and was able to stand the very high temperature conditions.

SHDERT was carried out in the "Venelle 2" deep well, kindly provided by Enel GP, that is located in the central sector of the MT survey area less than 2 km away from the San Pompeo 2 well.

2. METHODS

ElectroMagnetic (EM) methods play a fundamental role in the geothermal exploration due to particular sensitivity of the subsurface electrical resistivity to hydrothermal circulation. The distribution of electrical resistivity at depth in geothermal systems is really complex; a direct relationship between resistivity and hydrothermal circulation cannot be established. For instance, self-sealing and mineral alteration processes can provide very low resistivity structures in geothermal systems. Many papers have been published on the geothermal exploration by EM methods worldwide (e.g. Meju, 2002; Spichak and Manzella, 2009; Santilano et al., 2015b and reference therein). The Magnetotellurics (MT) represents the most common method for investigating deep geothermal reservoirs. In addition, we coupled an experimental DC measurement in order to constrain the resistivity response at the depth of the deep reservoir, hosted in the crystalline units.

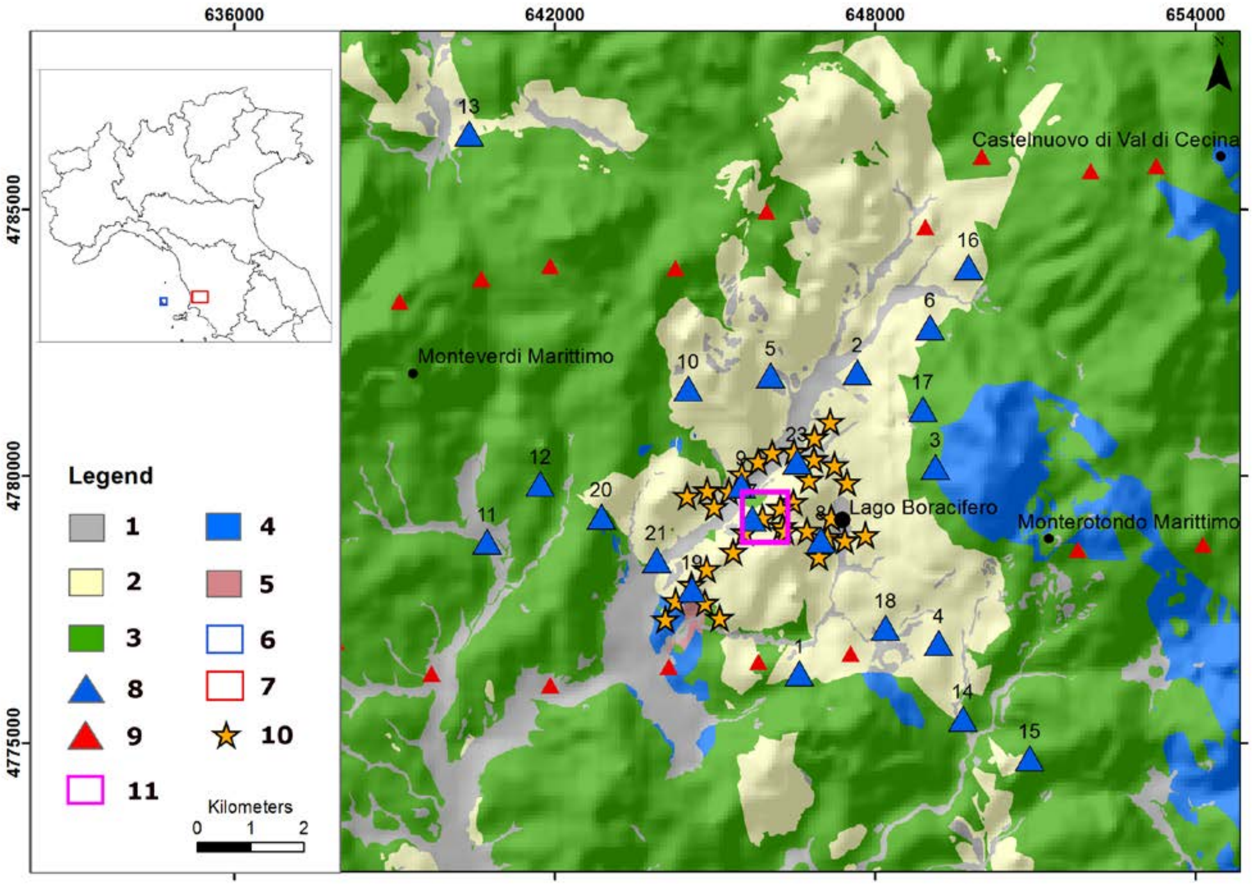

Figure 1: Schematic geological map of the Larderello geothermal area, simplified from the geological maps at scale 1:10000 (Tuscany Region website). 1) Quaternary deposits; 2) Neoautochthonous terrigenous deposits (Miocene-Pliocene); 3) Ligurian and sub-Ligurian Flysch complex (Jurassic-Eocene); 4) Tuscan Nappe formations (Upper Trias-Miocene); 5) Metamorphic Units (Paleozoic); 6) Remote site on Capraia Island; 7) Study area; 8) MT site acquired in IMAGE; 9) MT site previously acquired; 10) Position of surface current electrodes for the acquisition of the SHDERT; 11) Venelle 2 area.

2.1 Magnetotelluric survey

The Magnetotellurics (MT) is a method suitable for imaging the subsurface electrical resistivity from near-surface to hundreds of kilometres deep by using as energy source the natural induced primary EM fields on the Earth.

The method is commonly used for earth resources exploration and studies on the Earth's crust and mantle. In geothermal exploration, MT is widely applied worldwide contributing to the characterization of the geological, rheological and hydraulic conditions of geothermal systems. For a detailed description of the theory we refer to Chave and Jones (2012).

We carried out a MT survey in the south-western sector of the Larderello field near Monterotondo Marittimo town. Previous surveys and the first tests performed in this study highlighted a high EM noise in southern Tuscany mainly due to the near-field effect of the electrified railways. Therefore, we have dedicated special care to locate a site with high signal to noise ratio to be used as remote site for the remote reference (RR) processing of the MT data (Gamble et al., 1979). We installed a permanent remote station in the Capraia Island, belonging to the Tuscan Archipelago and located 55 km far from the coast and 80 km from the area of interest.

The survey was carried out during March and April 2016 using high-resolution, multi-channel 32-bit receivers able to record broadband time-series from 0.0001 Hz to 1kHz, tailored by Zonge International Inc. The two perpendicular horizontal components of the electric and magnetic fields on surface were measured with a L-shaped configuration of 100 meters electrical dipoles and two Zonge Ant/4 magnetometers.Considering the technical problems that forced to repeat some soundings, 22 MT sites were successfully acquired, and added to those already available in the area to be used for realizing the MT model of the westernmost part of the Larderello geothermal field. For each site, at least 17 hours were recorded using the sampling rate of 256 Hz. In addition over one hour with a sampling rate of 4096 and 1024 Hz was also acquired. We show in figure 2 an example of the MT observed data; apparent resistivity and phase of a sounding are plotted after a robust RR processing and the La Torraca et al. (1986) decomposition.

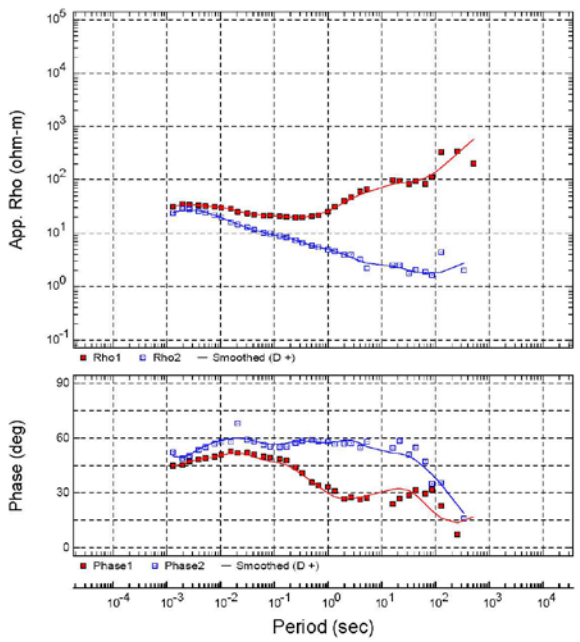

Figure 2: MT observed data, apparent resistivity and phase for the station Lard-3. The smoothed curve was computed using the D+ solution (Beamish and Travassos, 1992).

The preliminary results of MT data processing show that, although some of the soundings resulted too much affected by noise, most of them are suitable for imaging the resistivity distribution at depth.

Furthermore, we carried out an analysis of dimensionality and directionality by using the invariants method (Marti et al., 2005). At low frequencies, 3D effects can be observed over the whole dataset.

Inversion modelling of MT data is ongoing.

2.1 SHDERT

The Direct Current (DC) method has for a long time proven to be a successful method in geothermal exploration. An electric current is injected into the ground and the generated voltage signals is measured by electrodes on the surface (quadripole). The Electrical Resistivity Tomography (ERT) system for the exploration of deep targets (over 300 m b.g.l.) requires physically separated transmitter (Tx) and receiver (Rx) units. In deep geoelectrical explorations, a crucial task is the data processing, considering the large distance between the Tx and Rx systems (>2000 m) that strongly reduces the signal to-noise ratio. To overcome this drawback, for each quadripole position the corresponding voltage signal was filtered, stored and processed with advanced statistical packages (Colella et al., 2004; Rizzo et al., 2004, Tamburiello et al., 2008).

We designed an experimental high resolution Surface-Hole Deep Electrical Resistivity Tomography (SHDERT), which was tested in the Venelle 2 geothermal well. In short, the characteristics of the well are:

- 2.1 km deep, accessible down to 1.6 km;
- temperature higher than 250°C;
- pressure up to 130 bar;
- metallic casing down to 1 km.

In order to carry out surface-hole resistivity measurements in such extreme conditions, we built ad hoc multipolar geoelectrical cable, suitable for standing high temperatures up to 250°C, equipped with flexible steel electrodes (Fig. 3-4). The electrodes were located at different depth along the open-hole part of the well (1050m-1600m) with an electrodes spacing of 50 m.

During the whole experiment the well was cooled by a continuous injection of water, whose electrical conductivity generated also a good electric contact between the rock and the borehole electrodes.

Figure 3: Multichannel cable and the steel flexible electrodes.

Figure 4: The in-hole ERT system.

Two kinds of measurement were carried out: i) electrical resistivity measurement with transmitters on the surface and down-hole receivers (dipole-dipole configuration), ii) electrical resistivity measurement with down-hole transmitters and receivers (Dipole-Dipole and Pole-Dipole configurations).

A dipole-dipole array configuration was used, where an electric current pulse was sent into the ground via two surface electrodes (AB), and the potential drop was measured between two borehole electrodes (MN). The AB distances ranged between 400 and 1600 m, and the MN distances ranged between 50 and 550 m.

We used a Zonge transmitting station constituted by the GGT-10 transmitter and the ZMG-9 power system, which can inject into the ground a time-domain (50% duty cycle) square-waveforms current signal. A maximum energizing current of 10 A was injected into the ground (3-10 A) with a square wave of 32 s (Fig. 5). The borehole potential electrodes (MN) were connected to a multichannel receiver system made of 4 remote multichannel dataloggers, radio-connected to a personal computer, simultaneously recording a total number of 32 generated voltage signals (V). In total, 1740 voltage recording datasets, related to different current electrodes positions, were collected.

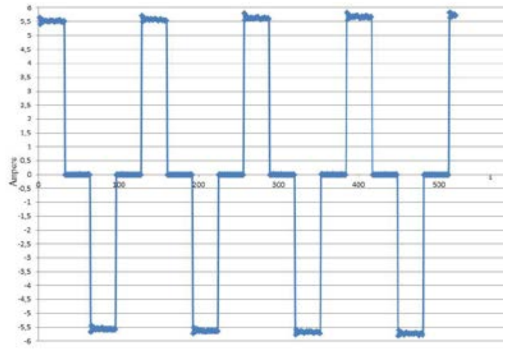

Figure 5: Example of a square wave of the injected current

Dipole-dipole and pole-dipole array configurations were used. Particularly, for dipole-dipole array, an electric current pulse was sent into the ground via two borehole electrodes (AB), and the potential drop was measured between two borehole electrodes (MN). For pole-dipole array, the electric current pulse was sent into the ground via a borehole electrode (A) and a surface one (B, remote electrode), placed at about 50 m far away from the well, and the potential drop was measured between two borehole electrodes (MN). Both current (AB) and potential (MN) electrodes were connected to the Syscal pro multichannel transmitter and receiver system (IRIS instrument) which can inject into the ground, thanks to an external power source, a time-domain (50% duty cycle) square-waveforms current signal. In this case, each current injection lasted 0.5 seconds and the output result was the apparent electrical resistivity distribution of investigated subsoil. In total, 3 different datasets, related to the different measurement days, were collected.

3. CONCLUSIONS

In this paper we described the design of the geophysical experiment for geothermal exploration by integrating EM and DC geophysical measurements. Despite the technical issues to carry out a SHDERT in such extreme physical conditions, the acquisition was successfully accomplished. The aim of this experiment is the exploration of the deep structures of the Larderello geothermal system. In the next future we are going to obtain the resistivity models of the studied area by integrating the different datasets.

Acknowledgements

The research leading to these results has received funding from the EC Seventh Framework Programme under grant agreement No. 608553 (Project IMAGE). We thank the colleagues that supported the field work during the MT and DC surveys. We thank Enel Green Power for the precious technical and logistical support on carrying out the borehole experiment.

REFERENCES

Batini, F., Bertini, G., Gianelli,G., Pandeli, E., and Puxeddu, M.: Deep structure of the Larderello field: contribution from recent geophysical and geological data, Mem. Soc. Geol. It. (1983), 25, 219-235.

Beamish, D. and Travassos, J.M.: The use of the D+ solution in magnetotelluric interpretation. J. Appl. Geophys. (1992), 29, 1-19. doi:10.1016/0926-9851(92)90009-A

Bertani, R.: Geothermal Power Generation in the World 2010-2014, Update Report. Proceedings of World Geothermal Congress 2015, Australia.

Bertini, G., Casini, M.. Gianelli, G., and Pandeli E.: Geological structure of a long-living geothermal system, Larderello, Italy, Terra Nova (2006), 18, 163–169.

Chave, A.D. and Jones, A.G.: The Magnetotelluric Method, Theory and Practice. Cambridge University Press (2012).

Colella, A., Lapenna, V. and Rizzo, E. High-resolution imaging of the High Agri Valley basin (Southern Italy) with Electrical Resistivity Tomography. Tectonophysics (2004), 386, 29-40.

Dini, A., Gianelli, G., Puxeddu, M., and Ruggieri, G.: Origin and evolution of Pliocene–Pleistocene granites from the Larderello geothermal field (Tuscan Magmatic Province, Italy), Lithos (2005), 81, 1–31.

Fiordelisi, A., Mackie, R., Manzella, A. and Zaja, A.: Electrical features of deep structures in Southern Tuscany (Italy), Annals of Geophysics (1998), 41(3), 333-341.

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

Gianelli, G.: A comparative analysis of the geothermal fields of Larderello and Mt. Amiata, Italy, in: Geothermal energy research trends, edited by: Ueckermann, H. I., Nova Science Publishers (2008), New York, USA, 59–85.

Gianelli, G., Manzella, A., and Puxeddu, M.: Crustal models of the geothermal areas of southern Tuscany (Italy), Tectonophysics (1997) , 281, 221–239.

LaTorraca, G.A., Madden, T.R., and Korringa, J. An analysis of the magnetotelluric impedance for three-dimensional conductivity structures. Geophysics, 1986, 51, 1819-1829.

Manzella, A., Ruggieri, G., Gianelli, G., and Puxeddu, M.: Plutonic-Geothermal systems of southern Tuscany: a review of the crustal models, Mem. Soc. Geol. It. (1998), 52, 283–294.

Manzella, A.: Resistivity and heterogeneity of Earth crust in an active tectonic region, Southern Tuscany (Italy). Annals of Geophysics (2004), 47(1), 107-118.

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

Marti, A., Queralt, P., Jones, A., and Ledo, J.: Improving Bahr's invariant parameters using theWAL approach. Geophys. J. Int. (2005) 163, 38–41.

Meju, M.A.: Geoelectromagnetic exploration for natural resources: models, case studies and challenges. Surveys in Geophysics (2002), 23, 133-205.

Rizzo, E., Iovine, G., Muto, F., Caputi, A., Capozzoli, L., Giampaolo, V., Pizzino, L., and Manzella, A.: Final results of 'Terme Caronte' geothermal area (Calabria, Italy). Atti del 33° Convegno Nazionale del GNGTS (2014).

Santilano, A., Godio, A:, Manzella, A., and Dini, I.: Electrical Resistivity Structures and their Relation to Geological Features at the Larderello Geothermal Field (Italy). Proceeding of Near Surface Geoscience (2015a), Turin (Italy).

Santilano, A., Godio, A., Manzella, A., Menghini, A., Rizzo, E., Romano, G., and Viezzoli, A.: Electromagnetic and DC methods for geothermal exploration in Italy, case studies and future developments. First Break (2015b), 33, 81-86.

Spichak, V.V. and Manzella, A.: Electromagnetic sounding of geothermal zones. Journal of Applied Geophysics (2006), 68, 459-478.

Tamburriello, G., Balasco, M., Rizzo, E., Harabaglia, P., Lapenna, V. and Siniscalchi, A. Deep electrical resistivity tomography and geothermal analysis of Bradano foredeep deposits in Venosa area (Southern Italy): first results. Annals of Geophysics (2008), 51 (1), 203-212.

Tuscan Region. Continuum Geologico at scale 1:10000. Last accessed June 2016. http://www502.regione.toscana.it/geoscopio/geologia.html