THE DEEP STRUCTURES OF THE LARDERELLO GEOTHERMAL FIELD (ITALY): RESULTS FROM A NEW ELECTROMAGNETIC STUDY
A. Santilano¹, A. Godio², E. Rizzo³, A. Manzella¹
¹ IGG-CNR, Pisa, Italy
² Department of Environment, Land and Infrastructure Engineering (DIATI), Politecnico di Torino, Italy
³ IMAA-CNR, Potenza, Italy

Introduction. The intrinsic complexity of geothermal systems and the need of an accurate integration of the geophysical parameters with the geological and hydrogeological properties still represent a challenge of the exploration geophysics. It is in such a scenario, we focused our research on the Larderello geothermal field (Tuscany, Italy), in order to relate the results of electromagnetic (EM) surveys with an integrated modelling of the system. Larderello is the oldest field under exploitation in the world. The production of geothermal electricity, in its modern meaning here was born. A century of industrial and scientific researches were not enough to understand all the geological, chemical and physical features of this complex system, and to solve the critical issues that are currently debated in the scientific community.

The main target of this research is the improvement of the knowledge on the deep structures of the Larderello field, formulating an accurate conceptual model including its deep roots with a focus on the heat source of the system and deep crustal fluids, the tectonics and its relation with the hydrothermal circulation. We acquired new magnetotelluric (MT) and Time Domain EM (TD EM) data close to Lago Boracifero. The data integrate the MT datasets previously acquired in the frame of exploration and scientific projects. We also propose an integrated approach to improve the reliability of the 2D MT inversion models, using external information from the geological model as well as an innovative probabilistic analysis of MT data.

The Lago Boracifero sector and the scientific challenge. We considered the Larderello system as a “Convective intrusive geothermal play” as proposed by Santilano et al. (2015). The exploited hydrothermal reservoirs are hosted in sedimentary, mostly carbonates, units and underlying crystalline rocks. Superheated steam is present to depth over 3.5 km with temperatures exceeding 350°C. Strong seismic reflectors in the metamorphic complexes, i.e. the H and K horizons, have been explained with rock fracturing and presence of fluids, even if their nature is not known. The heat source of the system is related to shallow igneous intrusions. The Larderello intrusive bodies, cored in several deep wells, can be classified as two-mica granites with ages ranging from 3.8 Ma to 1.3 Ma (Dini et al., 2005). In the Lago Boracifero sector (Fig. 1), a regional culmination of the seismic K-horizon occurs at depth of about 3 km b.g.l. Very high temperature and high pressure systems (> 400°C and pressure > 290 bar), possibly at supercritical condition are inferred at or close the depth of the K-horizon, and are shallow enough to be explored with current technologies. A pioneering deep drilling project (DESCRAMBLE, EU H2020) at supercritical conditions is now ongoing. Many scientific issues are still debated on the physics of the geothermal processes in this field. We particularly refer: i) to the anomalous low electrical resistivity values that were estimated locally in a vapour dominated crystalline reservoir (theoretically resistive), ii) to the uncertainties on the deep structures of the field, such as the occurrence of a molten magmatic intrusion and its geometry and iii) the role of faults in the hydrothermal circulation. Nowadays, the tectonic fluids pathways are not clearly figured out by the operator.

The magnetotelluric and time domain EM dataset. The geophysical study counts the analysis of old and new MT datasets for an amount of 40 soundings in the Lago Boracifero area. This sector was not investigated by Magnetotellurics, despite its scientific relevance.

In 2016, we carried out a new MT survey in the SW sector of the Larderello field near Lago Boracifero. Due to the near-field effect of the electrified railways in southern Tuscany, we installed a permanent remote station in the Capraia Island, located 80 km far from the area of interest. The broad-band time series were acquired with high-resolution, multi-channel 32-bit receivers in the range of 0.0001 Hz to 1 kHz, (Zonge system). 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 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 (Fig. 1). 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 processed the data and the directionality and dimensionality analyses have been performed. The results indicate a wide 3D structure at depth with a clear role of a 2D structure mainly at shallow level in the proximity of the Cornia basin.

We have selected 10 MT sites, with static shift effects, for TDEM data acquisition. The TDEM soundings were acquired by using a TEM-FAST 48 and laying out a rectangular loop of wire 50x50 and 100x100 m and pulsing it with a controlled current; the configuration was a coincident loop.

Methods. The results of a geophysical inversion can be influenced by the reliability of the starting model. Based on this concept, for each of the 4 MT profiles, three resistivity models were implemented and tested as starting model for the 2D inversion (Rodi and Mackie, 2001): i) homogeneous halfspace; ii) resistivity distribution by assigning resistivity values to units of the geological model; iii) interpolation of 1D models obtained with Particle Swarm Optimization (PSO). The homogeneous a-priori model is a halfspace with an electrical resistivity of 100 Ωm. The implementation of the a-priori models from geological information required some effort. First of all, the detailed 3D geological models for the Lago Boracifero area was built in Petrel environment. Hundreds of deep geothermal wells, seismic and geological data have been integrated. The study of six resistivity well logs allowed the definition of resistivity values to be assigned to each geological unit. In addition in the frame of the IMAGE project a deep surface to borehole ERT was acquired (Capozzoli et al., 2016). Electrodes were located in a very high temperature borehole, the Venelle 2 well, that is going to be deepened for the exploration of supercritical resources. The results have confirmed the low resistivity anomalies that were recognized by previous magnetotellurics surveys, which results were debated for a long time. Considering the large variability of the ground resistivity and the scarcity of direct data in the deep level of the system, the geological model could not be completely reliable as starting model for MT inversion. As a way to constrain the inversion using only MT information we also tested the use of a-priori models based only on the MT data and not on geology. We interpolated 1D models to obtain pseudo-2D resistivity models to be used as a-priori models for the deterministic 2D inversion. We present our attempt to treat the 1D magnetotelluric inverse problem with a probabilistic approach, by adopting the Particle Swarm Optimization (PSO), a heuristic method based on the concept of the adaptive behaviour to solve complex problems (Godio et al., 2016; Santilano, 2017). This approach allowed us also to perform a joint optimization of MT and TDEM data with an innovative scheme.
**Results.** The inversion models constrained with the PSO approach provided the necessary resolution for imaging the complex subsurface structure of the Larderello system. The results are consistent in terms of RMS, which are even lower than the corresponding ones obtained by geologically constrained inversions. The inversion models image low resistivity anomalies in the central sector of the profiles, in the proximity of a clear subvertical structure along the Cornia River. The upper units are very conductive (3-30 Ωm) due to lithology. The intermediate structural levels (up to 2500 m b.g.l.) coincident mainly with the Tectonic Wedge Complex and most of the Phyllitic Complex are characterized by resistivity values in the range of 40-200 Ωm (mostly 100 Ωm). These results are in perfect agreement with the deep ERT. On the other hand, in the Lago Boracifero area the Micaschist, Gneiss and Intrusive rocks are characterized by high resistivity values in the range of 2500-5000 Ωm as expected. Large low resistivity subvertical anomalies, with values of about 150 Ωm, locally interrupt the resistive metamorphic units at depth where an intense vapour dominated hydrothermal circulation is recognized (and exploited). At mid-crustal level, below 6 km depth, a further reduction of resistivity is recognized in all the MT Profiles in the Lago Boracifero area. These anomalies can be ascribed to the partially melted granitic intrusion that act as heat source of the field. Considering this assumption, the heterogeneous distribution of resistivity at this depth can be in part explained as different percentage of melting in the rock volume. The comparison between the resistivity models and the seismological tomography (Batini *et al.*, 1995) shows a positive correlation between low resistivity anomalies and the low P-wave velocity zone interpreted as a melted intrusion (Fig. 2).

**Conclusion.** The results of the magnetotelluric study of the Larderello field and their interpretation allowed us to contribute on the improvement of the conceptual model of the geothermal system. With regard to the deep structure, we detected a still partial melted igneous intrusion beneath the Lago Boracifero sector acting as heat source, based on the interpretation of the low resistivity anomalies. We highlighted also the fundamental role of a large tectonic structure, i.e. the Cornia Fault, antithetic respect to the northern Apennine and located along the homonymous river. In our opinion, this fault played an important role in the evolution of the Lago Boracifero sector of the field, favouring both the hydrothermal circulation and the emplacement of magma bodies, being possibly deep-rooted in the crust.

![Fig. 2 - MT Profile 1 plotted in 3D and compared with the seismic low velocity anomaly (Batini *et al.*, 1995) here filtered for the values below 5 km/s (modified from Santilano, 2017).](image-url)
Acknowledgements The work was carried out in the frame of the IMAGE Project (FP7, grant agreement No. 608553). Part of the study was developed in the frame of the PhD program at the Politecnico di Torino. We thank the fieldwork team.

References