Electromagnetic and DC methods for geothermal exploration in Italy – case studies and future developments

Alessandro Santilano[1,2*], Alberto Godio[2], Adele Manzella[1], Antonio Menghini[3], Enzo Rizzo[4], Gerardo Romano[5] and Andrea Viezzoli[3] present state-of-the-art applications of electromagnetic and direct current methods for geothermal exploration in Italy.

Geothermal energy is a renewable and eco-compatible resource suitable for base-load power and thermal production, which means a daily continuous energy production. In the past few years this source has been of interest for governments, companies and research institutes worldwide that are working for the increase of geothermal exploitation with the aim of reducing greenhouse gas emissions and fossil fuels consumption.

Italy was the first country (in 1913) where geothermal energy was exploited for industrial power production and is now the sixth-largest geothermal electricity producer in the world (Bertani, 2015). The geothermal potential of Italy, both for power production and direct uses, is really huge due to particular geological conditions; elsewhere it is mostly underexploited for non-technical barriers.

In Italy, many industrial and scientific exploration projects have been carried out in the last few years for assessing shallow and deep geothermal resources.

ElectroMagnetic (EM) methods play a fundamental role in the geothermal exploration due to particular sensitivity of the subsurface electrical resistivity (hereby resistivity) to hydrothermal circulation, thermal regime and rocks alteration. Many papers have been published on the study of geothermal areas by EM methods worldwide (Meju, 2002; Spichak and Manzella, 2009; Muñoz, 2014 and references therein).

In this paper, we propose an updated state-of-the-art of the main electromagnetic and direct current methods for geothermal exploration in Italy, describing innovative case studies and including a discussion about the direction of new researches.

The Magnetotellurics (MT) represents the most common and effective method for investigating deep geothermal reservoirs. A case study in southern Tuscany is herein described. We will also focus the attention on the resistivity measurements for shallow geothermal exploration by means of Airborne EM (AEM), Transient or Time Domain EM (TEM or TDEM) and Electrical Resistivity Tomography (ERT).

Among the various scientific projects for geothermal exploration that the Italian National Research Council (CNR) carried out, the VIGOR project (evaluation of the geothermal potential of Regions of Convergence) for Southern Italy provided the occasion of detailed geoelectromagnetic studies for assessing shallow and deep geothermal resources (Manzella et al. 2013a, VIGOR website). Some cases study of the VIGOR project are briefly described as: i) the innovative application of Airborne EM data acquired over large areas in Sicily and applied to the assessment of shallow geothermal potential and ii) a Deep Electrical Resistivity Tomography (DERT) acquired on a thermal area in Calabria region.

Resistivity of rocks in geothermal systems

A brief description of geothermal systems is required to frame the factors that influence the strong variability of resistivity and why geothermal resources are an ideal target for EM geophysical exploration.

A complete description of conventional and unconventional geothermal systems is widely given in literature (ENGINE, 2008 and reference therein). Considering the hydrothermal systems, which are the only geothermal systems under exploitation in Italy so far, the main constituting elements are: i) a heat source represented by a recent magmatic intrusion, ii) a reservoir that hosts the hydrothermal circulation usually characterized by secondary permeability due to faults and fractures and iii) a cap rock, an impermeable volume of rocks that avoids the dissipation of heat on the surface.

The energy production by conventional technology provides for the extracting of the hot fluids from a reservoir that represents the target of the geothermal exploration.

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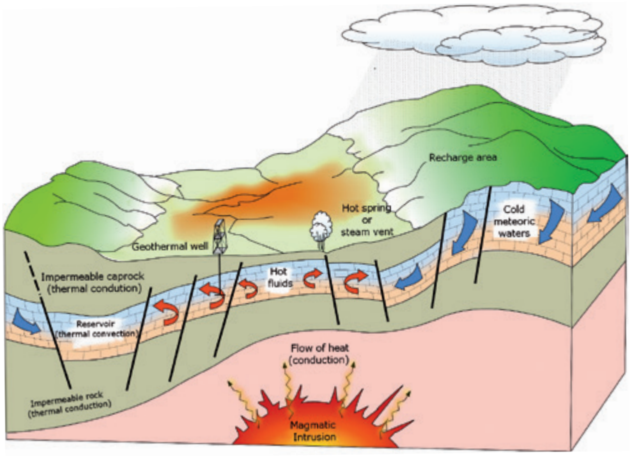

Figure 1 *Conceptual model of a geothermal system (from Dickson and Fanelli, 2004).*

The particular physical-chemical features of the thermal fluids circulating through pores and fractures strongly affects the bulk resistivity of rocks.

The high temperature interaction upon thermal waters and rocks implies a high solid content of fluids, often with brine features, which favours the electrolytic conduction and reduces the resistivity. As described in detail by Spichak and Manzella (2009) the increase of temperature strongly decreases the resistivity of fluids. These low resistivity anomalies related to the circulation of geothermal fluids are the main target of electromagnetic methods.

We stress that the distribution of electrical resistivity at depth in geothermal systems is really complicated and a unique relation between low resistivity anomalies and hydrothermal circulation cannot be established. For instance, self-sealing and mineral alteration processes can provide very low resistivity structures in geothermal systems.

In Italy, the main regional geothermal reservoir is hosted in Meso-Cenozoic carbonate rocks (Cataldi et al., 1995) with very high intrinsic resistivity of at least hundreds Ohm*m. By using electromagnetic methods, the carbonate reservoir can be detected because of the strong electrical contrast with the overlain siliciclastic deposits (low resistivity).

In areas characterized by very high temperature hydrothermal circulation, such as in Tuscany, very low resistivity anomalies inside the carbonate and metamorphic reservoirs have been recognized (Manzella et al., 2006).

Example of TEM methods

Transient EM (TEM) methods (Ward and Hohmann, 1988; Spies and Frischknecht, 1991; Christiansen et al., 2009) use a direct current flowing into an insulated transmitting loop, which is abruptly interrupted, inducing eddy currents in the subsurface. The rate of change of the secondary field due to decaying induced eddy currents is measured using an induction coil. The voltage decay (i.e., the 'transient') is measured as a function of time: just after the current in the Tx-loop is shut off, the current in the ground will be close to the surface, so that the measured signal provides information about the resistivity of the shallower layers. At later times the current will penetrate deeper in the ground, hence the measured signal is related to the resistivity of the layers at greater depth. By combining the response collected at different acquisition times, through inversion of the data, it is possible to achieve a 1D modelling of the subsurface, in terms of resistivity distribution with depth.

Recently, progress in TEM airborne systems (Siemon et al., 2009), enables the investigation of wide areas (in the order of hundreds of square km) and yielding the same lateral resolution of the ground-based survey.

TEM applications for geothermal resources have been a few. Some cases have been reported by Kauahikaua (1981), Wright et al. (1985), Pellerin et al. (1996), and Menghini et al. (2002). More often, the TEM method has been used for the 'static shift' correction of MT soundings, in the case of deep geothermal surveys (Pellerin and Hohmann, 1990; Wannamaker, 1991). As previously described, the electrical response of hydrothermal water is often poorly resistive, thanks to the high content in dissolved salts, but the possibility of directly detecting a geothermal reservoir is considered very challenging, due to the depth involved (from several hundreds of metres to kilometres).

A case-study reported by Menghini et al. (2010), utilized the TEM method in an area close to Viterbo town in central Italy, to detect the presence of the direct faults, which allow the rising of mineralized waters to the surface, as occurs with natural hot springs. The study also pointed to the importance of reconstructing the detailed structural features of the survey area, in order to understand the hydrothermal model. For example, a secondary geothermal reservoir was inferred within the more permeable and shallower layers (in this case calcareous turbidites).

Near surface high conductivity features have been pointed out by integrating AudioMagnetoTelluric (AMT) data and TEM in geothermal areas in Tuscany, while TDEM and Electrical Resistivity Tomography (ERT) were successfully integrated to map shallower preferential paths of thermal fluids in volcanic areas (Naples) (Bruno et al., 2003).

In the frame of the VIGOR project, Santilano et al. (2015) exploited Airborne EM data for estimating the geothermal energy that is exchanged by a ground volume unit. This is relevant for the design of GCHP (Ground-Coupled Heat Pump) systems. The study was based on the characterization of electrical and thermo-physical properties of rocks over large areas in western Sicily (Italy) by integrating Airborne Electromagnetic (SkyTEM system) data and laboratory measurements on rock thermal conductivity of samples.

Public well data, useful for reconstructing the complex geological and hydrogeological setting, were limited and the

AEM prospection was applied to define a 3D distribution of resistivity values. Three-dimensional modelling was performed in order to obtain a high-resolution 3D distribution of the thermal conductivity in areas characterized by a very complicated geological setting. Figure 2 shows an interpreted resistivity profile extracted by the 3D resistivity model of the Termini Imerese test site.

The integration of available geological information and 3D resistivity models allowed them to identify the lithological units that could be distinguished by their electrical resistivity contrast (Litho-Electrical Units) and to build 3D geological models. Laboratory measurements of thermophysics parameters on rock samples enabled them to assign a thermal conductivity value to each of the Litho-Electrical Units. The 3D distribution of subsurface thermal conductivity represented the main input for assessing the rate of thermal energy exchanged with the ground up to 200 m b.g.l.

Magnetotelluric method in geothermal exploration

The Magnetotelluric (MT) is a method for determining the subsurface electrical resistivity from near-surface to hundreds of kilometres deep by measuring the natural magnetic and electrical fields on the surface.

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.

The theory was proposed for the first time in different countries – by Tikhonov in the Soviet Union, Cagniard in France, Kato, Kikuchi and Rikitake in Japan, as cited by Chave and Jones (2012). The fundamental parameter in the MT method is the impedance tensor Z, the ratio of the measured electric and magnetic orthogonal fields. The tensor allows the computation of the apparent resistivity and phase for each frequency acquired.

The depth of investigation and skin depth of MT are strongly dependent upon the lowest frequency measured of the EM fields and the electrical resistivity of the rocks.

On the basis of frequency, MT methods are classified as Audio MT (AMT) from 10^4 to 10^1 Hz, and long-period MT (LMT) from 10^0 to less than 10^{-5} Hz (Chave and Jones, 2012). Broadband instrumentations allow the measuring of high and low frequencies and embed large parts of AMT and LMT. Usually, the lowest frequency measured for deep geothermal exploration is about 10^{-2} or 10^{-3} Hz while shallow geothermal exploration can be carried out by using the AMT frequency range.

In Italy, MT surveys are nowadays carried out in the frame of many exploration permits (e.g. Caranova et al. 2015). Important research studies have been carried out in the past few decades for improving the MT methodology for geothermal exploration (Larsen et al., 1995, 1996; Di Maio et al., 1998; Manzella, 2004; Volpi et al., 2003 and references therein). The basic and applied research is quite active in this field as proven by the recent Italian and European Projects as INTAS, I-GET, ENGINE and VIGOR projects and the ongoing IMAGE project (IMAGE website).

Example of MT survey

We briefly describe a study carried out in southern Tuscany for exploring the deep geothermal resources.

The investigation of deep fluid circulation in the Travale Geothermal Field (GTF), located in the south-eastern part of the Larderello system, is described in Manzella et al. (2006). The exploration and exploitation in this area are mainly targeted at the deep reservoir hosted in crystalline rocks. For a detailed description of this field the reader is referred to Bertini et al. (2006).

High and low frequency MT data, up to 10^{-3} Hz, were acquired in 59 sites (stations). The main critical issues of data acquisition refer to the EM noise and static shift or telluric distortion.

The dense network of DC electrified railways, widely diffused in Italy, strongly affects the low-frequency MT data creating a near source, dipolar and coherent signal very different from the plan wave MT signal. This problem was overcome by installing a remote site in Sardinia and using a remote processing technique. Other sources of EM noise can be ascribed to power plant operation and power lines that mainly affect high-frequency data. This noise was partially reduced by recording simultaneously MT-signals on two or more sites, used as local remote sites.

Finally, in order to face the effects of distortion or static shift due to local near-surface inhomogeneities, TDEM data

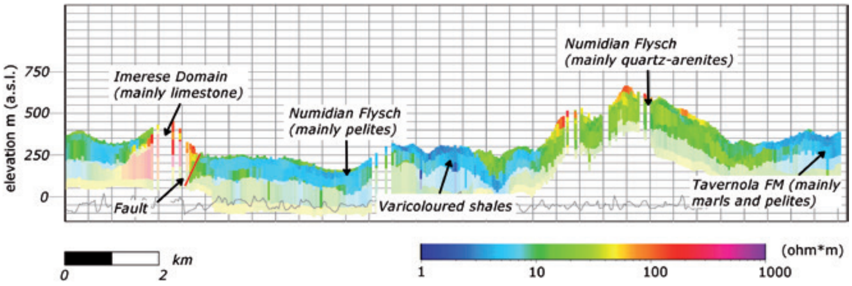

Figure 2 Resistivity cross-section along one of the flight lines in the Termini Imerese test site (Profile N-S 2). A schematic interpretation is provided (modified from Manzella et al., 2013b).

were acquired in some of the sites to constrain the MT response.

The MT data were decomposed (La Torraca et al., 1986; Smith, 1995) and then inverted with different algorithms (Spichak and Popova, 2000; Rodi and Mackie, 2001) to achieve the 2D and 3D resistivity models of the Travale GF.

Figure 3 shows the resistivity cross-section compared to a geological model. A fault zone has been resolved on the SW part of the profile. The most important feature is a low resistivity anomaly in the crystalline basement at depths of 1.5 km up to 3 km, where the deep fractured and highly productive reservoir is under exploitation. A deeper low resistivity anomaly is detected at a depth of 6 km, below the seismic marker known as K-horizon. This horizon is interpreted in literature as an indicator of the brittle-ductile rheological transition or as a possible reservoir at supercritical conditions.

The MT studies carried out in the Travale GF led Spichak and Zakharova (2015) to define the relationship between electrical resistivity values and deep temperature using their electromagnetic geothermometer.

Direct current investigation

The Direct Current (DC) method has for a long time proven to be a successful method in geothermal exploration. The DC method consists of injecting an electric current into the ground and in measuring the generated voltage signals by electrodes dislocated on the Earth's surface. The subsurface electrical resistivity is thus obtained by knowing the electrode spacing, geometry of the electrode positions, applied current, and measured voltage. The investigation depth of the DC method is related to the spacing of the electrodes and may vary depending on the subsurface conditions. In recent years, the electrical resistivity surveys have progressed from the conventional Vertical Electrical Soundings (VES) to Electrical Resistivity Tomography (ERT) that provide two-dimensional and even three-dimensional electrical images of the subsurface by new automatic instruments. Differently from the most commonly used ERT systems for shallow investigation (less than 300m b.g.l.), ERT systems for deep targets (more than 300m b.g.l.) require physically separated transmitter and receiver units and a careful data analysis before the data inversion. In deep geoelectrical explorations, a crucial task is the data processing of useful signals from voltage recordings, considering the large distance between the energising and receiving systems (Tx-Rx) that strongly reduces the signal-to-noise ratio. To overcome this drawback, for each electrode position the corresponding voltage signal is filtered, stored and processed with advanced statistical packages (Colella et al., 2004; Rizzo et al., 2004, Tamburiello et al., 2008).

Example of a deep DC survey

Recently, in the framework of the VIGOR project Deep Electrical Resistivity Tomography (DERT) has been performed in different areas of Southern Italy.

At the 'Terme Caronte' site (Lamezia Terme, Southern Italy), the geophysical investigation contributed to the characterization of deep geological and hydrogeological features (Rizzo et al., 2013; Rizzo et al., 2014). The DERT was carried out by a 'dipole-dipole' array survey with an electrode distance of 400 m and a maximum spacing Tx-Rx of 3600m. The instrument (build by CNR-IMAA-Geophysics Laboratory) is composed by a transmitter unit to inject the current (a square-wave signal) and a multi-channel receiver to record the voltage signals. The electrical resistivity distribution (Figure 4) clearly highlights the resistivity contrast

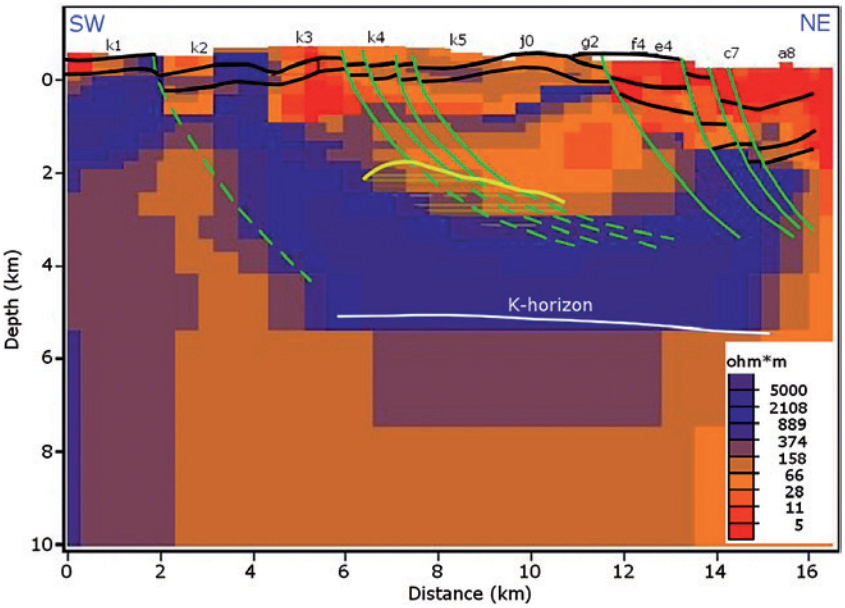

Figure 3 *Resistivity cross-section compared to the geological model of the Travale GF, (modified from Manzella et al., 2006). Black lines are the main geological unit interfaces; green lines are faults; yellow line is the H horizon (corresponding to a high productive zone); K horizon is the white line.*

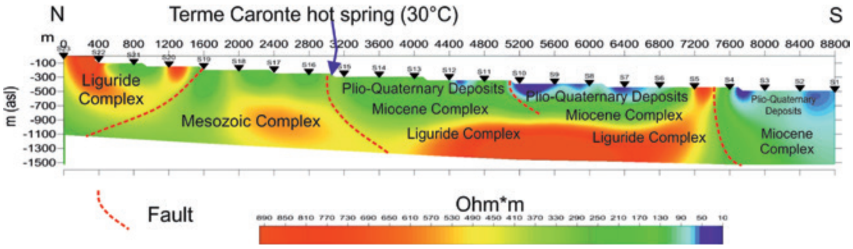

***Figure 4** DERT case study in Terme Caronte thermal area (modified from Rizzo et al., 2013).*

of the different geological units (Mesozoic carbonate rocks, Liguride Complex, Miocene and Plio-Quaternary deposits). Moreover, the main structures associated with the geothermal system and the connection with the hot springs of Terme Caronte are detected.

Future developments and concluding remarks

We have shown how several EM geophysical methods are useful for the exploration of shallow and deep geothermal resources through some case studies in Italy.

The MT scientific community is working hard to optimize 3D forward and inverse modelling and to reduce the effects of electromagnetic noise, in particular the coherent noise such as the one produced by DC electric railways. The AEM methodology is advancing both for hardware and modelling, aiming at deeper penetration without the loss of near-surface resolution.

Beside future improvements for the specific EM methodology, we underline the importance of data integration to support the exploration activities. In this regard, the research will focus on a better integration of geological and geophysical data for exploring a deep hydrothermal reservoir. Future challenges in resistivity methods will relate to developing a integrated modelling procedure of different surface geophysical methods and combining them to borehole data and other constraints, to obtain detailed geothermal models. This topic is central in the European IMAGE Project, which includes, the integration of geological, MT and DERT to explore deep geothermal reservoirs in southern Tuscany (Italy). The DERT will be acquired by CNR also using electrodes down a high-temperature geothermal well in Larderello.

The application of AEM for geothermal energy has been focused on the further investigation of the relationship between electrical resistivity and thermal conductivity, since they are both strictly related to lithology. By building detailed 3D resistivity models over wide areas with AEM, it is possible to obtain a detailed 3D distribution of thermal conductivity. The latter is crucial for shallow geothermal assessment purposes.

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