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Multidisciplinary Approach to the Study of the Relationships Between Shallow and Deep Circulation of Geofluids

Agnese Bianchi[1], Livio Bovini[2], Flavia Botti[2], Marco Doveri[3], Matteo Lelli[3], Adele Manzella[3], Giancarlo Molli[2], Domenico Montanari[1], Lisa Pierotti[3], Carlo Ungarelli[3], Alino Ungari[2], Luca Vaselli[3]

[1] Centro di Eccellenza per la Geotermia di Larderello, Larderello (Pisa), Italy

[2] Dipartimento di Scienze della Terra, Università di Pisa, Italy

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

bianchi.a@cegl.it, lbovini@dst.unipi.it, fbotti@dst.unipi.it, doveri@igg.cnr.it, lelli@igg.cnr.it, manzella@igg.cnr.it, gmolli@dst.unipi.it, montanari.d@ cegl.it, pierotti@igg.cnr.it, ungarelli@igg.cnr.it, aungari@dst.unipi.it, vaselli@igg.cnr.it

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ABSTRACT

We present a multidisciplinary integrated study performed to get insights into circulation pattern of geothermal fluids uprising in the Equi Terme area (Alpi Apuane, Tuscany). Geological-structural surveys were carried out to define the structural setting of the area and to characterize geometries and kinematics of fault-fracture systems. Chemical and isotopic analyses were carried out on thermal water and cold springs. Samples were repeatedly collected in the different seasons, measuring temperature, electrical conductivity, pH and total alkalinity. Furthermore, a geophysical survey has been carried out in order to get insights into the resistivity distribution at depth. The geophysical approach used MagnetoTelluric (MT) and Electrical Resistivity Tomography (ERT). This multidisciplinary approach proved to be a powerful tool, since it unravels the high complexity of this natural geothermal system and provides useful hints in order to reconstruct the complex fluid circulation pattern feeding the Equi Terme thermal spring.

1. INTRODUCTION

The Equi Terme low temperature geothermal system is drained by some springs and a single water well. The main spring has a flow rate of about 10 - 20 l/s and a temperature of 25°C on average, and it is exploited for thermal spa treatments. The strong temperature reduction of the geothermal fluids after rainy events represents a problem for the spa and the related tourist activity, one of the main economic source of the area. Some wells have been drilled in the area with the aim of reaching geothermal fluids either at higher temperature or not so strongly affected by meteoric events. These wells produced cold fluids and were then abandoned, but testified the need to better understand the fluid circulation in an area characterized by a very complex geology and hydrogeology.

In this contribution we present the results from a multidisciplinary integrated study performed to get insights into circulation pattern of geothermal fluids.

2. GEOLOGICAL SETTING AND STRUCTURAL GEOLOGY

The Equi Terme area (NW Alpi Apuane) (Figure 1) is located in a very complex geological situation. The Alpi Apuane represents a tectonic window that shows the deepest exposed structural levels (Tuscan Metamorphic Units) of the Northern Apennine.

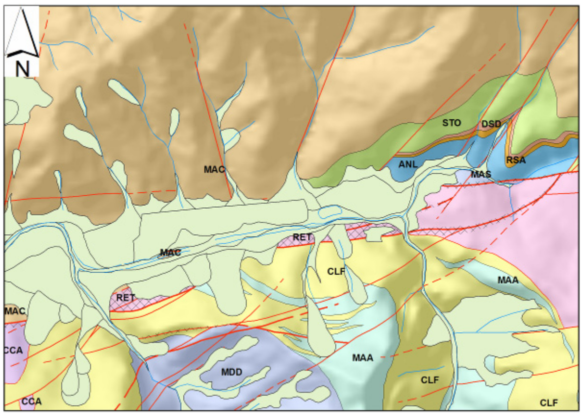

Figure 1: Simplified geological map of the Equi Terme area. Apuane unit: dolomitic marble (MDD), marble (MAA), cherty limestone (CLF); Tuscan Nappe: "Calcare Cavernoso" (CCA), 'Calcare e Marne a Rhaetavicula contorta' Fm, Calcare Massiccio' Fm. (MAS), "Calcari ad Angulati" Fm (ANL), "Calcare Rosso ammonitici" Fm (RAS), "Diaspri" Fm. (DSD), "Scaglia" Fm (STO), "Macigno" Fm (MAC).

The Northern Apennine is formed by a pile of tectonic units derived from the distal part of the Adriatic continental margin (Tuscan Domain) lying below the westerly-derived "oceanic" Ligurian and sub-Ligurian accretionary wedge units (e.g. Elter, 1975; Carmignani & Kligfield, 1990). In particular, in the northernmost part of the Alpi Apuane, the metamorphic rocks belonging to the Apuane Unit are tectonically overlayed with the unmetamorphic sequence of the Tuscan Nappe. The Apuane unit shows a lithostratigraphic sequence made up of a Palaeozoic basement (mainly phyllites and metavolcanics) unconformably overlain by a well-developed Upper Triassic-Oligocene metasedimentary succession. The Mesozoic cover includes Triassic continental to shallow water deposits ("Verrucano") followed by Upper Triassic-Liassic carbonate platform metasediments comprising dolostones ("Grezzoni"), dolomitic marbles and marbles (the "Carrara marbles"). Then, these are followed by Upper Liassic-Lower Oligocene cherty metalimestone, cherts, calcschists and sericitic phyllites. The Oligocene-Early Miocene (?) sedimentation of turbiditic metasandstones (Pseudomacigno fm.) closes the metasedimentary sequence. In contrast, the Tuscan Nappe consists of an Upper Triassic to Oligocene sequence detached from their original basement in correspondence of basal level of evaporates belonging to the Calcare Cavernoso Fm. (Baldacci et al.

1967; Cerrina Feroni et al. 1983). The Alpi Apuane deformation structures are interpreted as formed by two main tectono-metamorphic regional events (D1 and D2 phases of Carmignani & Kligfield, 1990), which were realized at 27-20 Ma and 11 Ma, respectively (Balestrieri et al. 2003; Kligfield et al., 1986). The latest stages of deformation, were associated with the development of brittle structures accommodating vertical movements locally exceeding 4 km. These structures are achieved in the last 5 Ma as constrained by low-temperature thermochronometry, which suggests the transition at 120-100°C at between 4 and 5 Ma in most of the metamorphic tectonic window (Abbate et al., 1994; Fellin et al., 2007 and references therein).

In the Equi Terme area, metamorphic rocks belonging to the Apuane Unit are juxtaposed to non metamorphic sequence of Tuscan Nappe through a pluridecametre to hectometre-thick fault zone dipping to N-NW. Geological-structural field surveys were carried out to define the structural setting of the studied area and to characterize geometrical and kinematic features of fault-fracture systems occurring along the fault zone. On the whole, the fault zone consists of volumes of intensely fractured and crushed rocks, which are bounded by a complex array of medium to high-angle fault surfaces showing a SW-NE to E-W trending and both strike-slip and normal oblique-slip movement. Moreover, a NNE oriented principal extension direction can be inferred from kinematic analysis of main faults mapped. The collected structural data show that the spatial variability of the bulk structural permeability of rocks within the fault zone is strictly linked to the geometrical relationships between the main fault-fracture systems occurring (Figure 2). In this framework, the circulation pattern of geothermal fluids results strongly controlled by the fault zone architecture.

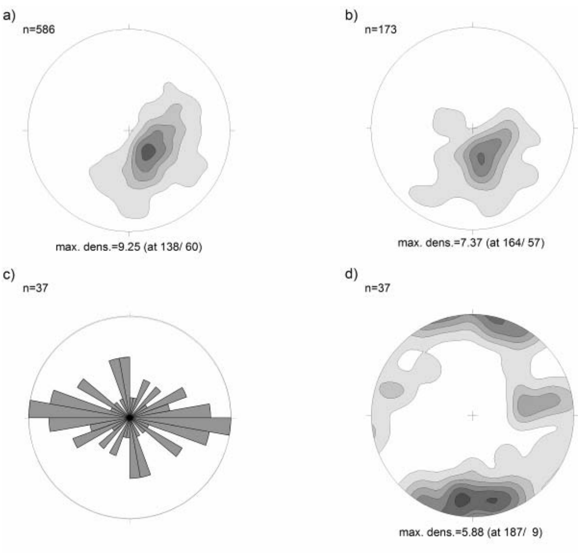

Figure 2: Equal area lower emisphere stereograms of structural data in the Equi Terme area. (a) Apuane unit: poles of the main foliation (Sp); (b) Tuscan Nappe: poles of stratification (S0); Rose-diagram (c) and poles of main fault surfaces in the Equi Terme area.

3. HYDROGEOLOGICAL SETTING

Equi Terme hydrothermal system is a part of north-western apuan hydrogeological complex and was studied by varius authors (Piccini and Pranzini, 1989a-b; Piccini, 1992; Piccini et al., 1997; Piccini et al., 1999; Piccini, 2001; Piccini 2002; Roncioni, 2002). Doveri (2004), starting from the study of Baldacci et al. (1993), on the base of geochemical composition suggests the hydrogeological scheme of north-western Apuane Alps (Figure 3), distinguishing the recharge areas of shallow (a) and deep (b) hydrogeological structures:

a) in the shallow hydrogeological structures the fluid circulation feeds springs characterized by low salinity and temperature (similar to atmospheric temperature);
b) in the deep structure, since the impermeable substratum is located at higher depth, the fluid circulation can feed both cold and warm springs, as in the Equi Terme area.

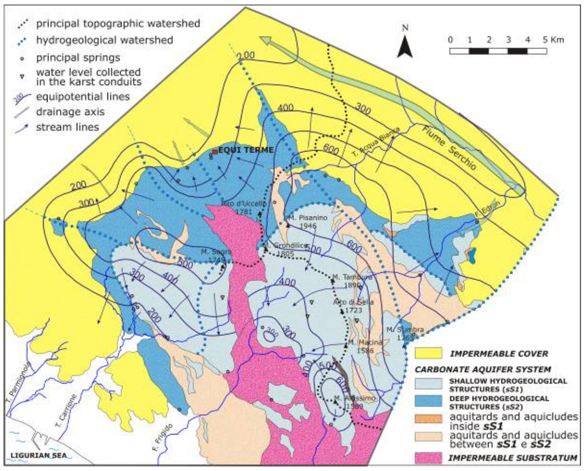

Figure 3: Hydrogeological sketch map.

Figure 3 also display piezometric pattern of the deep hydrostructures, obtained from various informations such as springs altitudes, morpho-structures conditions, water level collected in karst conduits and results of the dye tracing tests (Piccini and Pranzini, 1989; Piccini, 1992; Piccini et al., 1999; Piccini, 2001; Piccini 2002; Roncioni, 2002). In this way, preliminary evaluations about the hydrogeological basins distribution are possible. This scheme shows three different main zone characterized by maximum piezometric level of about 500 m a.s.w.l., (Mt. Sumbra, Mt. Tambura-Grondilice and Mt. Sagro). Stream lines suggest that Mt. Sumbra and Mt. Tambura-Grondilice should feed, at least partially, the springs of the Equi Terme area.

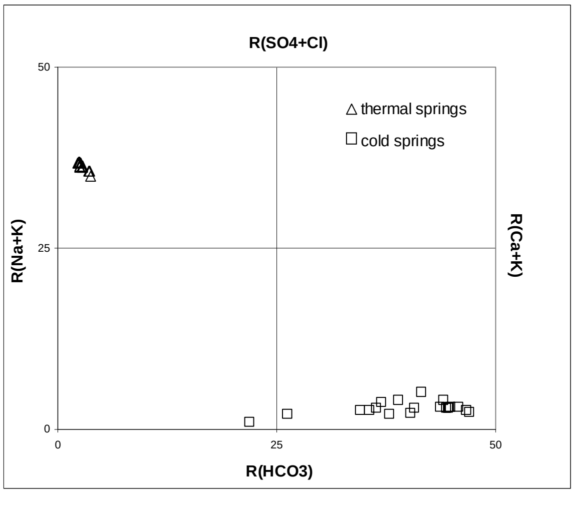

Figure 4: HCO_3 Langelier-Ludwig diagram.

3.1 Hydrogeochemistry

Chemical and isotopic ($^{18}O/^{16}O$, $^{3}H/H$, $^{34}S/^{32}S_{SO4}$ and $^{13}C/^{12}C_{DIC}$) analyses were carried out on thermal water and cold springs (located at different altitudes in the zone). Samples were repeatedly collected in the different seasons, measuring temperature, electrical conductivity, pH and total alkalinity at the tapping point. The thermal waters are of the Na/Cl type and the cold springs are of the Ca/HCO_3 type (Figure 4). Despite their Na/Cl composition, the thermal waters show significant amounts of SO_4 and Ca, which suggest, together with the $[^{34}S/^{32}S]_{SO4}$ values of 15.6 δ‰, a water interaction with Triassic evaporitic formations found at the bottom of the carbonate sequence. The maximum temperature (27°C) and ion concentrations (TDS = 4900, Cl = 2100 and SO_4 = 800 mg/l) are measured at the end of the dry season, whereas a consistent decrease of the chemical values (lowest TDS, Cl and SO_4, respectively 3800, 1700 and 600 mg/l) and temperature (lowest value 21°C) are observed during the rainy period (from autumn to spring). This is the results of a mixing between the cold, low-salinity Ca-HCO3 waters (TDS 250 - 350 mg/l; temperature 10 - 12°C), flowing at shallow depth within the carbonate formations of the Apuan Alps, and the deeper thermal component.

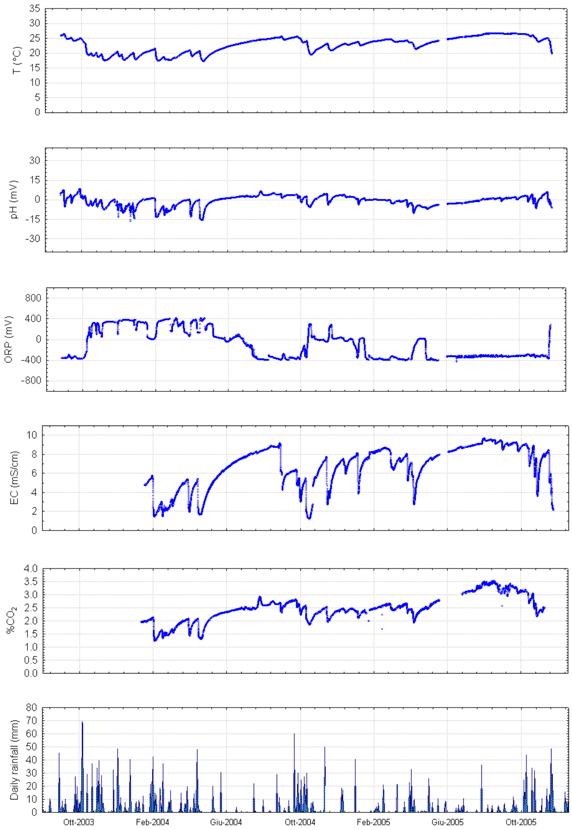

Figure 5: Continuous monitoring at Equi Terme station. The rainfall data (bottom) have been recorded at the Aulla station.

The mixing effect had already been evidence in a previous research funded by the Seismic Service Office of Tuscany Region (Italy) and regarding the earthquake geochemical precursors. For this study a continuous automatic monitoring station was installed in 2003 at the Equi Terme main spring (Pierotti, 2005, Cioni et al., 2007). The monitoring station operates with flowing water (about 5 litres per minute) and records the following parameters: temperature (T), pH, redox potential (ORP), electrical conductivity (EC) and the content of CO_2 and CH_4 dissolved in water. Data are acquired once per second; the average value, median value and variance of the samples collected are recorded over a period of 5 min. Figure 5 shows the data acquired up to December 2005. Chemical data have shown that mixing ratio depends mainly on the effect of the rainwater that recharges the karst shallow circulation. Rainfall influences all the parameters measured by the monitoring station (Figure 5), including the CO_2 concentration that lies in the interval between 1.23% (February, 2004) and 3.55% (September, 2005).

Apart from a single value of -7.2 δ‰, tied to a heavy rain event, the $^{18}O/^{16}O$ data of the thermal springs show narrow range of variation (-7.6/-7.5 δ‰), suggesting similar average recharge altitudes for the shallow and deep groundwater circulation components. Considering the isotopic values and the morphological and hydrostructural contest, the recharge areas should be mainly represented by the SE reliefs. $^{3}H/H$ values suggest relatively short circulation time and $^{13}C/^{12}C_{DIC}$ definitely indicates interaction between water and carbonate rocks.

4. GEOPHYSICS

A geophysical survey has been carried out in order to get insights into the resistivity distribution at depth, which in turn provides useful information about the lithological units of the investigated area and the fluid content. Two different methodologies were used: Electrical Resistivity Tomography (ERT) and MagnetoTelluric (MT). The former has been very useful to gain insights about the resistivity distribution concerning the shallow level; the latter provided information on the distribution of resistivity in the deep part of the system. The acquisition surveys were conducted from July 2008 till November 2008, for a total of 10 days of measurements, during which several acquisition of MT and ERT data has been carried out.

4.1 Electrical Resistivity Tomography

Due to its intrinsic characteristics, the ERT methodology could determine the details of the resistivity distribution down to a depth of 250 m in correspondence of the well and thermal springs.

The acquisitions were performed with different arrays (Wenner, Schlumberger, Dipole-Dipole, Pole-Dipole). ERT data have been acquired along two 1 km long profiles, using 48 electrodes 20 m apart. The effective investigation depth depends on the array used. The analysis of ERT data provided 2D models of the distribution of resistivity along the profiles, allowing a better definition of the area around thermal springs, where the two profiles are closer. The Profile 1 is located on the right side of the Catenelle creek, the Profile 2 on the other side of the valley (Figure 6). The electrodes (especially on Profile 2) are not aligned along a straight line due to the topography and logistics of the area and in order to follow the thermal springs next to the Catenelle creek. Along Profile 2 data were acquired in two different moments, using the same electrode position, in order to evaluate the effects of the well pumping before and after 20 hours of aquifer stimulation. In this monitoring a remote pole has been placed at a distance of about 2 km on the SW of the profile and used to deepen the depth of investigation. Here we show the results obtained with the Dipole-Dipole array, particularly suited for detecting the horizontal resistivity variation, which provided the most interesting results, imaging up to a depth of 160 m b.g.l..

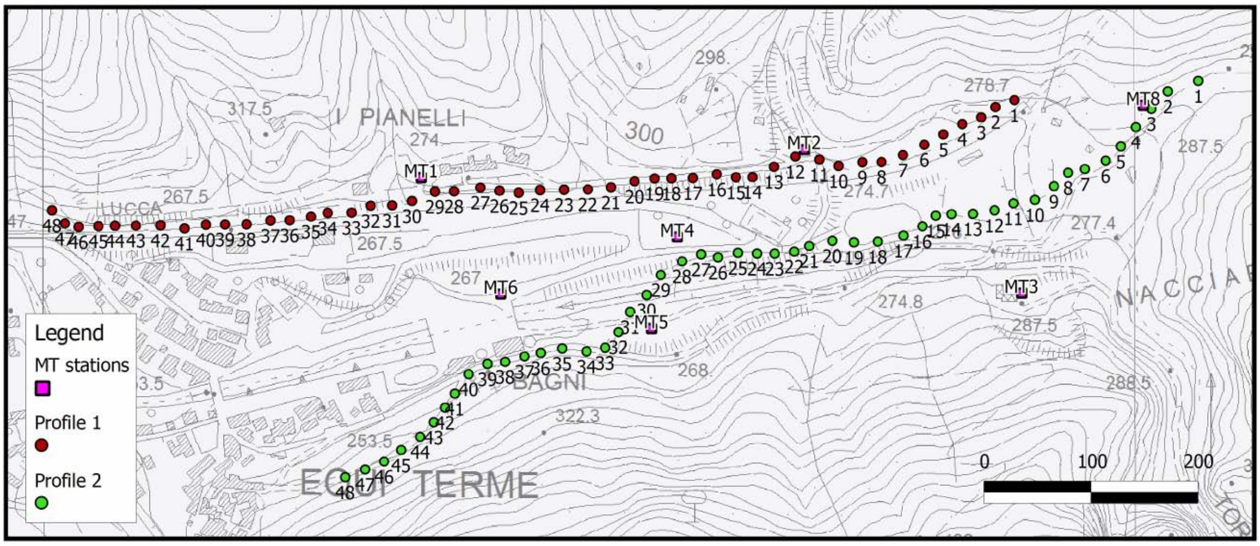

Figure 6: ERT profiles and MT stations.

The resistivity distribution along Profile 1 was interpreted as mainly due to a lithological variation and clearly define a fault that lowers the Scaglia Formation, rich in clay and impermeable (Figure 7). This latter probably influenced the fluid circulation at depth, creating an impermeable barrier.

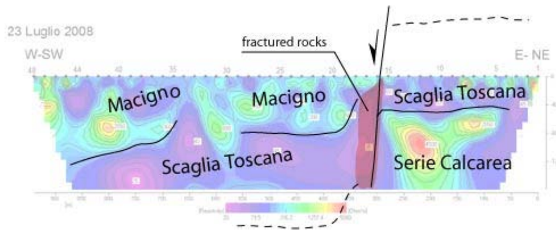

Figure 7: ERT resistivity section – Profile 1 – obtained using a Dipole-Dipole array, and juxtaposed geological interpretation.

The measurements on the Profile 2 have been done in two different moments: before and after the well pumping, in order to evaluate the answer of the aquifer to the hydraulic stimulation and to try to understand the possible path of the uprising thermal fluids. Figure 8 shows the resistivity sections along Profile 2, with a Dipole-Dipole array, before (up) and after well pumping (bottom). The investigated area seems to be roughly divided into two sectors characterized by a different resistivity: a shallow level characterised by low resistivity values lying above a deep and highly resistive level. In those sections several resistivity anomalies have been identified. The main reduction of resistivity are observed in correspondence of electrodes 39 - 40 (close to the thermal spring that feeds the spa), 29 - 31 (near the pumping well used for the test) and 19 - 18, at a depth of about 50 m, 80 m and 20 m, respectively. Two vertical high conductivity anomalies are also well displayed. After the water drainage at the well, the vertical conductive anomalies appear wider and the overall resistivity seems to decrease.

4.2 Magnetotelluric

Only 10 sites could be identified for MT acquisition due to the location of the investigated area in a narrow and steep valley. Although MT data resulted noisy due to the many power lines along the valley, it is possible to express some consideration. MT data have been collected in the frequency range 10^5 - 0.1 Hz, and acquired using a Stratagem system using different cable sets and receivers, characterized by a different sensitivity at depth, reaching an investigation depth of almost 3 km. Since the chemical analysis of thermal waters highlighted their deep interaction with evaporitic rocks (most likely rocks belonging to the Anidriti di Burano Formation) that are supposed to be present in the deep part of the studied area, a calibration of the MT data has also been performed out of the investigated area, at a measurement site located at Sassalbo (MS), where the evaporitic unit extensively crops out. Those Triassic deposits, composed of alternated gypsum/anhydrite levels and dolomite, proved highly resistive (1000 ohm·m).

The MT data have been edited and then modelled. Several 2D models have been obtained along fixed profiles, but they resulted too smooth and poorly indicative in a complex, 3D situation such as this. On the other hand there are not enough data to perform a refined 3D model. Therefore we show the results of the 1D modelling of the invariant curves, which are interpolated in sections, obtaining pseudo-2D models (Figure 9). The obtained models define the resistivity distribution at higher depth in comparison with those investigated by ERT. The resistivity section on the top, roughly corresponding to ERT profile 1, shows two main high resistivity areas: the first is located in correspondence of MT2 site at a depth of 50 m below surface, the second one is located at the eastern margin of the section, at a depth of 500 m below surface.

In the section related to profile 2 (Figure 9, bottom) two main sub-horizontal conductive areas are visible. This two areas seem to be vertically connected in correspondence of the MT5 site, which is close to the main springs and the well.

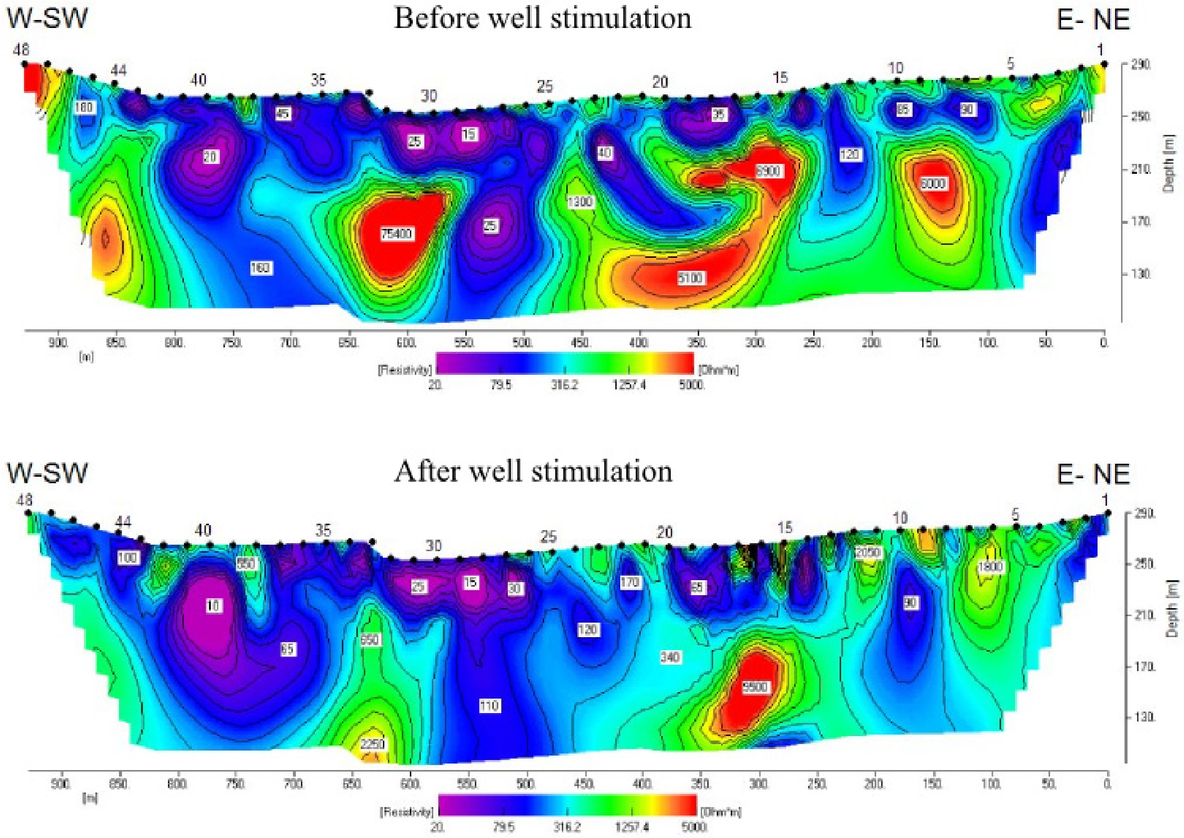

Figure 8: Resistivity sections – Profile 2 – obtained using a Dipole-Dipole array, before (top) and after well pumping (bottom).

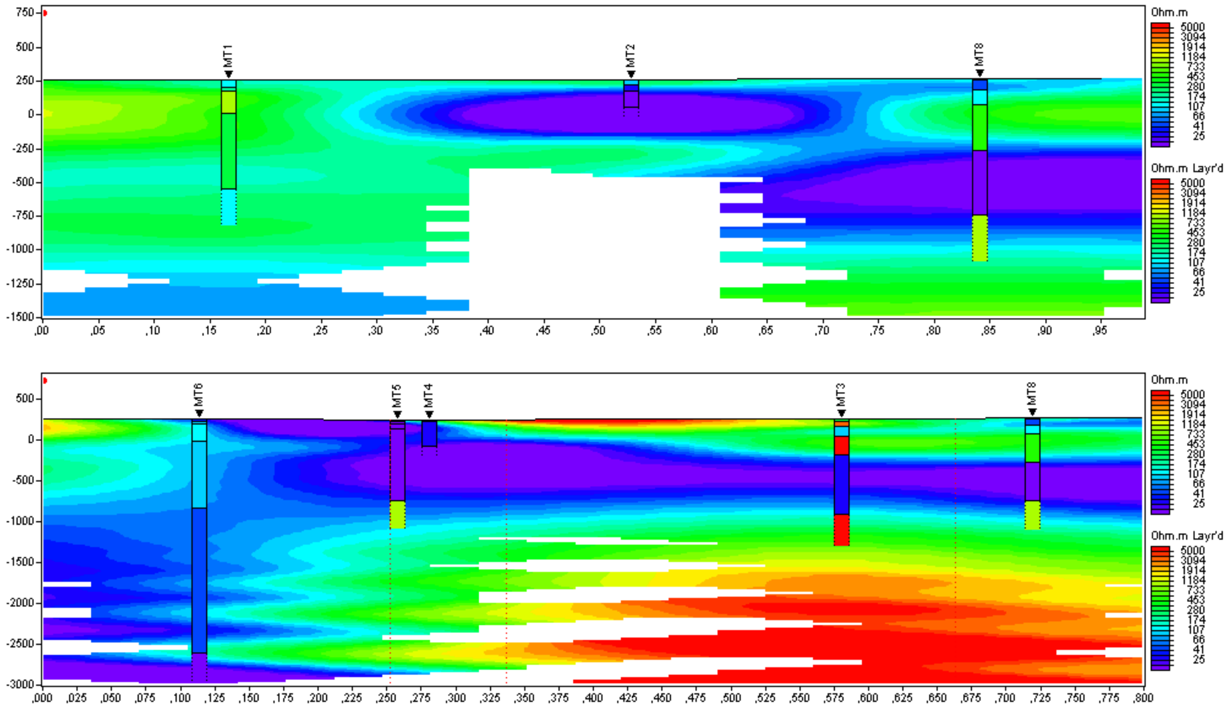

Figure 9: Resistivity section obtained by interpolation of 1D Occam inversion of MT data along ERT Profile 1 (top) and Profile 2 (bottom). 1D layered models are also shown.

5. DISCUSSION AND CONCLUSION

As evidenced by geochemistry results, the Equi Terme fluids derive from a mixing, at various ratio, of a karst shallow Ca-HCO_3 water and a deep Na-Cl water originated from the interaction with Triassic evaporitic formations at the bottom of the carbonate sequence. Their mixing ratio depends mainly on the effect of the rainwater that recharges the karst shallow circulation.

MT and ERT data have shown anomalies of resistivity that are correlated with geological units and with zones of higher permeability and fluid content representing possible fluid pathways. In both MT profiles (Figure 9) low resistivity areas are well defined at depth of about 500 m b.s.l.. Joint interpretation of geophysical, geological and hydrogeochemical data suggests that these highly conductive zones could represent areas of enhanced circulation within the evaporitic Formations, where water is enriched in Na-Cl. ERT data provides more details of the local fluid circulation. The most interesting data come from Profile 2 and the changes in resistivity determined by water drainage. Since the geological units below Profile 2 are mainly carbonatic units, we think that the conductive zones at shallow level are related to areas where the fracture systems are more developed. The conductive vertical discontinuities, crossing the deep and most probably less fractured resistive layer, seem to be correlated with the main fault systems identified from geological/structural surveys. These faults are interpreted to be the preferential way for the uprising of the thermal waters that have circulated inside the deep reservoir hosted into the evaporitic rocks. The cold meteoric waters, involved in the mixing process with hot thermal waters, probably flow within the highly fractured carbonatic rocks interested by the fault and fracture pattern characterizing the area. The change of resistivity distribution before and after the forced water drainage is most probably related to the change of the fluid salinity in the subsurface due to the different mix of cold and geothermal water. After 20 hours of drainage, mostly cold water has been drained and the salinity of the mixture is higher. If this interpretation is correct we may define what areas appears to receive a higher quantity of geothermal fluids, which are located below electrode 40, close to the spring feeding the spa, and electrode 10.

These results are in a preliminary stage of interpretation and requires some more check. However, this research has highlighted the extreme complexity of fluid circulation in the area and the importance of integrated interpretation of geological, geochemical and geophysical data.

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