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Electrical resistivity distribution in geothermal systems characterized by crystalline rocks

The magnetotelluric (MT) method is used to estimate the electrical characteristics of earth structures using naturally occurring electromagnetic fields. It is particularly suited to the task of exploring areas of high heat flow since these areas are commonly associated with dynamic activities such as magma emplacement, crustal fracturing, and the circulation of hot, electrically conductive fluids. Southern Tuscany, which is characterized by a high heat flow and the presence of two of the most important geothermal areas of the world, Larderello and Mt. Amiata, is an excellent test site for resistivity characterization. The region is characterized by sequences of sedimentary, metamorphic and igneous rocks, and the main geothermal reservoirs are located within the metamorphic basement, at depths of more than 2 km, at pressures of up to 70 bar and temperatures between 300 and 350 °C.
The MT surveys in southern Tuscany were undertaken primarily for geothermal and deep crustal exploration. For a long time MT surveys have encountered significant difficulties that mainly stem from three factors: 1) the high level of electromagnetic signals from industrial and cultural sources, which interfere with the natural fields used in the method; 2) the presence of very conductive shallow formations, and hence the necessity to acquire data for long periods; and 3) the naturally-occurring structural complexity commonly found in these areas, which requires two- or three-dimensional MT modelling for interpretation purposes, thus significantly increasing the amount of effort required by modelling.
The picture emerging from these MT surveys is that of a resistivity structure that is only partly related to the heat flow regime of the area. A very low resistivity has been found below the steam-dominated geothermal system of Larderello and below areas that have no clear connection to any geothermal system, whereas this reduction of resistivity is less conspicuous below the water-dominated geothermal system of Mt. Amiata.
The reasons of the resistivity variation in this region are an interesting subject: resistivity varies with lithology, both as matrix and alteration minerals, and with fluid distribution and state. The latter are in turn created and controlled by temperature, pressure and tectonic processes. In Tuscany rock matrix should not provide strong variation since resistivity changes from metamorphic to granitic rocks are little. Moreover, the most anomalous area is Larderello where the exploited geothermal fluid is superheated steam, which by itself should not contribute to a resistivity reduction. Partial melting reduces resistivity, and this effect is very probable in the medium-lower crust where teleseismic tomography defined low velocity bodies. However, melts are not present at the depths of geothermal reservoir where many resistivity anomalies are located.
What remains are two possible explanations for the resistivity reduction from 10^3 to 5 ohm-m observed in Larderello: the effect of alteration minerals and the presence of brines at liquid phase whose interconnection is sufficient to produce electrolytic conduction. The former is a very known effect in volcanic rocks and appears to be by far the main source of resistivity reduction even in water dominated systems. These aspects are now under study.

From a theoretical point of view

The bulk resistivity of formations within hydrological systems will be a function of the resistivity of the rock matrix and the resistivity of the saturating fluid. In "clean" porous rocks (no clays and effectively no matrix conductance), the resistivity of the rock will be controlled by the resistivity of the fluid (the saturating fluid). Archies law is a useful empirical relationship between bulk resistivity (ρ), porosity (φ), water saturation (S_w) and fluid resistivity (ρ_w)

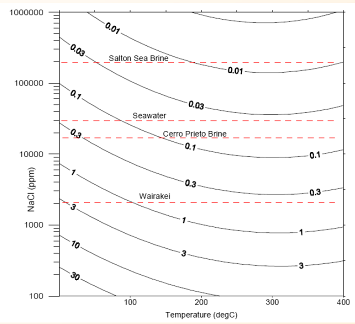
$$\rho = a\,\rho_w\,\varphi^{-n}\,S_w^{-m}$$

where a and n are constants (approximately 0.6 to 1.6 and 2 respectively) that are related to the character of the porosity. At saturations greater than 25%, $m \cong n$.

Because conduction within electrolytes is by ionic processes, electrolyte resistivity is directly related to viscosity which decreases with temperature. In contrast to metallic conduction mechanisms, ionic and semi-conducting materials both have an inverse exponential dependence of resistivity with temperature of the form

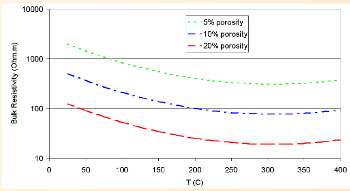
$$\rho = \rho_0\, e^{\varepsilon / RT}$$

where ε is an activation energy (commonly about 0.2eV in water and for saturated rocks, varying with degree of alteration), R is Boltzman's constant (0.8617×10^{-4} eV/°K), T is temperature (°K) and ρ_0 is the resistivity at theoretically infinite temperature.



The resistivity of saline fluids shows experimentally a correlation with the temperature in the range 20-400 °C, as shown above.
Although geothermal fluids contain a wide range of anions and cations, NaCl tends to be the dominant conductive species in the deeper parts of systems and other ions can be considered as Na or Cl equivalents for the purpose of estimating resistivity.
When Archies law is also applied, resistivity should vary with Temperature and porosity following the graph shown below

From Ussher et al, WGC 2000.

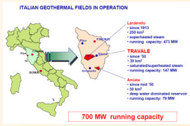


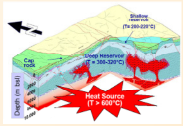
In theory, above a certain temperature and without conductive minerals, resistivity shouldn't decrease so much even in presence of fluids.

Is it experimentally proven?

… to an experimental point of view

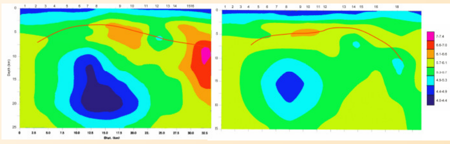
Significant reduction in resistivity has been observed at the depth of the geothermal reservoirs in Tuscany

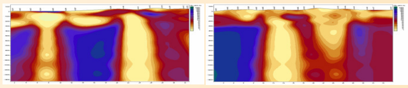




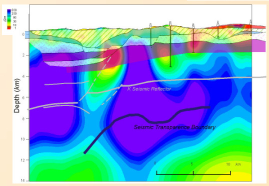
In Italy there are 2 geothermally exploited areas (Larderello-Travale/Radicondoli and Mt. Amiata) in one region (southern Tuscany)
Two main reservoirs characterize both areas: a shallow reservoir in carbonatic rocks, a deeper reservoir in metamorphic units
The reservoirs are steam dominated in Larderello-T/R, water dominated in Mt. Amiata (extinct volcano)
20 MPa and 300-350°C are found at 3 km

292 sites were acquired over the last 15 years, 168 of which, acquired for geothermal purposes, were referenced to a remote site located in the Capraia Island

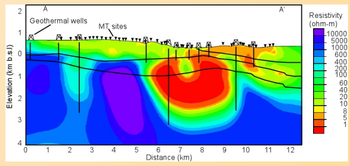




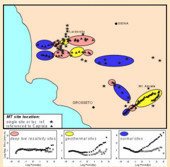
Larderello 1992. Site distance is 2 km, and lateral resolution is not very high. Low resistivity is, however, very clear although not directly comparable in location to known features.
Rock matrix should not provide strong variation since resistivity changes little passing from metamorphic to granitic rocks. Moreover, the exploited geothermal fluid is superheated steam, which by itself should not contribute to a resistivity reduction. Partial melting reduces resistivity, and this effect is very probable in the medium-lower crust, where teleseismic tomography defines low velocity bodies. However, melts are not present at the depths of geothermal reservoir where resistivity anomalies are located.
What remains are two possible explanations for the resistivity reduction from 10^3 to 10^0 Ωm observed in Larderello: the effect of alteration minerals and the presence of brines at liquid phase whose interconnection is sufficient to produce electrolytic conduction.



Amiata (1994). Continuous profiling acquisition (distance 250 m)
The correspondence between areas of low resistivity inside the resistive basement and geothermal reservoirs was very evident in the Mt. Amiata water-dominated system. The lowest resistivity, however, was found outside the exploited geothermal system, in a place of high heat flow characterized by a main fault.



Amiata (1999). Continuous profiling acquisition (distance 250 m)
Data are unable to predict the exact location and direction of the fractures at such great depths but they identify very clearly the areas that are affected by deep circulation of geothermal fluids.



The deep, low resistivity anomalies were found below the geothermal area of Larderello and in areas located west and south-west of the Amiata area but outside the main geothermal area, whereas deep resistivity in the central Amiata area has been observed to increase.
The MT data seem to indicate that the intrusions lie at greater depth in the Amiata area than in the Larderello area, and that intrusions comparable to those at Larderello may be present in areas that have still to be explored.
The connections at depth between these many magmatic bodies has still to be investigated. A clear transition to low resistivity in the medium and deep crust is absent in southern Tuscany, suggesting that the effects of temperature and fluid distribution do not depend on the transition to ductile conditions.

The actual research

INTAS Project

THREE-DIMENSIONAL ELECTROMAGNETIC AND THERMAL TOMOGRAPHY OF THE ACTIVE CRUSTAL ZONES

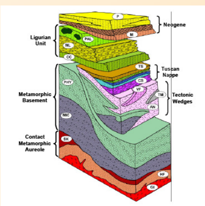
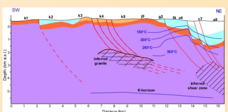
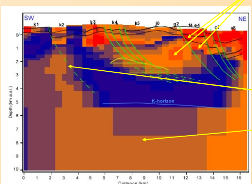


Figure 2.4 - Geological and structural setting of the Travale test site

[P] Marine sediments (L.M. Pliocene), [M] marine and continental sediment (U. Miocene), [PAL] Palombini Shale (L. Cretaceous), [ML] Marl and Limestone (U. Cretaceous), [CC] Shale and Limestone of the Canetolo Complex, [TS] Sandstone and Shale (U. Cretaceous - L. Miocene), [CS] Limestone (U. Trias- Malm), [AN] Anhydrites (U. Trias), [VF] Quartzite and Phyllites of the Verrucano Formation (M.L. Trias), [TM] Phyllites of the Mersino Formation (U. Palaeozoic), [PHY] Phyllites of the Metamorphic Basement (L. Palaeozoic), [MIC] Micaschist of the Metamorphic Basement (L. Palaeozoic), [SK] Skarn, [HF] Hornfels, [GI] Granite (2.6-3.0 My)

From A. Manzella, V. Spichak, P. Pushkarev, V. Kulikov, B. Oskooi, G. Ruggieri, Y. Sizov: 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, January 30-February 1, 2006

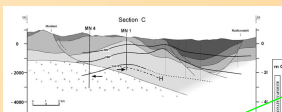


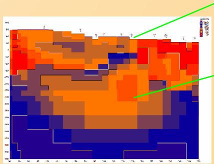


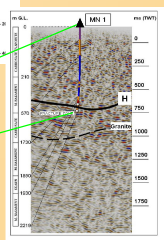
low resistivity anomalies inside the resistive basement

high-angle, conductive fault zone-like structure close to Boccheggiano fault

broad, deep crustal conductor below the seismic K-horizon







A broad reduction of resistivity has been defined in the ravale geothermal area, which correspond to the explited deepgeothermal reservoir. This reservoir is steam-dominated, and the fluid is defined as super-heated or dry steam.

The strong resistivity decrease, at the moment not clearly explained by lithological changes, open new questions regarding the importance of alteration, mineralization and fluid nature within the geothermal reservoir.

The understanding of the fluid-rock interaction processes and the fluid evolution are necessary in order to define a complete model of the geothermal system, that can be used to explain the origin of the field as well as predict its evolution and the duration of the geothermal resource.
To reconstruct this model, the knowledge of the reservoir rocks and fluid composition at the pressure and temperature conditions characterising the geothermal reservoir is crucial.

The correlation between the physical characteristics of the rocks, the location, nature and productivity of the fractured horizons and the related resistivity can led to the reconstruction of the geometry of the deep geothermal reservoir. It would be also of main importance to understand the nature of fluids circulating in the reservoir. Both interstitial and adsorbed water may be contained in geothermal reservoirs, where local conditions in microfractures might be very different from the average conditions observed at large scale. The studies of actual and paleo-fluids, contained in the fluid inclusions, may be of help in understanding fluid circulation and its evolution with time.

On the base of information derived from petrology and fluid inclusions, petrophysical experiments will be able to reproduce realistic physical condition at small scale.

This will be the main IGG contribution in the I-GET Project .