The Role of Magnetotellurics in Geothermal Exploration

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Foreword

MT is one of the most used geophysical methods for geothermal exploration. Due to its characteristically deep investigation depth, it is mainly used for deep geothermal exploration and high temperature fields.

Topics of this presentation

- Geothermal resource concepts and requirements for its profitability
- Goals to be achieved by MT-geothermal exploration
- Why and for what resistivity from MT data (with examples)
- Needs & gaps in my view
- Shallow geothermal assessment with EM (airborne TEM) data
It refers to the thermal energy stored in the earth *at accessible depth*. Thermal energy in the earth is distributed between the constituent host rock and the natural fluid possibly contained in its fractures and pores at temperatures above ambient levels. Geothermal (or secondary for closed loop GSHP and partially for EGS) fluid is the carrier medium that brings geothermal energy up through wells from the subsurface to the surface.

Certain conditions must be met by a geothermal resource to be viable.

The first requirement is *accessibility*. This is usually achieved by drilling to depths of interest, or reaching resource location by deviated wells.
The second requirement is sufficient reservoir productivity. For hydrothermal systems, one normally needs to have large amounts of hot, natural fluids contained in an aquifer with high natural rock permeability and porosity to ensure long-term production at economically acceptable levels.
In the so-called Enhanced or Engineered Geothermal system (EGS), where permeability and fluid flow circulation are artificially improved, productivity is increased.
When sufficient natural recharge to the hydrothermal system does not occur, as is often the case, a reinjection scheme is necessary to ensure production rates will be maintained. This would ensure the sustainability of the resource.
• Image prospective geothermal features without drilling
• Define boundaries (lateral and vertical) of reservoirs
• Identify drilling targets

Main permeability is driven by fracture and faults. **some tens% of wells are not economic**
Goals to be achieved by MT-exploration Geophysics 2: during and after production

• Continuously characterize the reservoir during energy extraction
• Follow the effect of production and fluid re-distribution, including the formation of steam or gas cap
• Characterize the rock fabric to define fluid flow paths within reservoir
• Track injected fluids
• Characterize formations during deep drilling and stimulation in order to predict reservoir performance/lifetime (effectiveness and sustainability)
It is not wise to define a particular sequence of geophysical surveys as being applicable to all potential reservoirs.

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<th>Target</th>
<th>Physical property</th>
<th>Density</th>
<th>Magnetic susceptibility</th>
<th>Electrical resistivity</th>
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Degree of relationship

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<th>Strong</th>
<th>Moderate</th>
<th>Weak</th>
<th>None</th>
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Institute of Geosciences and Earth Resources
National Research Council of Italy
Resistivity depends on both **host rocks** and **pore fluid** properties

**Rocks**
- Temperature & Pressure
- Lithology, Clays (Surface conduction)
- Microstructural properties (e.g., permeability, porosity)

**Fluids**
- Amount
- Nature (liquid or vapor phase, other liquids and gases)
- Salinity
At normal temperature at the earth surface, silicate minerals have very high resistivity.

The higher the temperature, the lower the resistivity.

Approaching the melting point of a rock the resistivity becomes low enough to become comparable with resistivities in water-saturated rocks.

From Karya and Shankland, 1983
The conductivities of both the electrolytes and the rock matrix are temperature dependent in a manner that causes a large reduction of the bulk resistivity with increasing temperature. The maximum enhancement in conductivity is approximately sevenfold between 350°C and 20°C for most electrolytes.
Pressure influence resistivity mainly in connection to fluids and, to a lesser extent, to reconnection of solid phases.
Why resistivity?
Temperature and Pressure

The sensitivity of MT to temperature, especially when combined to the presence of a liquid phase (partial melt) has been used for imaging magmatic heat sources. This interpretation is made more robust when confirmed by other data.

An example from Iceland (Oskooi et al)

Low velocity bodies defined by teleseismic tomography and corresponding low resistivity bodies.
Geothermal resources may be hosted in any kind of rock
Resistivity is used to map lithology
High heat flow conditions ➔ rift zones, subduction zones and mantle plumes. Thick blankets of thermally insulating sediment covering a basement rock that has a relatively normal heat flow ➔ lower grade

Other sources of thermal anomaly:

• Large granitic rocks rich in radioisotopes
• Very rapid uplift of meteoric water heated by normal gradient
The resulting resistivity is also related to the presence of clay minerals, and can be reduced considerably when the clay minerals are broadly distributed.

Clays not only decrease the resistivity by themselves, but also increase the surface effect (frequency-dependent IP)

From Pellerin et al., 1996
From Anderson et al., WGC2000
The effect of clay over the resistivity is important in geothermal areas since clayey alteration minerals are very frequent, particularly in volcanic rocks.

Comparison of the resistivity structure with geological data in volcanic geothermal fields has shown a good correlation with alteration mineralogy.
Resistivity should be always considered with care. Experience has shown that the apparent one-to-one correlation between low resistivity and the presence of fluids is not correct, since alteration minerals produce comparable, and often higher reduction of resistivity with respect to fluid flow.

Moreover, although the hydrothermal systems in volcanic rocks have an associated low-resistivity signature, the converse is not always true.
In volcanic rocks **TDEM** and **MT** have defined the main structure, driven mainly by alteration minerals.

*From Karlsdottir, ENGINE Workshop1*
Geothermal waters have high concentrations of dissolved salts which provide conducting electrolytes within a rock matrix.

From Keller
Geothermal waters have high concentrations of dissolved salts which provide conducting electrolytes within a rock matrix.

This effect is enhanced by temperature effects.

As a result, it is not unusual to see an increase in conductivity – decrease of resistivity by an order of magnitude or more in a geothermal reservoir compared with rocks hosting a fresh water reservoir.

From Wright, Ziolkowski & Hobbs TLE 9/02; after Wilt & Alumbaugh, 1998
The correspondence between areas of low resistivity inside the resistive basement and geothermal reservoirs was very evident in the Mt. Amiata water-dominated system. Geothermal brines in the reservoirs and fluid-filled main fractures and faults can be imaged by MT.
Why resistivity?

Fluid phase

From Roberts et al., 2002

vapour phase

liquid phase
2D TE-TM inversions of MT data in Larderello – Travale geothermal area.

The reservoir is hosted in metamorphic and granitic rocks and is a dry steam reservoir. Why low resistivity anomalies?

We excluded they are the effect of alteration minerals.

I-GET project results
Why resistivity?
Fluid phase

Productive fractures and low resistivity anomalies at the same location.
Is there a liquid phase involved in the complex hydraulic structure?
Is MT providing info regarding areas of enhanced productivity?
To be confirmed.
Research is in progress in the frame of IMAGE project.
Main needs and gaps in geothermal fields
in my view

• Improve anisotropy analysis
• Improve data quality in noisy areas
• Improve resolution
data integration with other EM and geological/geophysical information
• Demonstrate usefulness for monitoring reservoir evolution
As part of planned geophysical activities in the VIGOR Project, a SkyTEM survey has been carried out in Sicily, in late 2011, on two test sites:

- Investigated area ~1500 km² for Western Sicily and 300 km² for Termini site;
- 150 m flight line spacing for Termini Site;
- 1 km flight line spacing for regional scale in Western Sicily and 100 m flight line spacing for infill areas around main thermal springs ("Montevago", "Calatrasi" and "Terme Segestane").
The geophysical results are composed by 3D cell distribution of resistivity \((X,Y,Z,\rho)\). Resistivity slice maps (both in depth and elevation a.s.l.) and resistivity cross-sections have been drawn from both smooth (multilayers) and blocky (few layers) models.
AirborneEM for shallow geothermal assessment

3D resistivity distribution

Integrated analysis of resistivity and geological-lithological data (on surface)

Picking out the resistivity values and definition of Litho-Electrical (LE) Units

3D model of «λ» thermal conductivity (constant value for each LE unit)
By characterization of rocks thermal properties by lab measurements on samples, we defined a 3D thermal conductivity distribution in an area of very complex geology and strong vertical variability.

- the undisturbed ground temperature at 50 meters b.g.l., derived from the analysis of average annual air temperatures and heat flow
- the monthly energy loads of a reference building

Thermal energy that can be exchanged by a unit volume of ground for a reference GSHP plant (algorithm in Galgaro et al., Geothermics 2015)
Thank you for the kind attention