Exploration of Geothermal High Enthalpy Resources using Magnetotellurics – an Example from Chile

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Introduction

Geothermal energy sources are formed by heat stored in rock at depth. In regions with high heat flow, like at volcanically active plate margins, high total thermodynamic energy is accumulated in the so called high enthalpy resources. To explore for these resources up to a pre feasibility stage a range of geoscientific methods is used in a defined sequence starting with regional reviews and remote sensing followed by geologic-, hydrologic-, geochemical and geophysical surveys.

The applied geophysical methods usually comprise temperature measurements (gradient boreholes), seismology, magnetics and resistivity methods, including Magnetotellurics (MT). Geothermal surface manifestations like hot springs, fumaroles, geysers and the associated geological and geochemical settings are indicating the presence of a geothermal reservoir. Particularly resistivity methods may be used for delineating the lateral and depth extensions of such potential reservoirs. The Magnetotelluric method is frequently used for this purpose since it easily covers the necessary exploration depth down to 5 km.

The role of electrical resistivity

Unaltered volcanic rocks generally have high resistivities which can be changed by hydrothermal activity. Hydrothermal fluids tend to reduce the resistivity of rocks

- by altering the rocks,
- by increase in salinity or
- due to high temperature.

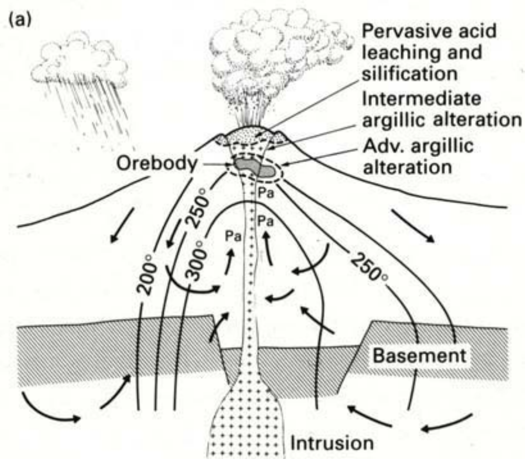

Figure 1: Sketch of a geothermal resource in volcanic terrain of the acid sulphate type and associated alteration. Arrows indicate the circulation of meteoric water (after Evans 1997).

In high enthalpy reservoirs, i.e. fluid temperatures above 200 °C, hydrothermal alteration plays the predominant role. In a volcanic terrain (fig. 1) the acid-sulphate waters lead to different alteration products depending on the temperature and thus on the distance from the heat source. With basalts as country rock smectite becomes the dominant alteration product in the temperature range from 100 °C to 180 °C. At higher temperatures mixed layer clays and chlorite become dominant (fig. 2).

Laboratory measurements indicate that smectite (expandable) clay minerals show very low resistivities even with resistive fluids as saturant (fig. 3, Emerson and Yang 1997). While smectite clay exhibit resistivities below 5 Ohm*m other (non expandable) clays have higher resistivities. Since the abundance of smectite is restricted to a temperature range from 100 °C to 180°C a smectite layer (or cap) is formed around a hot reservoir at the corresponding distance. Layers both above and below this smectite layer have higher resistivities, thus a succession of high-low-high resistivities with depth is indicative for a geothermal reservoir of this type (fig. 4) where the higher resistivities below the clay cap point to the core of the reservoir and represent a possible drilling target. The MT method may detect this pattern which is expected at depth of several hundreds of meters down to 1500 m (restricted due to feasibility reasons).

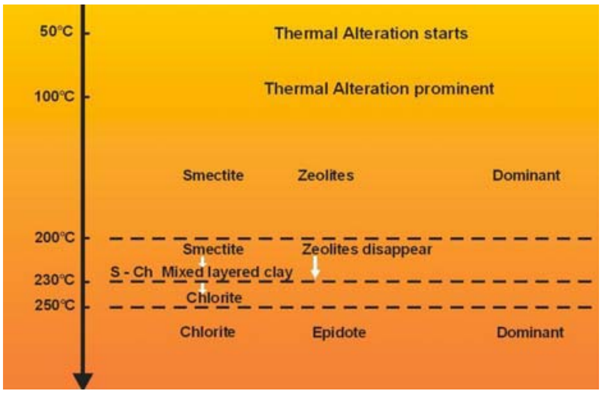

Figure 2: Alteration mineralogy with increasing temperature in basaltic country rock. In the temperature range 100°C to 180°C smectite becomes the dominant alteration product and generally forms a smectite/bentonite clay cap (source: Geological Survey of Iceland ISOR).

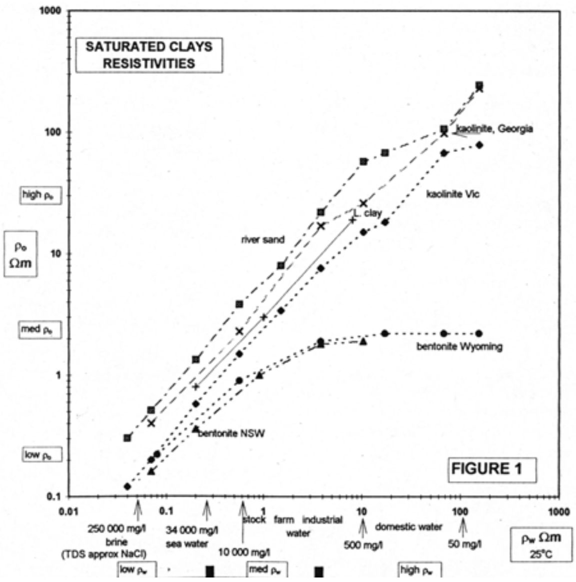

Figure 3: Bentonite clay (mineralogy: smectite) exhibits resistivities around 2 Ohm*m even if the saturant fluid has high resistivity (after Emerson & Yang 1997).

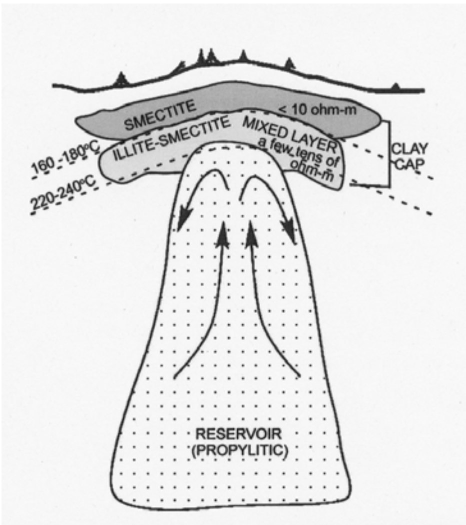

Figure 4: Schema of a generalised geothermal system. The smectite cap formed exhibits resistivities in the range of 2 Ohm*m, the mixed layer around 10 Ohm*m (modified after Johnston et al. 1992).

An Example from Chile

Within a geothermal exploration program electromagnetic surveys have been conducted in the 9th region of Chile, northwest of the Sierra Nevada volcano (fig. 5). Along MT profile P1 (fig. 6) in a NW bearing from the Sierra Nevada volcano 10 MT soundings (up to 100 s period) have been recorded.

Figure 5: Chile location map. Right circle: Sierra Nevada prospect area. Source: http://www.turistel.cl

Time series processing included visual inspection of the recorded data and excluding disturbances and heavily noise affected parts of the time series. Although very time consuming this approach proved to be the best means to extract maximum information from the noise contaminated time series. These preconditioned time series were then transformed into the frequency domain by a FFT using adapted window lengths. With a coherency based algorithm the Fourier spectra were then averaged and the impedance tensor estimated. The impedance tensor has been rotated mathematically by a constant angle derived from the swift angle at low frequencies. This results in a data set with consistent orientation with one axis approximately along the valleys which is taken as direction for the E-field and assigned the TE-mode. Static shifts of the resistivity curves have been removed by means of the MT response derived from TEM measurements at the same locations.

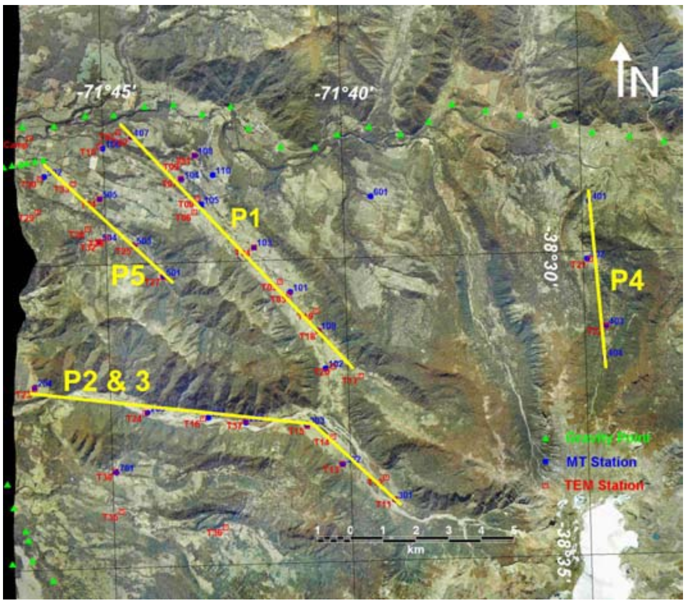

Figure 6: MT profile locations superimposed on an aerial photo of the survey area. The Sierra Nevada volcano is located in the SE corner. In the North you see the Rio Cautin (along the green Gravity stations). Only MT profile P1 shows resistivity lows of interest to geothermal exploration.

The subsequent 2D modelling has been performed using an algorithm by Mackie implemented in the software WinGLink. Both, TE- and TM- modes were taken into account in the 2D modelling.

A shallow conductor in the range of soundings 107 and 108 (fig. 7) is due to a hot aquifer (Manzanar aquifer) and has been investigated in detail with TEM (see

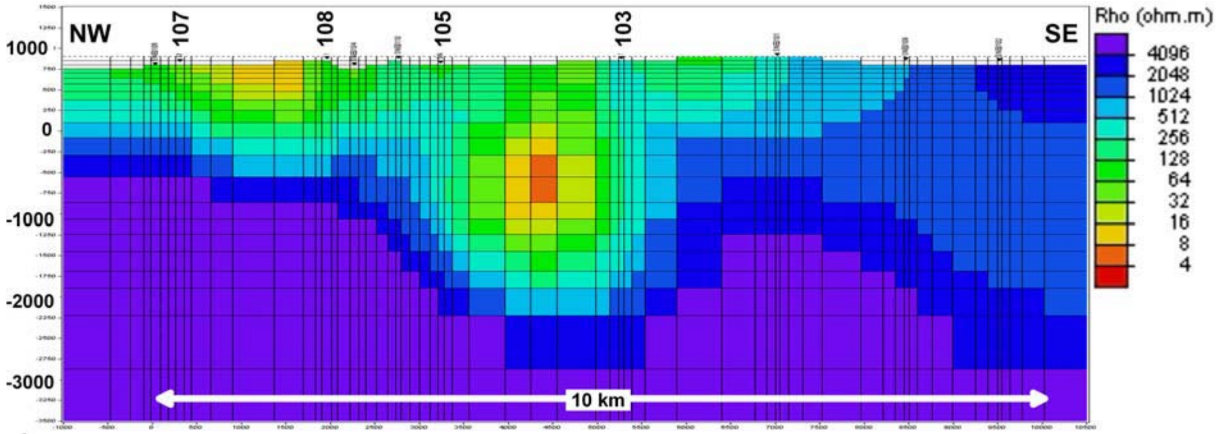

Figure 7: MT profile P1 trending from NW to SE. The interpretable depth reaches about 6 km. Resistivity lows are found at 1.3 km depth (550 mbsl) between stations 105 and 103 as well as a shallow anomaly between stations 107 and 108.

contribution by G. Reitmayr, this volume). In addition to the TEM interpretation given there we can conclude from the MT model a depth extension of this aquifer to a maximum of 600 masl, i.e. an aquifer thickness of max. 400 m.

At a depth of approximately 600 mbsl a good conductor shows up between soundings 105 and 103. This conductor could be associated with alterations or hydrothermal fluid flows. To the SE end of the profile resistivities increase above 1000 Ohm*m and do not indicate any alteration zone or pathways for highly mineralised geothermal waters, flowing from the Sierra Nevada (EL Toro fumarole and hot well) to the Cautin river at Manzanar or Malalcahuello (fig. 8). Fluid flows, as proposed by conceptual models based on geochemical analyses, will probably be restricted to faults linked to the dextral strike slip system of the Liquine-Ofqui Fault Zone (LOFZ) but are not detected by the MT data gathered.

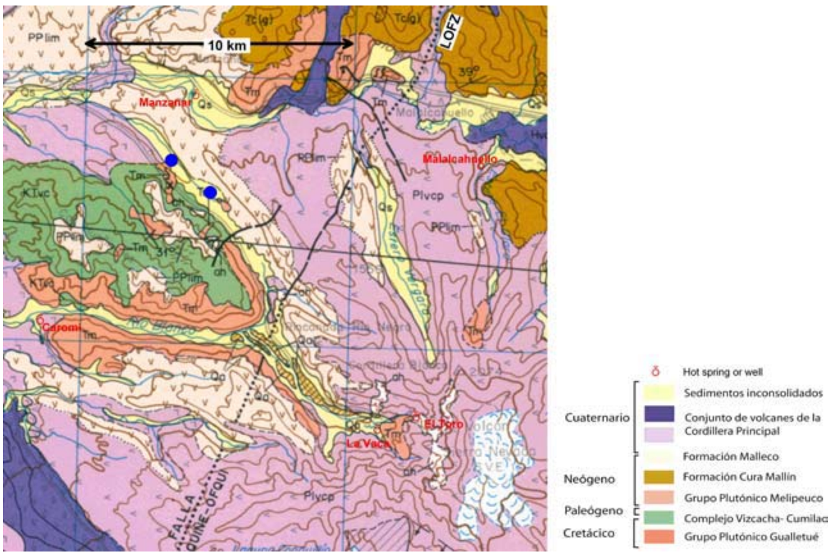

Figure 8: Part of the geological map covering the survey area. Main elements are quartenary volcanic rocks (violet, blue), volcanic-sedimentary untit (green) and quarternary valley infills. LOFZ= Liquine-Ofqui Fault Zone, major dextral strike slip system (transpressional regime), NNE trending. Blue dots = MT sounding points 105 and 103.

Possible causes for the resistivity low

The central resistivity low could be caused by argillic alteration of a recent geothermal system. Since the extension of the anomaly is rather small and its resistivity in the range from 4 to 8 Ohm*m, it seems more likely due to mineralised fluid flow in faults. The aerial photo (fig. 6) shows a SW-NE trending tectonic lineament in that area supporting this assumption. The shallow resistive zone is most probably linked to the Manzanar aquifer. In the given environment also fossil alterations, altered pyroclastics or glacial clays could at least contribute to low resistive anomalies.

Acknowledgements

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