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Contribution of Magneto-Telluric Method to Geothermal Development in El Salvador

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ABSTRACT

The Magneto-Telluric method (MT) is used in geothermal exploration programs as the only effective way to map resistivity variations from near surface to depths of several kilometres, given an estimated depth of the reservoir. In El Salvador this method has contributed to the development of the geothermal resources providing reliable information about the location and characterization of the most promising geothermal systems.

The geophysical interpretation for the Ahuachapán geothermal reservoir indicates that deep conductive rocks are present between Ahuachapán and Chipilapa.

The reservoir in the Berlin Geothermal field corresponds to an uplifted resistive layer at depth, corresponding to philitic and propillytic alteration facies, with resistivity values ranging form 40 to 90 ohm-m inside the resistive basement, at higher values, temperature inversion is attempted.

The San Vicente geothermal reservoir was associated with an uplifted resistive layer at depth as well as a positive residual gravity anomaly. The propillytic reservoir was intercepted by the first exploratory well.

1. INTRODUCTION

The magneto-telluric method (MT) has been used extensively in geothermal exploration. MT relies on the detection of small potential differences generated by electromagnetic waves propagated from the ionosphere. The natural magnetic field has waves with a wide range of frequencies ranging from 0.0001 to 1000 Hz. The high frequency signals originate in lightning activity; the intermediate frequency signal come from the ionosphere activity and low frequency signals are generated by ionospheric and magnetospheric currents that arise when plasma emitted from the sun interacts with the earth's magnetic field, by sun-spots resonances (Manzella, 1994)

In order to penetrate deep into the geothermal reservoir (Deeper DC resistivity methods), the measurements are usually taken in the lower frequencies because these signals travel further into the earth than high frequencies.

During field measurements as shown in Figure 2, the magnetic fields Hx, Hy and Hz, are measured in the X, Y and Z axis respectively, while the induced electric fields Ex and Ey are measured in the X and Y directions. These five components are measured over different frequencies.

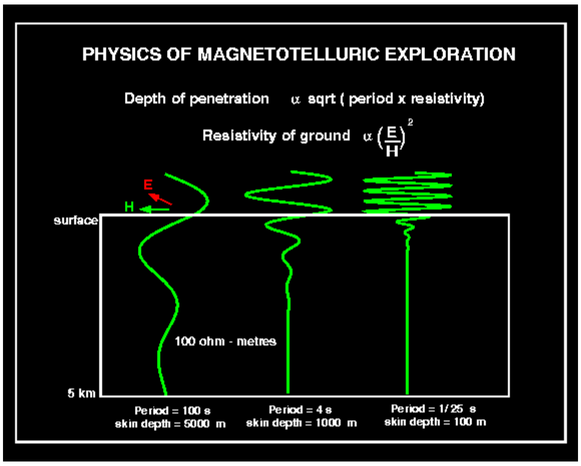

Figure 1: Electromagnetic waves recorded by MT method. (taken from www.geophys.washington.edu)

The locations for the magnetic sensors should be apart from the telluric lines to minimize interference between sensors. They should also be away from trees to avoid noise due to ground vibration by wind. Bury the sensor coils in the ground to minimize noise from movement and temperature variation. Hx and Hy should be placed horizontally and Hz vertically.

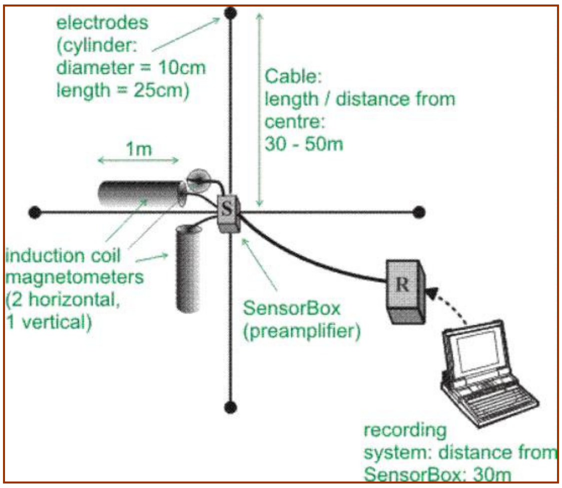

Figure 2: MT array for collecting data in the field. (taken from www.gfz-potsdan.de)

The resulting data is transformed and apparent resistivities in X and Y directions ρ_{xy} and ρ_{yx} using Fourier Transformation, while the depth of investigation (δ) is function of frequency. The governing equations are:

$$\rho_{xy} = \frac{1}{5f}\left|\frac{E_x}{H_y}\right|^2 \quad \rho_{yx} = \frac{1}{5f}\left|\frac{E_y}{H_x}\right|^2 \text{ and } \delta = 355\sqrt{\frac{\rho}{f}}.$$

The MT poor resolution for higher frequency at the shallow levels was improved by doing a TDEM sounding (Time Domine Electromagnetic Method) in each MT location.
MT surveys are used in geothermal exploration programs as the only effective way to map resistivity variations from near surface to depths of several kilometers, which in turn are controlled by formation parameters such as secondary alteration, fluid content, salinity, porosity and temperature.

1.2 Typical Resistivity Structure of a High-Temperature Geothermal System

The typical structure of a high-temperature geothermal system is presented schematically in Figure 3. The resistivity of the smectite zone is primarily determined by the type and intensity of alteration, modified by the degree of saturation and actual temperature, and is generally between 1 and 10 ohm-m. The percentage of illite increases with temperature, forming mixed-layer clay at 180°C. Above this temperature, the smectite content continues to decline, and pure illite commonly appears at greater than 220°C with other high-temperature alteration minerals (chlorite, epidote, etc) in the propylitic alteration assemblage, with typical resistivities lie between 10 and 60 ohm m (Errol et al, Geothermal Congress 2000).

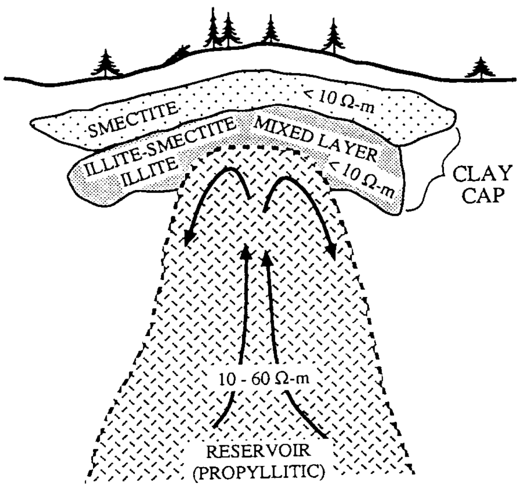

Figure 3: Schematic of a generalized geothermal system (from Johnston et al, 1992)

A geothermal field in a region of low relief will form the low resistivity smectite cap directly above the high-temperature geothermal reservoir. In such cases, shallow resistivity anomalies are reliable indicators of the general location of geothermal fields, although less definitive in boundary areas. In steeper terrain, however, where a significant hydrological gradient is present in the sub-surface, the overall structure of the geothermal system is rather more complex. The conductive smectite layer may be quite deep over the system upflow and much closer to the surface in cooler outflow areas (Mulyadi, 2000).

While geothermal systems are usually associated with low resistivity at shallower levels, the high-temperature geothermal reservoir itself has a resistive signature, due to lower porosity due to lithostatic load and resistive alteration minerals such as Epidote, Quartz and Chlorites. The upflow is located where the conductive-resistive interface attains its highest elevation. Conductive anomalies within the reservoirs can represent large fractured zones to be used in defining drilling targets (ENEL, 2004).

2. MT CONTRIBUTION IN GEOTHERMAL EXPLORATION IN EL SALVADOR

The main contribution of this method to the knowledge of the main geothermal area in El Salvador of is presented as the followings.

2.1 Ahuachapán Geothermal Field

The first MT survey was carried out by CICESE (Centro de Investigacion Cientifica y de Educacion Superior de Ensenada) in 1990. A total of 122 MT sounding were measured on a 60 km^2 area in Ahuachapán, Chipilapa area. As result, a deep conductors of less than 5 ohm-m was identified between 500 and 1000 meters depth associated with the Ahuachapan reservoir. A good correlation between the producer and high temperatures wells and the deep conductive anomaly was found as is shown in the Figure 4. The distribution of the shallow high-conductivity zones agrees with the hydrothermal alteration zones mapped at the surface, suggesting that at shallow levels the argillitization process contributes significantly to the low resistivity (CICESE 1993).

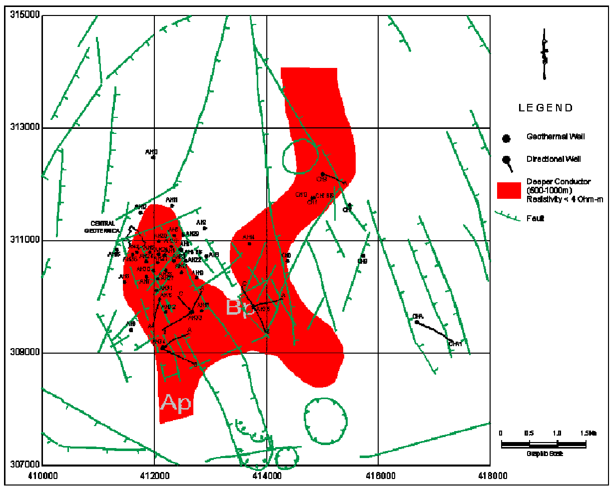

Figure 4: MT low resistivity anomaly in Ahuachapán Geothermal field (from CICESE, 1993)

A new MT survey combined with TDEM was carried out in 2004 by Geosystem and interpreted by ENEL (from Italy), 50 new sounding were added. The shallowest sub-horizontal levels of the conductor, where the minima resistivities (< 5 Ohm-m) are associated to the cover. The reservoir signature is represented by deep conductive rocks with maximum thickness (2000 m) between Ahuachapán and Chipilapa. The shape of the deep resistor is interpreted (with the aid of gravimetric modeling) as an ancient unique culmination below Ahuachapan-Chipilapa now masked by geothermal fluids signature, lowering in resistivity as shown in Figure 5 (ENEL, 2004).

Based on this model, four geothermal targets for production wells were proposed, two of them, AH35C and AH33C have been drilled with successful results.

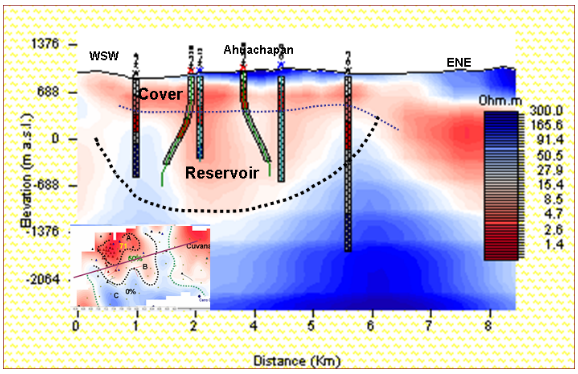

Figure 5: ENEL interpretation of MT survey at Ahuachapán-Chipilapa area

2.2 Berlin Geothermal Field

An MT survey comprising 57 soundings over a prospect area of about 50 km², was carried out in 1994 by Phoenix and interpreted by GENZL (Geothermal Energy of New Zealand Limited) in 1995, and reinterpreted in 2000.

Based on an integrated reinterpretation of the magneto-telluric (MT) resistivity data and existing well information, GENZL estimated that The Berlin geothermal reservoir has an area of between 10 and 13 km² and the productive wells the current field are distributed over less than 20% of the proposed reservoir. It also suggests that the upflow zone is located further to the south of the current production zone. A production well 1.5 to south east was proposed from this study (Figure 6).

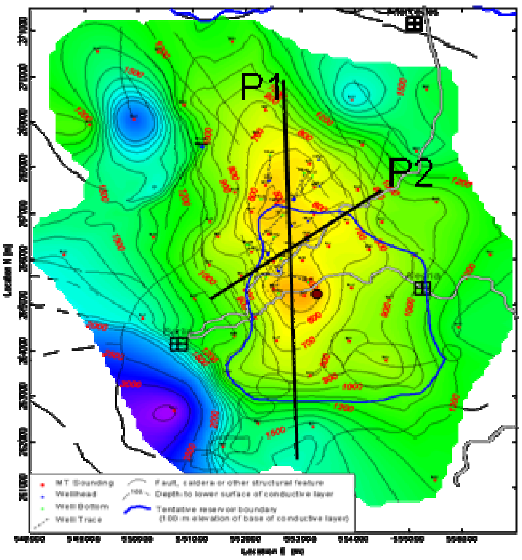

Figure 6: GENZL reinterpretation results of MT survey at Berlin Field (taken from GENZL, 2000)

Twenty additional MT soundings were carried out by Phoenix (from Canada) in 2001, mainly in the southern part of production zone. The integrated interpretation was done by WestJec Company (from Japan). This interpretation was based on the belief that a high temperature reservoir might be present within faults and fractures, which are associated to geoelectric anomalies and discontinuities in resistivity that may lead to the targeting of high permeable zones (WestJec, 2001). The distribution of low resistivity zones is normally associated with alteration zones, the combination of the position and extent of the low resistivity zones and electrical discontinuities can assist in correlating geological features. The detection of these lateral variations of resistivity at depths is important because it can indicate the existence of faults or fracture systems separating different environments. Thus, electrical discontinuities are primarily deduced from resistivity sections and maps at different elevation to check for continuity. In addition, if electrical discontinuities are overlain by low resistivity zones, they become better indicators of hydrothermal activity. Therefore, this study was addressed to map electrical discontinuities to assist in the definition of possible drilling targets when the integration of the whole database is carried out (WestJec, 2001).

Seven primary discontinuities were detected as is shown in the Figure 7. The zones where discontinuities F1, F2, F5, F6 and F7 were mapped are believed to be showing zones of higher permeability, i.e. where these parental fluids are presently moving. Discontinuities F2, F3, F5 and F6 are suggested as targets for production wells and the intersection between discontinuity F4 and La Planta fault for reinjection purpose.

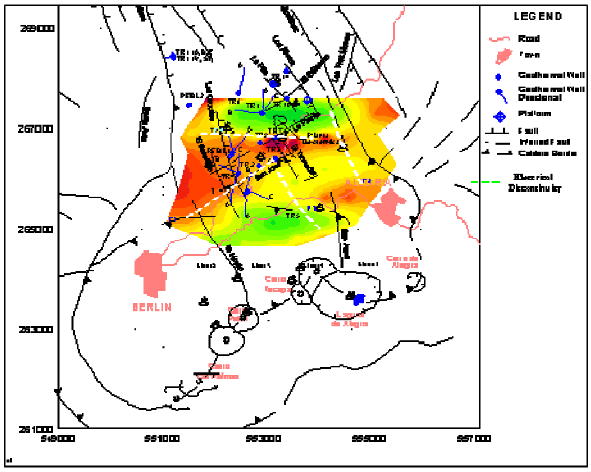

Figure 7: WestJec Interpretation of resistivity discontinuities (white dotted lines)

Based on the WestJec model, the reinjection well TR10-A was drilled for targeting the F4 resistivity discontinuity with unsuccessful results. Nevertheless, the production wells drilled in to this MT resistive anomaly, located at the southern part of the production zone, found good permeability and temperature.

From the same MT database of the Berlin geothermal field, WestJec and ENEL constructed two different reservoir models. The first based in the fractures and resistivity discontinuities, and the second based in typical structure of a high-temperature geothermal system. The wells drilled based on these models were successful in the production zone, but not in the reinjection zone, where well TR10A failed.

Fifty additional MT soundings were carried out by Geosystem (Itlaly) in 2005, mostly in the north and west of the geothermal field. The reservoir was associated with an uplifted resistive zone with a cover of a thin conductive layer, as is shown in Figure 9.

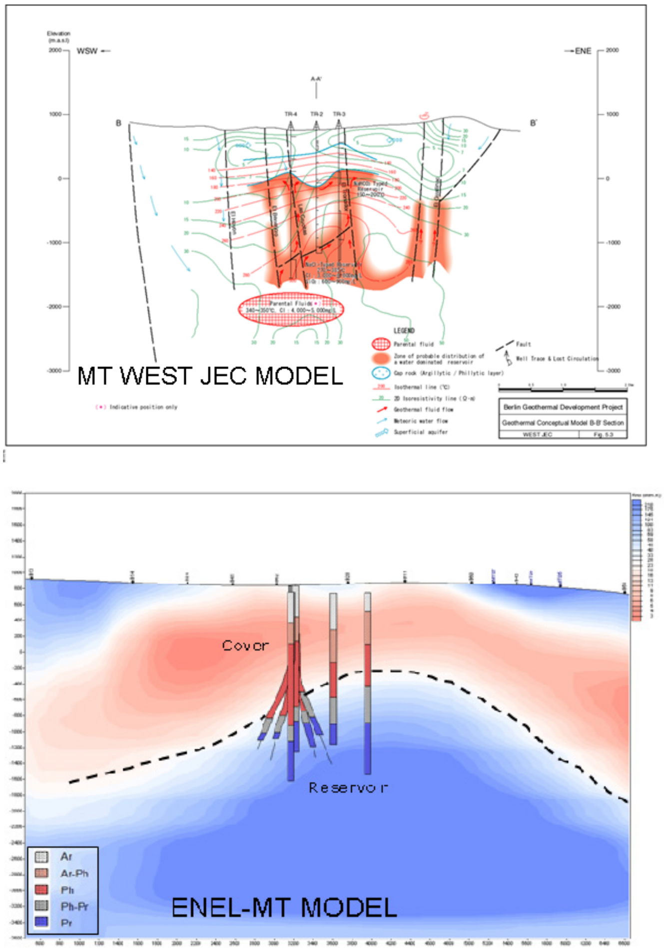

Figure 8: Comparison between West Jec and ENEL MT model of Berlin Geothermal field, from the same database and profile

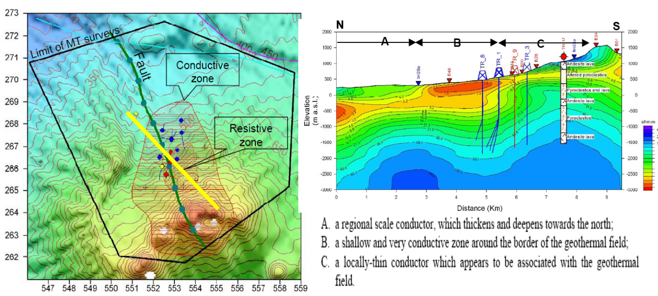

Figure 9: Geosystem MT model of Berlin based on the 3D analysis data

Based on the results of geothermal wells drilled by ENEL in the southern part of the well field, the MT model was adjusted to the well data, mainly to the temperature and mineralogy alteration. The produced reservoir corresponds to an uplifted resistive layer at depth, corresponding to the philitic and propillytic alteration facies with resistivity values ranging form 40 to 90 ohm-m, at higher values, a temperature inversion is observed, as is shown in Figure 10.

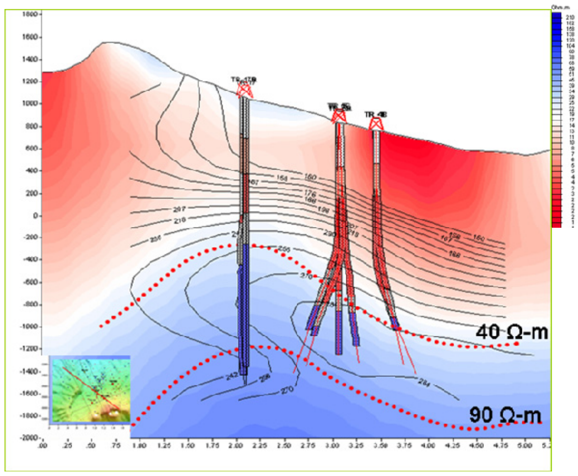

Figure 10: MT adjusted model based on the results of the drilled wells in the southern part of the production zone

2.3 San Vicente Geothermal Field

An MT survey was carried out by Geosystem in 2005. A total of fifty eight soundings were measured in the northern part of the San Vicente volcano. The quality of the data from most of the MT sites was good. Similar to Berlin, the reservoir was associated with an uplifted resistive layer at depth as well as a positive gravity anomaly is shown in Figure 11.

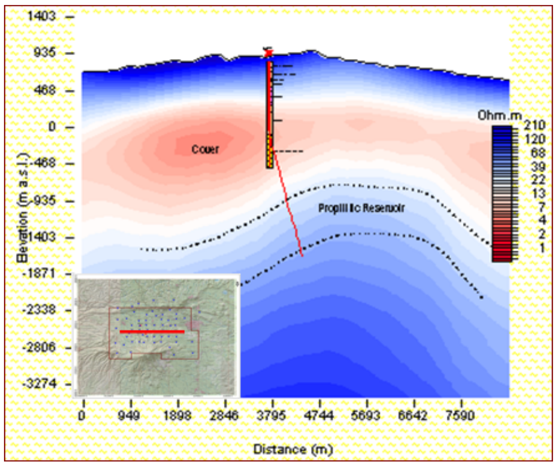

Figure 11: LaGeo interpreted geophysical reservoir based on 3D data analysis

In order to confirm the geothermal resource three deep exploratory wells were proposed, inside the main MT resistive anomalies as is shown in Figure 12.

The MT model was confirmed by the first directional geothermal well SV1A. The uplifted resistive basement associated with the propyllitic reservoir was intercepted at the depth range predicted by the model. However, there is a temperature inversion at the bottom of the well as is shown in Figure 13. It seems that a cooling process is active inside of the geothermal reservoir of San Vicente or the system is partially fossilized.

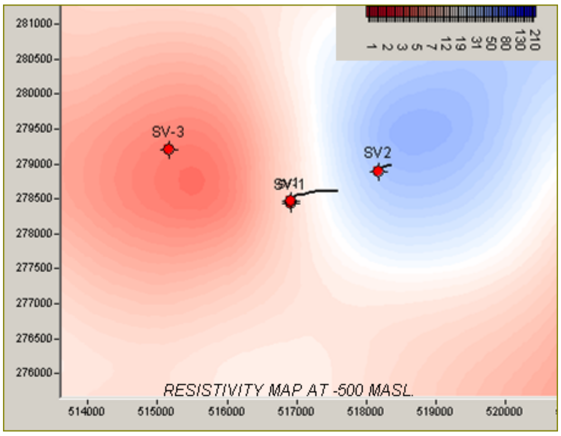

Figure 12: Lageo proposal sites for exploratory wells at San Vicente geothermal area

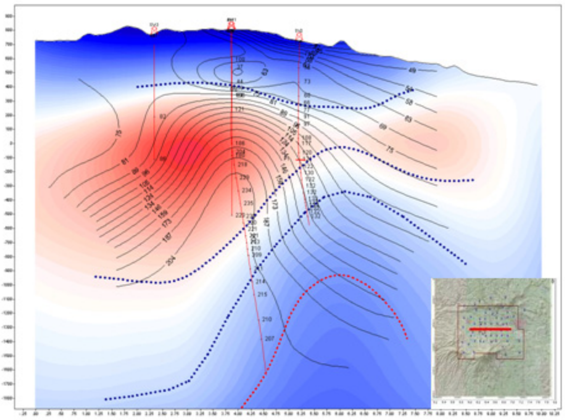

Figure 13: MT profile and measured temperature of the well in San Vicente area

From the results of the geothermal wells, a new zone of interest for deep exploration was confined to south of the well SV1 centered in the resistivity discontinuity as is shown in the Figure 14.

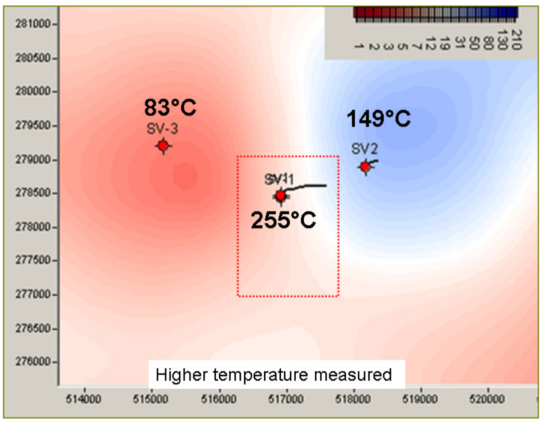

Figure 14: New interesting area for future deep exploration

CONCLUSION

MT surveys are used in geothermal exploration programs as the only effective way to map resistivity variations from near surface to depths of several kilometers.

This method has contributed to development of the geothermal in El Salvador, providing reliable information about the location and distribution of the productive reservoir, as well as to increase of the productivity through the successful positioning of production and reinjection wells in various geothermal fields.

The geophysical interpretation of the Ahuachapán geothermal reservoir indicates the existence of deep conductive rocks, which present their maximum thickness (2000 m) between Ahuachapán and Chipilapa. The shape of the deep resistor is interpreted with the help of 2.5 D gravity modeling analysis, as an ancient unique culmination below Ahuachapan-Chipilapa now masked by signs of geothermal fluids, lower in resistivity (ENEL 2004).

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Based on the results of geothermal wells drilled by ENEL in the southern part of the well field, the MT model was adjusted to the well data, mainly to the temperature and mineralogy alteration. The productive reservoir corresponds to an uplifted resistive layer at depth, corresponding to the philitic and propillytic alteration facies with resistivity values ranging form 40 to 90 ohm-m. At higher values, a temperature inversion is observed.

The MT model of San Vicente geothermal area was confirmed by the first directional geothermal well SV1A. The uplifted resistive basement associated to the propyllitic reservoir was intercepted at the range depth predicted by the MT model. But there is a temperature inversion at the bottom of the well. It seems that a cooling process is active inside of the geothermal reservoir of San Vicente or the system is partially fossilized.

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