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GEOPHYSICAL CONCEPTUAL MODEL OF THE SAN VICENTE GEOTHERMAL AREA, EL SALVADOR

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ABSTRACT

For the purpose of evaluating the thermal potential of the San Vicente geothermal area, a geophysical prospect study of standard gravity, magnetic and magneto telluric (MT) measurements combined with the electromagnetic method in the time domain (TDEM) was carried out between February and April, 2005. The study area for the gravity was 250 km^2, for the MT-TDEM 80 km^2, and 40 km^2 for the magnetics. The concession area is 100 km^2. As a result, a geophysical conceptual model was created. The interpreted geophysical reservoir is distinguished by a highly resistive basement and a positive gravity anomaly with an estimated area of 12-14 km^2 and a thickness of 800-1,000 m. The seal cap is associated with a very conductive layer with resistivity values less than 10 ohm-m.

1. INTRODUCTION

In 1993, CEL carried out gravity and resistivity studies in the San Vicente geothermal area (ELC, 1995). These surveys consisted of 233 measuring points for gravity in an area of 220 km^2 and 37 vertical electric soundings (Schlumberger) in an area of 24 km^2. Most of the sounding identified in a clear manner, two geoelectric layers, a superficial resistive layer with a thickness between 250 and 450 m, and resistivity between 100-1000 ohm-m; and a conductive layer with resistivity ranging between 5 and 50 ohm-m and an estimated thickness of 600 m. Due to the limited penetration capacity of the DC electric resistivity method, very few sounding was able to identify the resistive basement, so it was not possible to know neither its location nor its extension. From the above results, geophysical prospecting studies were recommended with more penetration capacity, and with the intention of a campaign of MT soundings.

With the purpose of evaluating the thermal potential of the San Vicente geothermal area, geophysical prospecting studies were carried out from February to April, 2005. The techniques applied were the standard gravity, magnetic and magneto telluric (MT) methods combined with the electromagnetic method in the time domain (TDEM). The area covered for gravity was 250 km^2, for MT-TDEM 80 km^2, and 40 km^2 for magnetics. The concession area is 100 km^2 (Figure 1).

Qualitative analysis of the gravity and MT-TDEM data allowed delineating relevant structures with E-W and NW–SE directions. A geophysical conceptual model was prepared with site proposals and objectives for exploratory wells.

2. GRAVITY SURVEY

Around 480 gravity stations in an area of 250 km^2 were analysed. The data set was processed with a density value of 2.2 gr/cm3 (Handal, 1994), which is one of the values averaged from the analysis of three profiles Nettleton carried out in 1993. For the density selected, Bouguer and residual anomaly maps were prepared. 2D quantitative analysis was carried out over several profiles.

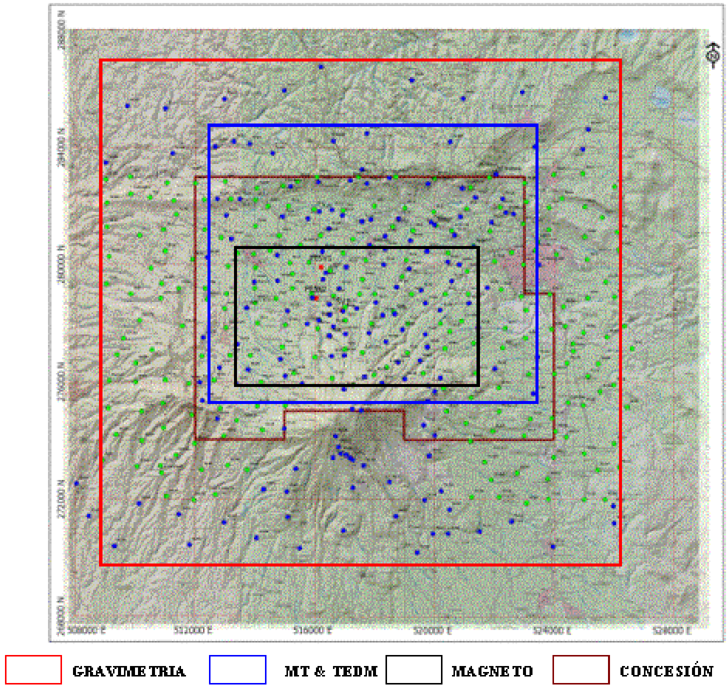

FIGURE 1: Concession and surveyed areas in San Vicente, using different geophysical methods

The Bouguer anomaly map (Figure 2), reproduces the regional structural features as the central graven with an E-W direction. The strong isocontours gradient in this direction, with values ranging from 5 to 9 milligals to the north of the Verapaz and Tepetitán towns, suggests a sudden sinking of the central graven in this area. Another structural system, suggested by the behaviour of the Bouguer anomalies, is the gradient of the isocontours observed in a NW-SE direction, which could constitute a preferential direction in the circulation pattern of geothermal fluids.

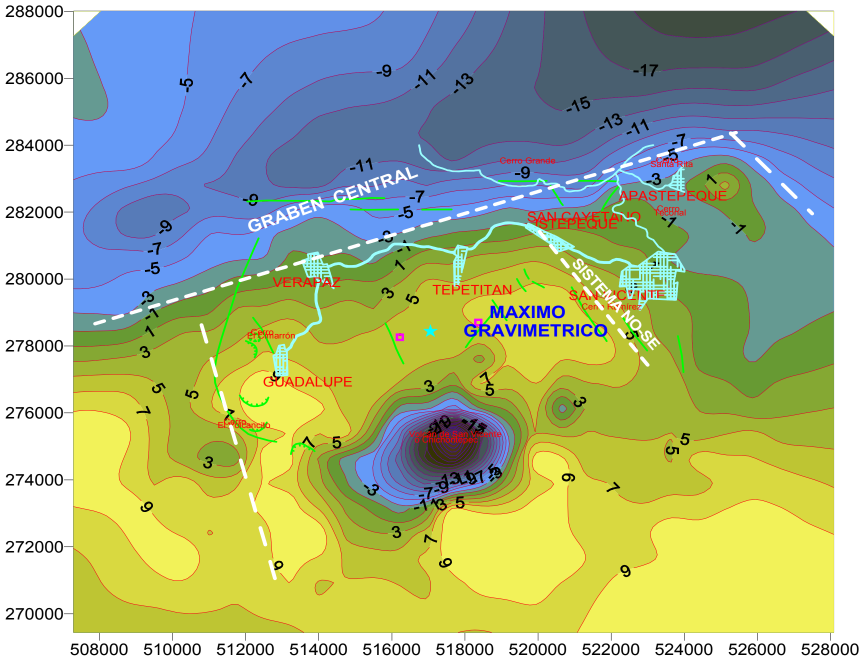

FIGURE 2: Inferred structural alignments from the Bouguer anomaly map

The residual anomaly map (Figure 3) associated to the central graven is observed clearly in the north and south edges of the study area. To the north, a fringe of negative values is observed, three kilometres wide (in the blue colour) that is interpreted as the sunken part of the central graven. In the north edge of the area, positive values of residual anomaly have been observed; again that is interpreted as the uplift part of the graven. These evidences suggest a system of HORSE-GRABEN-HORSE in the north part of the study area. The coincidence between the verified structures and the structural alignments related to the central graven from the behaviour of Bouguer residual anomalies (Geosystem, 2005) is very important.

Another structural feature that has been clearly evidenced by the Bouguer residual anomaly map is the one associated with a local system in the NW-SE direction. Some of the faults are supported by the field structural measurements carried out by LaGeo's geologist (see Figure 4).

The presence of a maximum gravimetric to the east of the SV-1 well could be reflective of the appearing of a densified stratum for sealing the pores, due to the deposit of secondary minerals of a chlorite or epidote type during the circulation of geothermal fluids. In the volcanic environment of geothermal fields, the abundant presence of these minerals is a guide's indicator to identify of the geothermal reservoir.

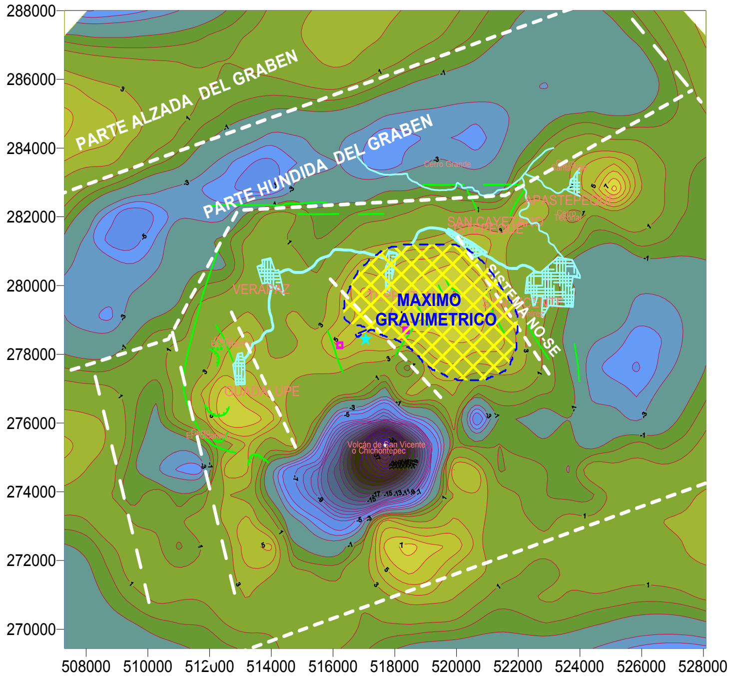

FIGURE 3: Structural limits inferred from the Bouguer residual anomaly map

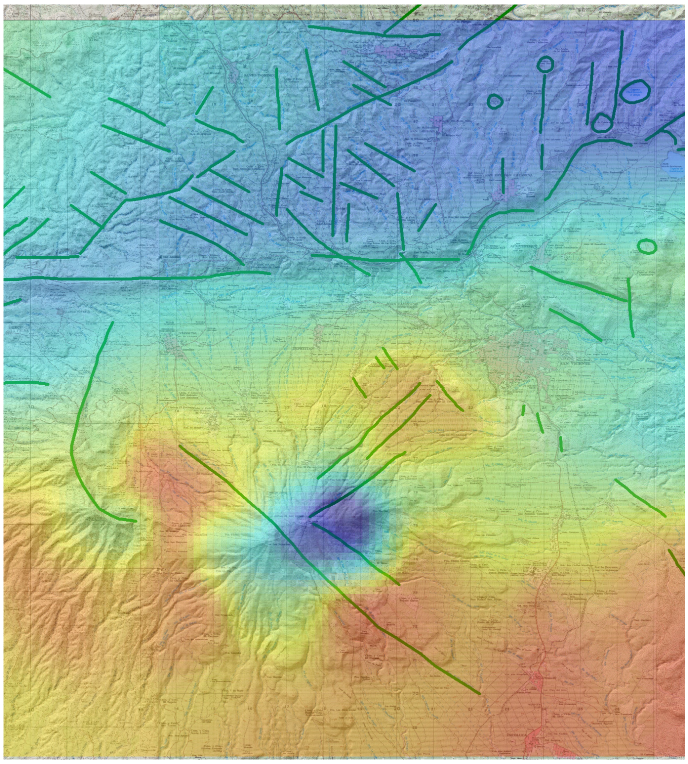

FIGURE 4: Correlation of structural lineaments and gravimetric anomalies

3. MAGNETIC SURVEY

The main objective of the magnetic study is to contribute information of the San Vicente geothermal area so as to know the relationship among the geothermal activity, and the tectonic and stratigraphy of the area by means of the interpretation of the anomalous underground rocks' magnetic properties (Escobar, 2005). Most of the rocks are not magnetic; however, certain types of rocks contain enough minerals to originate significant magnetic anomalies. The data interpretation that reflects differences in the local abundance of magnetization is especially useful to locate faults and geologic contacts (Blakely and Simpson, 1995).

The magnetic study was focused on the north flank of the Chichontepec volcano from the East of Verapaz to the West of San Vicente. About 2,000 stations were measured every 50 meters, along 21 lines each spaced at 250 m in the E-W direction.

The magnetic anomalies can be originated from a series of changes in lithology, variations in the magnetized bodies' thickness, faulting, pleats and topographical relief. A significant amount of information can leave a qualitative revision of the residual magnetic anomalies map of the entire magnetic field. In this sense, we can say that the value of the survey does not finish with the first interpretation, but rather it increases as more geology becomes known.

It is more important, at the beginning, to detect the presence of a fault or intrusive body, than to determine their form or depth. Although, in some magnetic risings, such determination cannot be made in a unique manner, the magnetic data has been useful because the intrusive is more magnetic than the underlying lava flows. The faulting creates spaces so that the warm fluids displace and therefore alter the guest rocks. The hydrothermal system's temperature and the oxygen volatility will determine the quantity of the present loadstone in the area of the faults and therefore, their magnetic response.

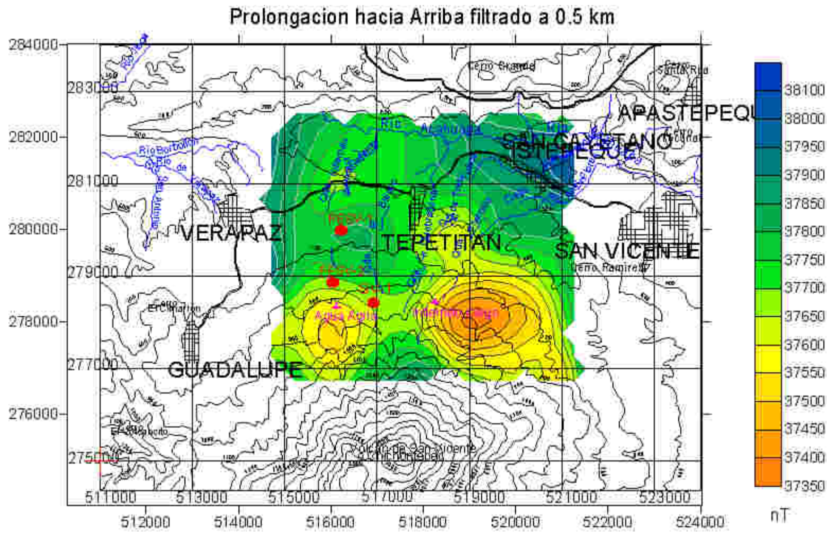

FIGURE 5: Map of magnetic anomalies, upward continuation

From the results obtained with the terrestrial magnetism, it was possible to detect two anomalies of low magnetic susceptibility coinciding with the areas where Infiernillos Ciegos and Agua Agria are located (Figure 5). These anomalies are considered to be possible candidates for intersecting promising places for a geothermal development. Among the two anomalies, an area of a relatively high magnetic susceptibility was detected. This area probably indicates the contrast of lava flows for its bigger susceptibility values and probably the high magnetism is a reminder of the present minerals. The potential areas in the 2 anomalies appear to be low due to magnetic materials, which are usually altered during the faulting, destroying the magnetism.

In the western part of the area studied (between Verapaz and the wells PESV-1 and PSEV-2), there is an area of relatively low anomaly in the north-south direction that goes from Agua Agria towards the north highlighting low depths and probably representing a discharge area. This area of unclear nature is limited to the west for values relatively larger than the susceptibility which represents borders that define the geothermal system. Additionally, in the NE part of the area an anomaly of high values of susceptibility is located, probably being the hydrothermal area limit. The Infiernillos Ciegos anomaly seems to extend even more towards the SE of the studied area. To confirm and to clarify their extension, the magnetic survey could be extended around 1 km.

4. MAGNETO TELLURIC SURVEY

A MT-TDEM survey was carried out, consisting of 58 soundings at the north flank of the Chichontepec volcano. The remote reference station was located five kilometres south-east, in the Obrajuelo area, in a place geologically stable and with minimum influence of cultural noise.

The quality of the data in most of the places was good, except for some soundings located near towns, where the influence of the domiciliary electric net was inevitable. Maps for constant elevation of values of 500, 0, -500, -1000, -1500 and -2000 m a.s.l. were created. Figure 6 shows the maps at 500, -250 and –1000 m a.s.l.

At 500 m a.s.l., a superficial resistive body is observed in the central and north part of the study area. A smaller conductive one, at 10 ohm-m appears in the southern part, where there is superficial evidence of hydrothermal alteration within the areas of Agua Agria, and Infiernillos Ciegos fumaroles being the best representatives. The west resistivity body presents values between 10 and 20 ohm-m, giving the idea that it is a conductive stratum with smaller alterations; due to its distance from the area of main hydrothermal alteration or system fluids ascent. To the southeast of Apastepeque, a small resistive spot appears with values of 10-12 ohm-m that intersects the isocontours of 6 ohm-m predominantly extended in the study area.

The maps of -250 and -1000 m a.s.l. present similar characteristics. In both of them, the small resistive island observed at sea level extends in a southeast direction covering 30% of the study area with maximum values of resistivity of 60 ohm-m down to -1000 m a.s.l. Deeper soundings have intercepted the resistive basement. Figure 6, shows the exploratory wells of the San Vicente geothermal area. They were not able to intercept the resistive basement (the blue colour area), since they are located in the western border of this basement.

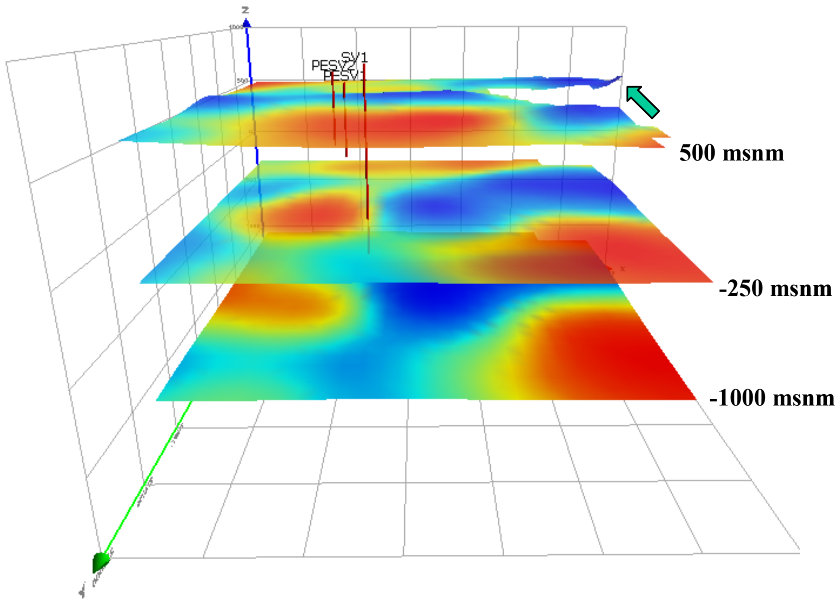

FIGURE 6: 3D view resistivity maps at constant elevation; vertical lines: SV-1 and exploratory wells.

The underground geoelectric information of the San Vicente geothermal area was analyzed in profiles from the results of the 3D modelling. Several geoelectric sections were built. The resistive behaviour in depth corresponds to a clear sequence of superficial resistive stratum, medium conductive and resistive basement, which is typical of a geothermal system in a volcanic environment.

The second stratum observed is a conductive layer with resistivity lower than 15 ohm-m, which is a reflection of an altered clay layer of argillitic and argillitic filitic type, as the mineralogy of well SV-1 confirms. Its thickness varies drastically in the E-W direction. In the part of the study area near well SV-1, it reaches values of up to 1,000 m but in the central part it decreases to 500 m, where the resistive basement reaches its highest elevation. In the N-S direction, the thickness variation is minimum.

The third stratum constitutes the resistive basement with values at 20-100 ohm-m. It presents a form of a wrapped up bell for the conductive layer, run off in the central part of the study area and it grows deeply. The transition between the conductive one and the resistive basement can be the reflection of the horizon between the argillitized area and a propilitized stratum with minerals as chlorites and epidote which temperature formation ranges from 230 to 250°C.

In a high temperature reservoir, in a volcanic environment, a resistive basement is generally associated with resistivities ranging within 10 and 60 Ohm-m. The one in this function is the fluid salinity, the rock guest's porosity and the temperature with a type of propilitic alteration.

The circulation of the geothermal fluids with lower temperature at higher levels is responsible for the intermediate layer argillitic alteration, whose resistivities vary between 1 and 10 Ohm-m. The smallest conductive layer at 10 Ohm-m depends on the type and alteration intensity, as well as of the stratum temperature. At a superficial level, a resistive stratum associated with young material prevails with little alteration, influenced by a superficial aquifer, and the content and degree of the clays alteration.

The geothermal field of Berlin presents this geoelectric behaviour at depth. The reservoir is associated with the resistive basement with values ranging from 20 to 50 Ohm-m. Most of the producing wells are located inside the resistive basement. The seal cap is associated with the conductive stratum composite for Argillític -filític clays alteration and smaller resistivity values at 10 Ohm-m. The San Vicente geothermal area presents similar features as Berlin's theoretical pattern.

Taking into account that the values of the conductive layer are lower in Berlin and that the superior roof of this layer comes closer to the surface, it can be inferred that this system has a larger hydrothermal activity and a higher temperature, as is confirmed. The temperature range estimated by the geothermometers in the case of San Vicente is from 240 to 280°C and for Berlin from 280 to 320°C.

The reservoir volume would be inside the resistive basement, if its resistivity range is considered to be between 15 and 50 Ohm-m, a thickness can be inferred between 600 and 800 m.

5. MT AND GRAVITY INTEGRATED INTERPRETATION

The quantitative interpretation of the gravity data supports the pattern suggested by the MT results. In summary, the reservoir according to MT is associated with a resistive layer in depth with values between 15 and 40 ohm-m, a thickness of 600-800 m and a probable extension of 12 km^2 are estimated (see Figure 7). The SV-1 exploratory well is located at the western flank of this resistive, and it does not reach at depth this layer interpreted as the inferred reservoir.

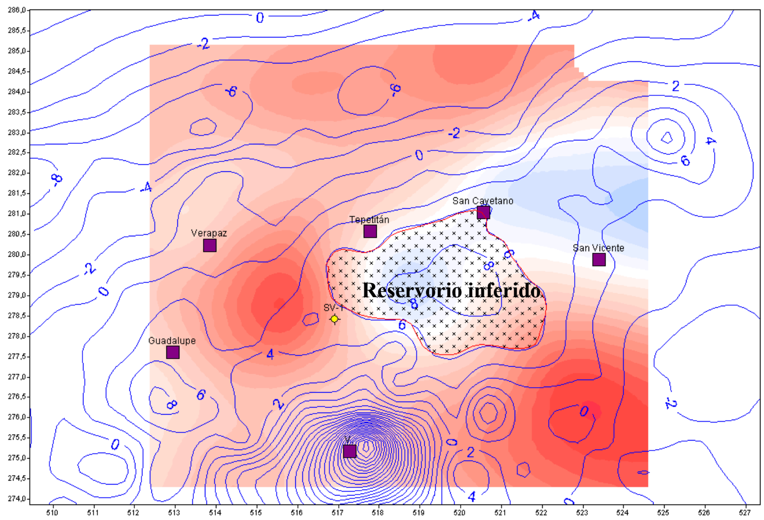

FIGURE 7: Inferred extension of the resource based on the correlation of the gravimetric maximum (contours map) and the resistive basement (colours map)

The 2D gravity modelling results are good. The error among the calculated curve (shown in green) and the interpolated field curve (shown in red) is less than 10% (Figure 8). The existence of good correlation between both models gives greater consistency to the conceptual pattern where the reservoir is associated to a maximum gravimetric and a resistive basement.

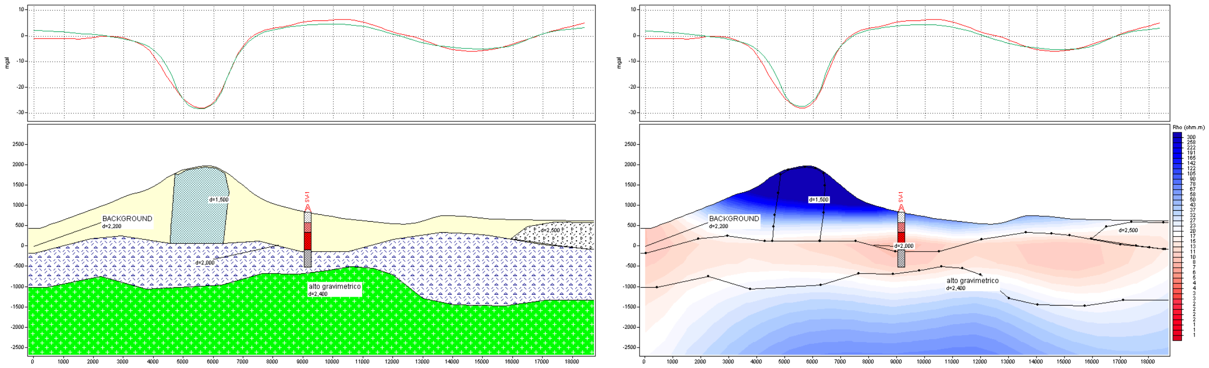

FIGURE 8: Correlation between gravity and MT models

The density of 2.2 gr/cm^3 was assigned to the superficial stratum, associated to the volcanic material inserted with clays with different alteration degrees and/or saturation of fluids coming from a shallow aquifer. A density of 2.0 gr/cm^3 was assigned to the conductive stratum, associated to altered clays (seal cap). The temperature range inferred for this layer is from 150 to 180°C. For the MT resistive basement associated with fractured andesite lavas with propilitic alteration, a density of 2.4 gr/cm^3 was assigned.

The modelling result of the gravimetric profiles evidences the maximum gravimetric run off within the south of the study area, near to the exploratory wells. The models suggest that the well SV-1 did not intercept the high gravimetric structure; and its termination was in the intermediate stratum with density of 2.0 gr/cm3 associated with the seal cap, as is shown in Figure 8. The correlation among both techniques is evidenced in the 3D image of MT results and in the superposition of a gravimetric 2D model shown in Figure 9 in which the correlation of the resistive basement with the gravimetric basement is seen; as well as the existent one between the MT conductive layer and the intermediate gravimetric stratum with an estimated density of 2.0 gr/cm^3.

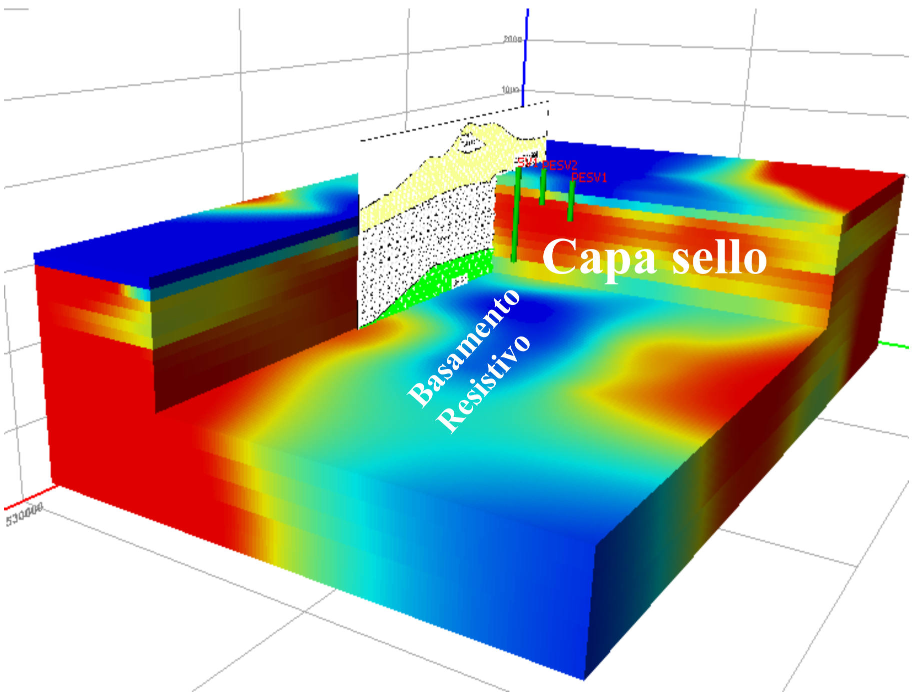

FIGURE 9: An integrated geophysical 3D model from MT and 2D gravimetric profile

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