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GRAVITY SURVEYS CONTRIBUTION TO GEOTHERMAL EXPLORATION IN EL SALVADOR: THE CASES OF BERLÍN, AHUACHAPÁN AND SAN VICENTE AREAS

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ABSTRACT

In El Salvador, the gravity method has been applied in most of the geothermal areas. The contribution of this technique regarding the understanding of the sub surface geology of the main geothermal areas in El Salvador had been really useful. The gravimetric method is a passive method. It involves the measuring of the acceleration due to the Earth's gravitational field. The variations in gravity are due to density lateral changes of the subsurface rocks in the vicinity of the measuring point. The advantage of the gravity survey is an economic method. No damage is caused to the environment, the equipment is portable and easy to use, there is no need to inject any disturbance into the ground and it provides results in a relatively short term. Gravity measurements provide information about underground rock densities, which contribute to a better understanding of the subsurface geology. The method provides information about the regional and local structural geological fault systems. The results of this method's application for Berlín, Ahuachapán and San Vicente areas are presented in this paper.

1. INTRODUCTION

The gravity method is passive, that involves the measuring of the acceleration due to the Earth's gravitational field. The variations in gravity are due to density lateral changes of the subsurface rocks in the vicinity of the measuring point. The equipment used to measure the variations in the Earth's gravitational field is called a gravimeter. The gravity values are expressed in milligals (mGal), a unit of acceleration where 1 Gal equals 1 cm/sec^2. This technique has several important advantages such as: the economic method, as it provides results within a short term, it causes no damage to the environment, the equipment is portable and easy to use, and there is no need to inject current into the ground.

Gravity measurements provide information regarding underground rock densities, which contribute to a better understanding of the subsurface geology. Gravity Surveys are used for modelling the Earth's crustal structure, for locating bedrock fractures, buried topographic valleys, subsurface voids such as abandoned mines, caverns, and sinkholes, and others. Due to faults commonly juxtaposing rocks of differing densities; the gravity method is an excellent exploration choice for identifying the structure setting of the geothermal areas (Figure 1).

In order to obtain information about the sub surface density from the gravity measurement, it is necessary to make several corrections to the measured value. The final corrected values of the gravity anomaly, is called Bouguer anomaly and is given by:

$gc = gobs - gn + 0.3086h - 0.04193r\ h + TC$
(in mgal) (1)

where Gobs: Gravity readings observed at each gravity station after corrections have been applied for instrument drift and earth tides.
0.3086h: The gravity variations caused by elevation differences in the observation locations.
0.04193r h: Correction from the excess mass material between the station and sea level.
gn: normal reference gravity according to an international formula.
TC: The terrain correction accounts for variations in the observed gravitational values

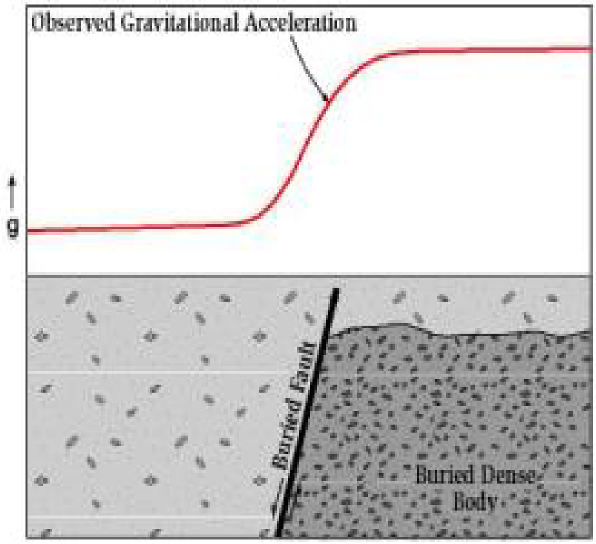

FIGURE 1: Gravity anomaly and a buried fault

Assuming these corrections have accurately accounted for the variations in gravitational acceleration, the Corrected Bouguer Gravity can be assumed to be caused by variation density beneath the observation point.

Some possible causes of density contrast and gravity anomalies in a geothermal field are: an increase of stratum density due to the mineral deposition during the geothermal fluid path; stratum alteration, faults and dykes, intrusive rock, porosity variations, and others. Most of the high temperature geothermal systems over volcanic arcs in a subduction zone setting are associated with heat transfer from a deep intrusion, which occurs at higher levels in the upper brittle crust. Culling intrusions are usually very dense bodies. Occasionally, higher gravity intrusions can be recognized by a gravity survey (Hochstein and Soenkono, 1994).

In El Salvador the gravity methods had been applied in most of the geothermal areas. This paper shows the contribution of this technique in the understanding of the sub surface of the main geothermal area in El Salvador.

2. THE CASE OF BERLIN GEOTHERMAL FIELD

Gravity survey is one of the most useful exploration tools applied in the Berlin geothermal field, its result has contributed to the better understanding of the conceptual model of this geothermal system.
More than 400 gravity stations have been measured in two different surveys carried out by CEL 1994 and LAGEO in 2001 and 2005. The data was processed using a density value of 2.3 gr/cm^3, a value derived from the average data measured from the well cores (Larios, 1987).

Bouguer and residual Bouguer anomaly gravity maps as well as a first and second horizontal derivative map had been created for this density value. The residual anomaly map is drafted eliminating the effect of the regional morphology over the area of study. As a result, the local structural effects are more evident, and the regional structural features are enlarged.

The Berlin residual anomaly map shows features associated with important geological structures described as follows (Figure 2). The west and east field limits are featured by the presence of a gravity gradient from positive and negative anomaly values. These boundaries are in good correlation with Guallinac and Las Crucitas faults. This combination of positive and negative residual anomalies results from the combined effect of numerous extrusion and piroclastic flows with different density. A negative gravity anomaly appears over the Tecapa volcanic complex, probably due to the lower density material filling subsurface fractures or the vapour saturation. The main geothermal reservoir area is located over a positive gravity anomaly. The density increase of this area could be associated with the propilitization due to the mineral deposition during the geothermal fluid circulation, and consequently the reduction of porosity.

The quantitative analysis performed along profiles provides information about the subsurface beneath the geothermal field. Figure 3 shows a 2.5 D analysis profile located in a NW - SE direction. A good fitting was achieved between the calculated and measured curves. The seal cap is associated with a stratum of 2.1 gr/cm^3 density, which is represented by the abundant presence of clay alteration minerals with a relatively high alteration degree. The reservoir cap presents a 2.45 gr/cm^3 density value. This cap is lifted in the field's southern part, in the production well zone. This layer is associated with fractured lava filled by geothermal fluid. The basement density of 2.6 gr/cm^3 is estimated. This is related to tertiary rock. A good correlation was observed among the magnetoteluric (MT) distribution layers. The conductive layer (lower than 10 ohm-m) is associated with the reservoir seal cap, and it corresponds to the lower density stratum. The productive reservoir distinguished by its resistivity values in between 15 and 60 ohm-m corresponds to the top of the resistivity basement. The increase of the resistivity is associated with the reduction of porosity.

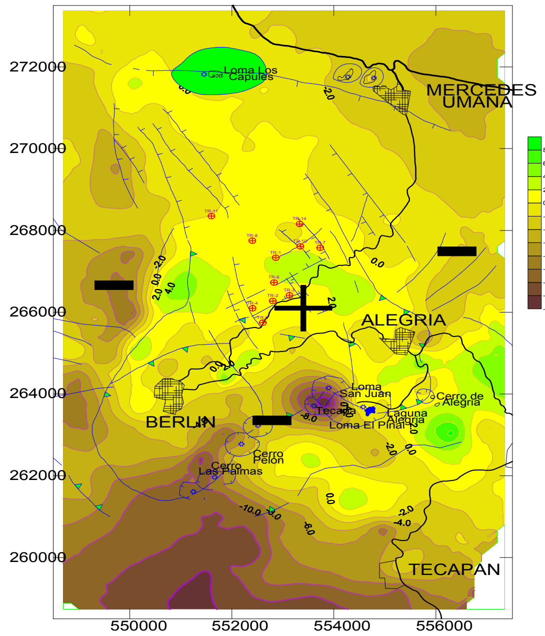

FIGURE 2: Berlin residual gravity map

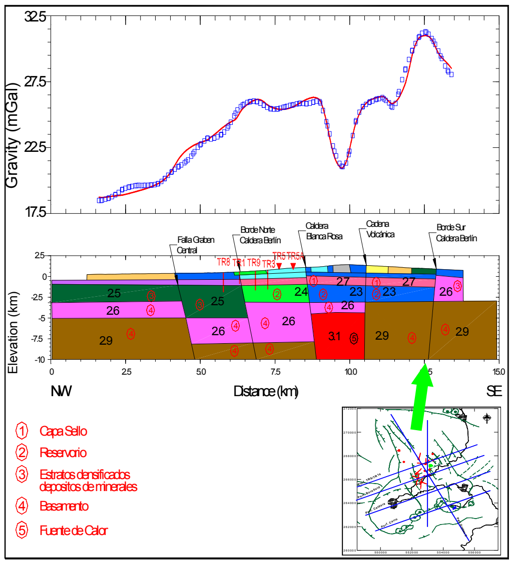

FIGURE 3: 2.5D model of N-S profile analysis (CEL, 2000)

3. THE CASE OF SAN VICENTE GEOTHERMAL AREA

The gravity survey carried out in the San Vicente Geothermal area provided useful information for the understanding of the conceptual model of the geothermal field. The regional and local structures were delineated based on the anomaly gravity maps created from the gravity data. The results of MT and gravity combination allowed the delineation of the producer reservoir geometry.

Two main gravity surveys were carried out by CEL in 1993 and by LAGEO at the beginning of 2005. A total of 480 gravity stations were measured in both surveys. The equipment used consisted of two analogical gravity meters: Worden (by CEL) and a digital gravity meter Scintrex, model CG-3 (LAGEO). The density value 2.2 gr/cm^3 was used for the preparation of gravity anomaly maps, taken from the average values of three Nettleton profile analyses performed by CEL (ELC, 1993).

For the selected density, Bouguer, regional and residual anomaly maps were prepared. A 2D analysis over several gravity profiles combined with an MT resistivity layer sequence was carried out using the Wing Link Software. The Bouguer anomaly map shows evidence for the regional influence of the E-W El Salvador central graven. The high gradient of gravity iso-contours are aligned in this direction. Local NW-SE geological structures are lightly observed in this anomaly map; those play an important roll in the geothermal pattern fluid circulation (Figure 4a).

A better resolution of the mentioned structures is observed in the residual Bouguer gravity anomaly map (Figure 4b). The E-W graven faults mapped by LaGeo's geologists present a good correlation with the gravity contrast anomaly. New and better defined NW-SE structures are observed in this residual anomaly map. This result allows having a better image of the structural map of the San Vicente geothermal area.

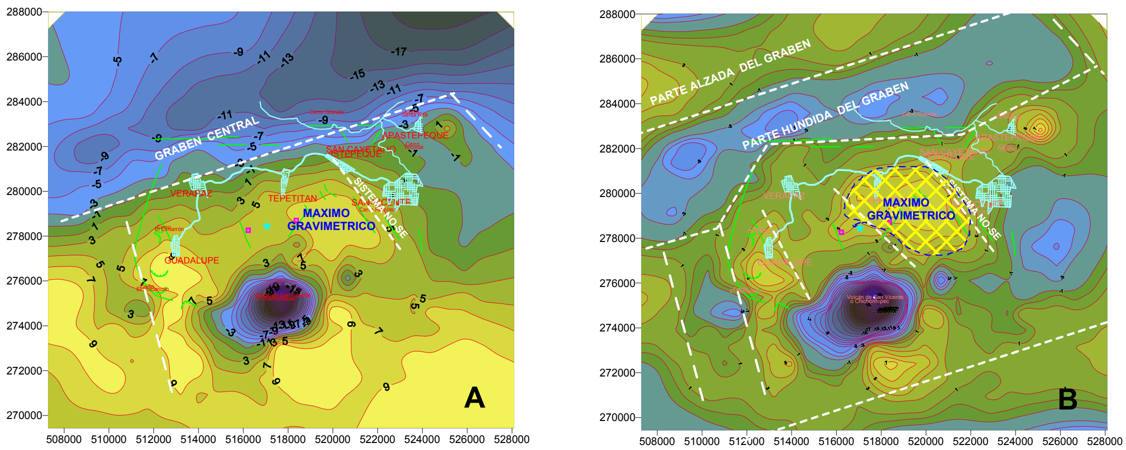

FIGURE 4: a) Bouguer and b) Residual Bouguer anomaly maps of the San Vicente geothermal area

A positive gravity anomaly body at depth is observed to the northeast of SV-1 well. This is congruent with the high resistivity core observed in the MT map at –250 m s.n.m. (Figure 5), which is associated to the propilithic productive reservoir (LaGeo, 2005). Two dimensional interpretations of the gravity data have been performed along with several profiles. The initial guess was created based on the MT resistivity contrast layer. The correlation between both methods along the profiles is as follows:

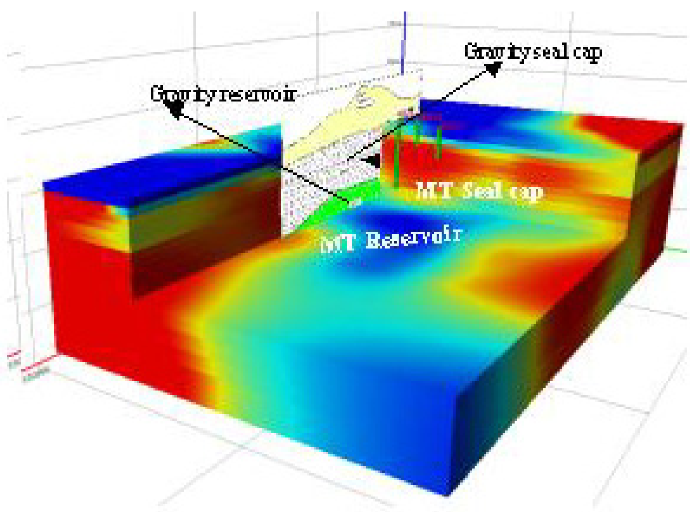

FIGURE 5: Correlation of 2D gravity model and 3D MT resistivity anomaly

The conductive layer associated with altered clays corresponds to a 2.0 gr/cm^3 gravity density layer.

The range associated with temperature inferred runs from 150 to 180°C. The MT resistivity basement associated with fractured andesitic lavas with propylitic alteration corresponds to a 2.4 gr/cm^3 density gravity layer. It is believed that this layer represents the producer of the high temperature reservoir (Figure 5).

4. THE CASE OF THE AHUACHAPAN GEOTHERMAL FIELD

The gravity data set consists of 330 stations in a total area of 300 km^2. This data was gathered by LaGeo in two different surveys, 2001 and 2003, using a digital gravity meter Scintrex model CG-3. The data was processed for a density of 2.2 grc/cm^3 selected from the density distribution base measured on cores coming from the Ahuachapan geothermal wells (ENEL, 2004). For the selected density, Bouguer, regional and residual anomaly maps were prepared. A 2D analysis over several gravity profiles combined with an MT resistivity layer sequence was carried out using the Wing Link Software.

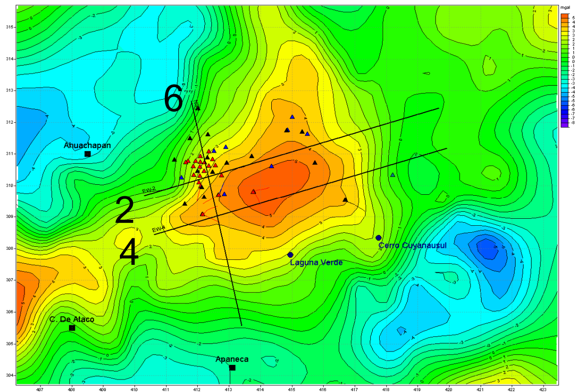

FIGURE 6: Residual anomaly map of the Ahuachapán geothermal area (ENEL 2004)

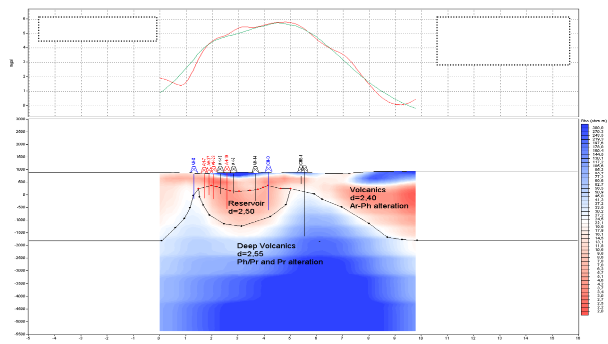

FIGURE 7: Correlation of the 2D gravity model and the 3D MT resistivity anomaly

The residual Bouguer map shows that an Ah-core field is located on the NW limit of a relatively shallow gravimetric maximum with an ENE-WSW trend, which belongs to the regional structural trend observed in this area (Figure 6). A secondary gravity NNW-SSE trend is identified following the Chipilapa wells towards the north, which could be associated with a local geological structural system.

The positive anomaly distinguishing the Ahuachapán geothermal field could be related to a shallow 3D dense body, which is not connected to a particular structure, but associated with the propylitization of volcanic rocks altered as a consequence of the geothermal system's strong thermal activity. The 2D gravity model was prepared using the 3D MT background and the information of the hydrothermal alteration (Figure 7). The final adjustment congruent with MT and gravity data was:

- A shallow low density body (2.35 gr/cm^3) associated with the argillic, and argillic-pyllytic altered rocks.
- An intermediate 2.45-2.5 gr/cm^3 density body related to the propilitized reservoir layer in accordance with a deep MT conductive cap.
- A deep dense body of 2.55 g/cm^3 with a shape consistent with the deep MT resistor and propylitic facies top.

This correlation is similar to the one observed in the San Vicente and Berlín geothermal areas among the MT resistive basement, the propilitized zone and the maximum gravimetric body. It can be considered an important tool in geothermal exploration and to fix the limits of known andesitic geothermal fields (ENEL, 2004).

5. CONCLUSIONS

In El Salvador, the gravity method had been applied in most of the geothermal areas. The contribution of this technique to the sub surface geology understanding of the main geothermal areas in El Salvador was really useful.

The Bouguer anomaly map provides information about the regional geological structure system. A better resolution of the local structural system faults is obtained by the residual Bouguer anomaly map. In some cases, such as in San Vicente, this local fault system is not seen at the surface, because it was buried by volcanic materials from recent geological events.

The combined analysis among 2D gravity and 3D MT resistivity layer models and the mineralogical data from the geothermal wells is an important tool for geothermal exploration and for fixing the limits of known andesitic geothermal fields.

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