# INTERPRETATION OF GEOPHYSICAL DATA FROM THE SAN VICENTE GEOTHERMAL PROSPECT, EL SALVADOR

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**Abstract**

*Sati Vicente Geothermal Prospect is located at the Eastern part of El Salvador. Pleistocene and Holocene Andesite Basalt pyroclastics and lavas are widespread all area around. Emanations of gases and deposits of clay minerals are present on two hydrothermal manifestation zones on the north slope of Chichotitepec Volcano. Acid sulfate-chloride waters discharge through the manifestations and alkali sodium-bicarbonate waters have been identijied in the lower parts of the area. A temperature of 250 °C measured in a well 1346 m deep (SV-I) corresponds with the presence of epidote hydrothermal mineral and is consistent with gas geothermometry.*

*Residual gravity anomaly indicates the North and South upthrow blocks of a graben, WE direction, 8 Km wide and a maximum depth of about 800 m. A low density body is indicated by the residual gravity data underneath the Chichontepec volcano and is inferred to be high porosity concealed products of Pleistocene volcanic events. Two outflows, to the North and the East of the hydrothermal manifestations, are indicated by the resistivity traversing data. 1D Interpretation of the resistivity sounding data show that the vertical resistivity structure of this area consists of mostly 3 layers. Due to a masking effect of a thick low resistivity stratum, a deep hot reservoir intersected by the geothermal well SV-1 does not show any low resistivity signal.*

## 1.0 INTRODUCTION

The San Vicente Geothermal Prospect is located about 60 Km to the East of San Salvador, the capital city of El Salvador (Fig. 1). Exploration studies carried out in the eastern zone of El Salvador between 1965 and 1978, revealed the San Vicente geothermal area (Fig. 1). Two thermal zones were suggested as targets of detailed surveys. The first one, a priority zone, is situated about 4 Km to the North of Chichontepec crater; the second one lies 2 Km to the South of San Vicente township (Jacobo, 1992). Two shallow and one deep exploratory well were drilled in the priority zone between 1978 and 1980. 230 °C hot chlorine water was found at 1346 m depth. It is estimated the prospect could generate between 60 and 170 MWe (CEL, 1988).

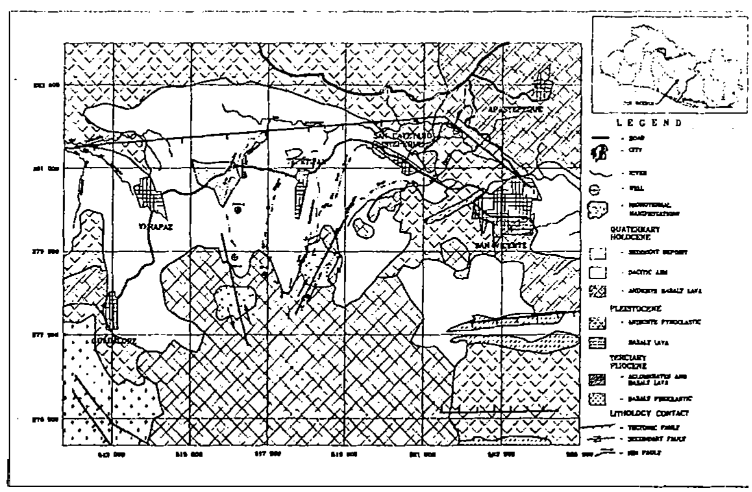



*Fig. 1. Location and Geological siting of the San Vicente Area*

DC resistivity, gravity and geochemical detailed surveys were carried out from November 1992 until April 1993. Those were realized immediately after 12 years long civil conflict had finished. The purpose of this paper is to interpret the geophysical data, to delineate a preliminary probable subsurface structure and to assess the vertical and horizontal resistivity boundaries of the San Vicente Geothermal Prospect in order to suggest a more limited zone where feasibility studies may be required.

## 2.0 GEOLOGICAL SETTING

A Central graben, called Central Fosse, was formed in whole of Central America during the early Pleistocene epoch due to the subduction of the Cocos plate under the Caribbean plate. That structure crosses El Salvador with a WNW-ESE strike. San Vicente area is situated at the East of the graben (CEL,1989). Geological exploration of the San Vicente field (Fig. 1) was included in the earlier study of the eastern part of El Salvador. Structurally the area is controlled by the faults of the Central Fosse whose scarp can be seen at the northern edge of the area. Because of an overlaying volcanic deposition it can not, however, be seen at the southern edge. At the east edge of the same area a **NE-SW** system is present. To the **NE** of the main volcano, in correspondence with a NW-SE system, the surroundings of the Ramirez and Candelaria Hills are associated with a small horst. Two secondary fractures with NNE and NNW strike also are also evident on the north slope of the main volcano. It has been thought that a ring fault, on the West of this volcano, could be a testimony of a Pliocene caldera. (Meyer Abich, 1956).

The principal 2173 masl Chichontepec Volcano was formed inside of that old caldera. It consists of two Holocene craters. Pleistocene basalt lavas and andesite pyroclastics are widespread over a Tertiary basement formed by agglomerates, tuffs and andesite-basalt lavas. Pliocene rocks are exposed on the old Cimarron volcano, Candelaria hill and remain on the upthrow of the graben. The downthrow of the graben has been filled by andesite-basalt lavas of the Holocene epoch, which are visible over the flanks of the volcano. A thin layer of dacite ash overlays the above formations. The ash is at least 1700 years old and it came from a near caldera formation (called Ilopango) or probably from a nearest pit crater.

## 3.0 SURFACE THERMAL ACTIVITIES

San Francisco Agua Agria (agria means acid) and Infiernillos Ciegos (it means sealed hell) surface hydrothermal inanifestations are located about 840 m asl on the north slope of the volcano. They are a result of secondary fracturing. They are 2 Km apart and each one has an area of around 0.1km$^2$. They are mainly characterised by acid (pH=3) hot springs that release carbon dioxide, steaming ground, emanations of sulphur gases. The host andesite rocks have been intensely altered to clay minerals. Both manifestations present fumaroles that are more intense in San Francisco Agua Agria than Infiernillos Ciegos. The springs and gases of the fumaroles have temperatures of about 100 °C. Warm thermal springs (36°C) are widespread along the Acahuapa, San Cristobal and Amapupulta Rivers at the N and S of the San Vicente township .

## 4.0 DRILL HOLES

During 1978-1980 three exploratory wells were drilled to a maximum depth of about 1346 m. They can be divided into three stratigraphic units. The shallow unit consists of andesite-basalt lava flows with thin interlaying pyroclastic rocks. Its thickness is variable: 375, 210 & 275 m in PSV-1, PSV-2 and SV-1 wells, respectively. The 690-700 m thick intermediate unit is shown completely only in the SV-1 well and it is formed mainly by agglomerate, lithic tuff and lahar interlayered with fragments of andesite-basalt lava. In the VS-1 well only, the top of the deeper unit has been identified as basalt lavas and it can be associated with the Tertiary basement. A permeable zone was found between -260 and -506 masl. It could be qualified as an intermediate permeability due to pyrite, quartz and calcite deposition. This horizon belongs to the deeper stratigraphic unit or the Tertiary basement. Clay minerals are present along the whole profile and reveal acid fluids. Boiling occurs in the well and due to carbon dioxide loss, calcite is deposited. Calcite should be less in the production zone because of the low epidote deposition. In the above zone calcite increases as a result of the in-flowing meteoric waters that are heated by the rising geothermal fluids.

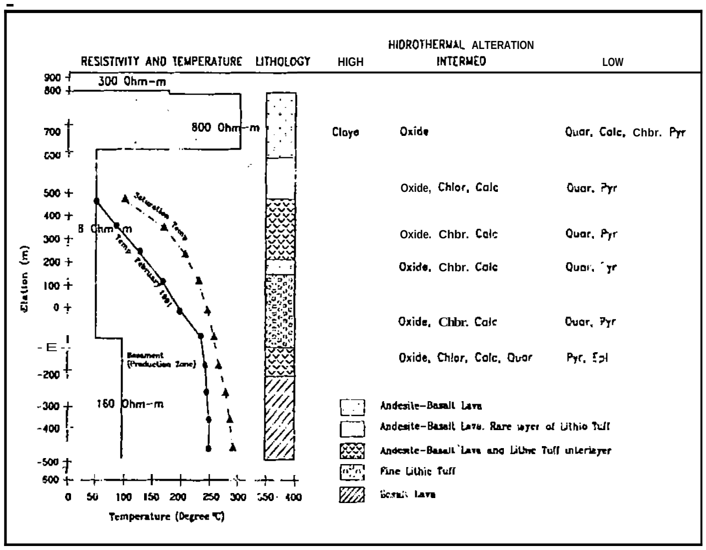
## 5.0 GEOCHEMICAL RESULTS

Water samples from 58 thermal and cool sources, 26 artesian wells, *2* from SV-I well and gas's samples of the main hydrothermal manifestations were geochemically analyzed. They have been classified as following: a)Alkali Bicarbonate, b) Sodium-Bicarbonate, c) Alkali-Sulphate and d) Alkali-Chlorine waters.

Triangular Na-K-Mg diagrams indicate that deeper NaCl waters of the SV-I well show partial equilibrium with 260-280 °C. Acid sulphate waters and mainly $CO_2$, $H_2$ and $H_2S$ gases discharge through thermal manifestations. (CEL, 1993). Gas's geothermometry has indicated 252-310 °C in the geothermal reservoir that corresponds to the last logging temperature (Fig 2). Due to dilution and mixing through the path of condensate gases, warm thermal activity is found in the North (Acahuapa River) and the East (Amapupulta and San Cristobal Rivers) lower parts of the San Vicente area.

## 6.0 RESISTIVITY DATA.

drilling target to be developed under future feasibility studies. The soundings shown field K or KQ curves type. During 1D interpretaticn., equivalence problems were found in **ail** soundings. However, that *was* solved by fixing the known geological parameters in the setting SV-1 soundings. From Figure 2, the depth of the hot production zone roughly corresponds to the top of that high electrical resistivity basement. It will be assume that the reservoir is inside the tertiary basement and that it cannot be detected **as** a signal of low resistivity because of the "masking effect" of upper low resistivity layer (Akiyoshi, and Tagomori. 1990). The conductor layer (8 Ohm-m), which consist of andesite-basalt lavas and lithic tuffs, has been




layer is situated approximately between 600 and -60 masl. The cold 200 m thick layer, at shallow level, has a high resistivity (800 Ohm-m) because thermal alteration here is probably less intense. The thin upper layer is included as part of this layer.

### 6.1. LATERALRESISTIVITY

Apparent resistivity isocontours have been made for AB/2 = 500, 1000 and 1500 m (Figures do not show map for AB/2=1000m). If the boundary of low resistivity area is assumed to be the 20 **Ohm-m** contour, all of those maps reveal **similar** low resistivity distributions ***of*** either belt or ellipse shape. For AB/2=500 m two anomaly zones can be determined, both concentrated at the San

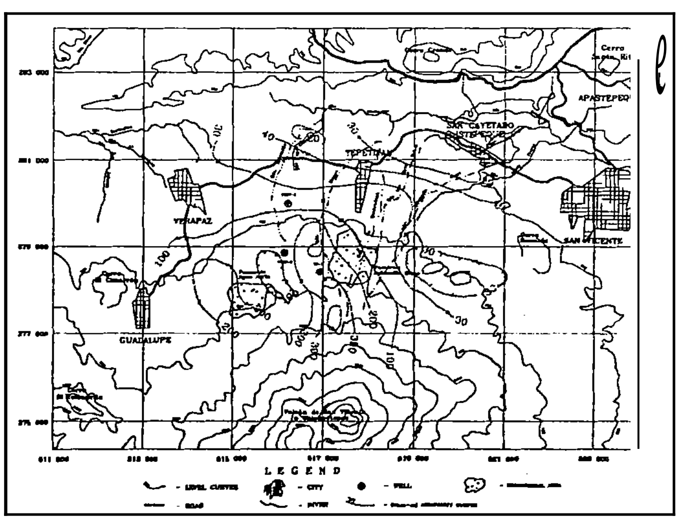



***Figure 3. Apparent resistivity isocontoursfor AB/2=500 m***

Francisco Agua Agria and Infiernillos Ciegos surface acidic alterations(Fig. 3). They are separated by a very high resistivity contour. This lies among the secondary faults and is widespread over the complementary area. For AB/2 =1500 m the low anomalies appear again surrounding those thermal activities. The one close to Infiernillos Ciegos extends to the SE. In Agua Agria the low anomaly is widespread to the North up to the surroundings of Acahuapa River. It should be noted again that the lowest values of resistivity in both thermal activities, are separated by high resistivity isocountours. A structure of outflow over steeper terrain can be inferred at San Vicente, which is discharging to the N between Verapaz and Tepetitan Village and to the S of Ramirez Hill. Both discharges are probably in correspondence with the warm mixing shallow waters along the Acahuapa, San Cristobal and Amapupulta Rivers that have been already pointed by the geochemical study (Fig. **4).**

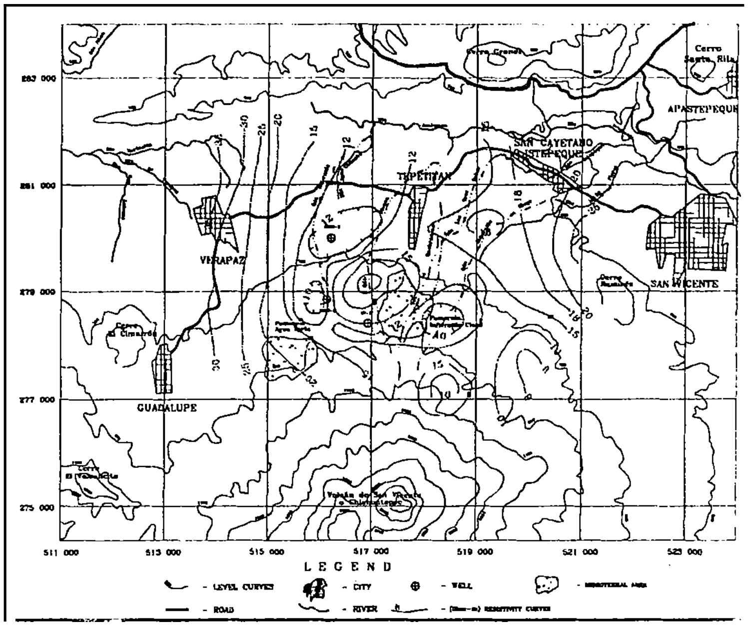



***Fig 4.** Apparent resistivity isocontours for AB/2=1500 m.*

**7.0 GRAVITY DATA**

Gravity measurements were conducted on 233 stations uniformly distributed. They cover approximately 216 $Km^2$ area at **San** Vicente Prospect (Figure 5). As a result of the last civil conflict, measurements could not be made to the South of the Chichontepec crater. The aim of the gravity survey is ***to*** define the geological structures related to any geothermal system in the area. Topographic correction was carried out by Hammer method for a distance up to 20 Km. The elevations for radius 15 and 50 m were estimated in the field; those between 50 m and 4.5 Km were determined from a topographic map scale 1:50000. For radius between ***4.5*** and 20 Km the elevations were digitalized on an area of 60X60 $Km^2$ . A set of topographic maps, scale 1:50000, was used to do this work. In this case an unit grid 500 m side was used (Dobrin, and Savit. 1988. Parasnis. 1986). By using a 2.0 $g/cm^3$ density and computer programs a standard topographic correction was calculated. The latitude correction was computed using the international formula of 1967 (Dobrin and Savit. 1988). An error of 50 m latitude (1.5 sec) is taken into account to estimated the accuracy of latitude correction. Bouguer anomalies were computed using 1.8, 2.0, 2.2, 2.4 and $2.6X10^3 Kg/m^3$ (Fig. *5).* The uncertainty in the Bouguer anomaly values can be estimated by assuming that the errors are random type. For the accuracy of 0.3 m in elevation, which affects the Free Air and Plate reductions (elevation factor), a maximum error of 0.07 mgals is expected if the density is fixed to the minimum $1.8X10^3 Kg/m^3$. An error of maximum 0.08 mgal is expected in the latitude correction (1.5 sec accuracy of position). Assuming 0.2 mgal accuracy in each gravity loop of two hours and by 0.2 mgal accuracy in topographic correction, the maximum expected total error in the Bouguer anomaly values should be 0.4 mgal. Because density data from samples are not available, terrain density **was** estimated by using the Nettleton

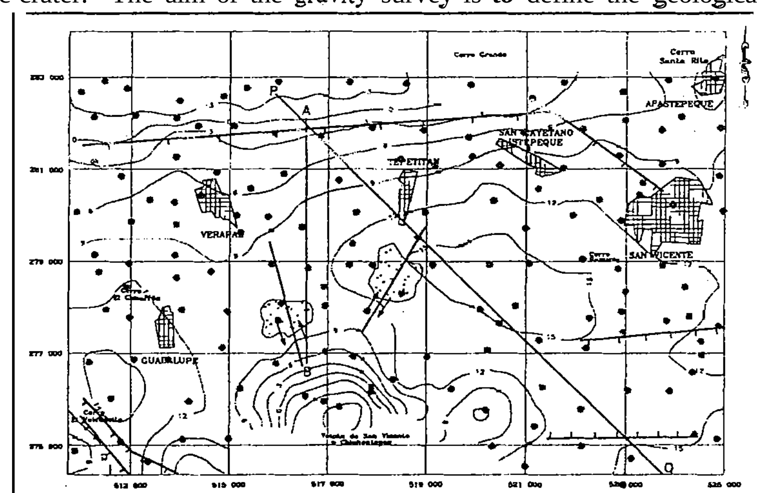



***Figure 5.** Site stations (dot)and Bouguer anomaly isocontours (d=2.60g/cm$^3$)*

density was estimated by using the Nettleton procedure along some profiles. These lied over pyroclastic and Tertiary rocks at the N and **NE** parts of the area. From Nettleton a means shallow densities were: a) Pyroclastic rocks: 1.8-2.0 $gr/cm^3$ density for the rocks in the volcano and the northern part of the study area. b) Basal-andesite lavas: 2.3-2.6 $g/cm^3$ density for rocks distributed in the surroundings of the Tepetitan, Verapaz and San Vicente Cities. Due to mostly rocks in the area of study are andesite-basalt and the above results, Bouguer anomaly map at $2.6 g/m^3$ density has been selected for the interpretation procedure (Fig. 5). It will assume that the most representative density for the Pliocene rocks is $2.6 \times 10^3$ $Kg/m^3$.

### 7.1. REGIONAL AND RESIDUAL GRAVITY ANOMALIES.

Because local variations are of interest in this small scale survey, a trend analysis has been carried out in order to separate the regional effects of long wave length from the Bouguer anomalies and to obtain a residual gravity anomalies of short wave length. Figure 5 shows the map of absolute Bouguer anomalies calculated using $2.6 g/m^3$ terrain density. The smooth, almost constant anomalies at the northern edge, indicate a regional trend. Traces of this trend are noted at the SW and SE part of the map. Steeper anomalies in the central area are associated with the residual anomalies. **A** computer programs(Soengkono,S. Personal communication) was used to determine a low order polynomial equation representing the regional anomaly (in mgal) i.e,

$$Ag_{regional} = ax^2+by^2+cxy+dy+ex+f \qquad (1)$$

where a=-2.62E-9, b= -1.22E-7, c=4.65E-9, d=0.35E-2, e=1.62E-3, f=-9.04E3. X and y are East and North coordinates in meter, respectively.

### 7.2. QUALITATIVE INTERPRETATION OF THE RESIDUAL ANOMALY

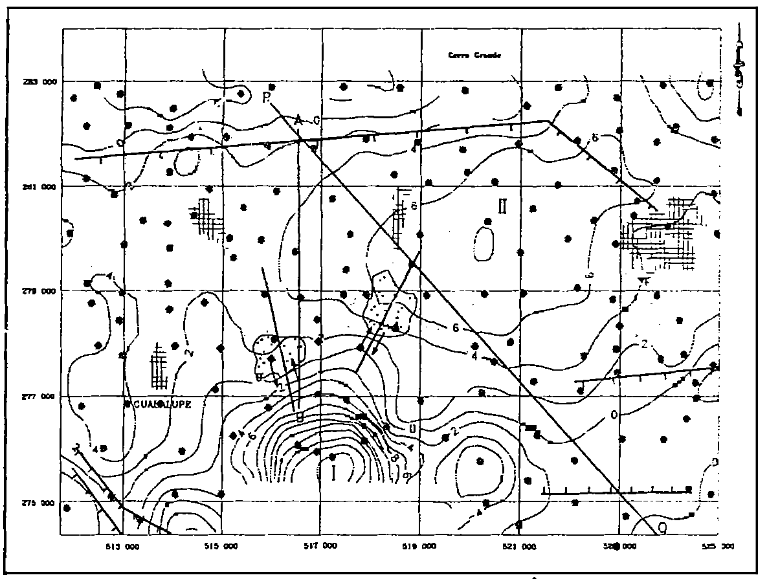


*Figure 6. Residual Bouguer anomaly ($d=2.6 g/cm^3$)*

Two main anomalies can be observed in the residual gravity map shown in Figure 6. The anomalies are the negative anomaly I and the positive anomaly II. The negative anomaly I to the South of the principal hydrothermal manifestations are probably associated with deep rocks that are less dense than the Tertiary basement. These rocks, probably consist of less consolidated basalt 'and/or andesite pyroclastics, underlie the Holocene andesite-basalt lavas of Chichontepec Volcano that have a greater density. To the West of the Volcano negative anomaly is noted over Pliocene scorias. It is possible that the scoria are widespread underneath andesite-basalt lava flows of the Chichontepec Volcano. Acidic fluids are discharging 2 Km to the North of the gravity low and suggest that part of negative anomaly could also be associated with "leaching" process. The positive anomaly II lies between San Vicente City and the Chichontepec Volcano. It indicates the presence of material denser than the basement. Here the depression due to a graben has been infilled by andesite-basalt lava flows which overlie the older volcanic eruption products. This anomaly extends to the West where a local WE gradient of about +0S mgal/Km may indicate reduction in the density of the infilling rocks. At the **SE** of the area of study, a low gradient (about +0S mgal/Km) in the SE direction is probably associated with the dip of shallow basement underlaying the Pleistocene andesite pyroclastics. In this area the basement could be associated with the south upthrow block of the **NE** striking Pleistocene Central Fosse. Along the northern edge of the map a steeper negative gradient (around -4 mgal/Km) is obseved in the N direction. It corresponds to the scarp (Fig 1) **of the** northern upthrow block of the **NE** striking graben. This graben is approximately 8 Km wide in the whole San Vicente area. To the West of the study area the small values of the residual anomaly probably reflect the Tertiary rocks of almost homogenous density. The negative gravity anomaly I could also be interpreted to indicate the occurrence of a system of buried andesitic and basaltic cones. This system probably was formed during the beginning of the Quaternary period, contemporary to the graben formation. Coarse fragments of scoria found in the west edge of this anomaly support basaltic composition of the inferred cones. A portion of andesite pyroclastics unit, widespread in the edges the Chichontepec Volcano, are the indication of the andesitic composition. As can be seen in the residual map (Fig. 6), the negative anomaly I splits into three almost circular areas, which probably correspond to the location of those inferred concealed volcanoes. In spite of gravity measurement was not taken to the South of the Chichontepec crater, this volcanic complex appears to be situated along the southern margin of the Central graben. The size of this complex is roughly 10 Km in the WE and 4 Km in the NS directions. Early geological studies have suggested an association of two circular walls, on the West of the Chichontepec Volcano, with ring faults of a probably caldera of Tertiary origin. In this gravity survey, the western area of the gravity anomaly I appear to be located in the surroundings of the circular walls (see Figs. 1 and 6). Their scarps may also be cause of the negative anomaly. The circular walls may probably be not a result of a calderic event, but perhaps due to weathering or erosion process, which possibly have occurred on the inferred volcanic complex.

### 7.3. 2-D GRAVITY MODELLING.

than the basement cause negative anomalies.

*Table I. Inferred Values of **Rock** densities.*

| Rock Type | Age (Epoch) | Density ($g/cm^3$) |
|---|---|---|
| Basalt-andesite pyroclastics (scoria-ash) | Pliocene Pleistocene | 2.00-2.40 |
| Basalt-andesite lavas | Pleistocene Holocene | 2.80-2.90 |
| Lava and Tuff | Pleistocene | 2.45-2.75 |
| Basalt lavas agglomerates (Basement) | Tertiary | 2.60 |

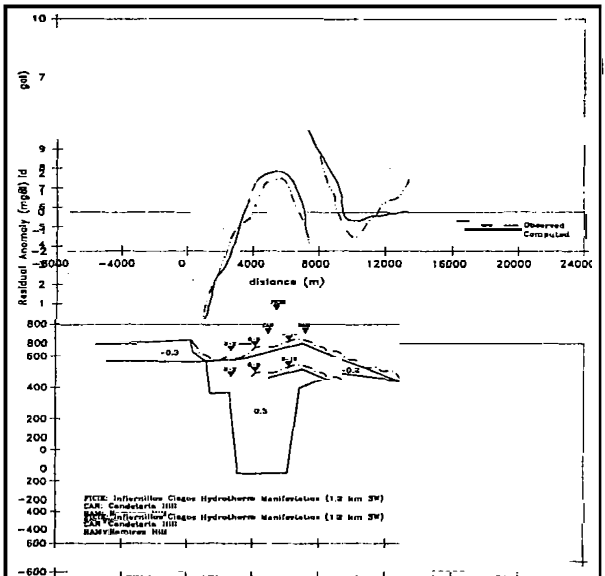


*Fig. 7. 2D interpretation of residual anomaly along profile PQ.*

The model along the profile PQ (Fig 7) shows a gross structure of the Central graben, which consists of a set of normal faults in the Tertiary basement. The graben, about 8 Km wide at the surface, becomes narrower (roughly 3 Km wide) at about 300 m depth. The density of this body would have decreased. Above this layer the density increases because of the calcite and quartz moderate deposition in the cavities of the fractured lavas and tuffs. To the North, the density increases as results of cooling fluid. The temperature should reduce as a consequence of the condensate fluids mixing with meteoric water. Hot gases ($H_2S$ and $CO_2$) which reach the structure of low density (2.0g/cm3) should rise through the faults, where they react with the andesite host rock and the inflow meteoric waters to produce the acid sulphate and the bicarbonate fluids. It should be noted that the resistivity values remain corresponding with the temperature, clay minerals, saturated porous and clean rocks along the path of the fluids, even though the deeper reservoir can not be detected by electrical survey because it is masked by shallower low resistivity layer.

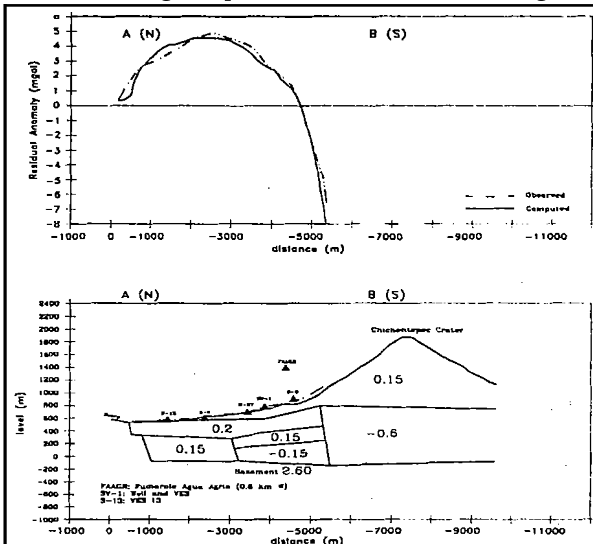


*Fig. 8. 2D interpretation of residual anomaly along profile PQ.*

## 8.0 CONCLUSIONS & RECOMMENDATIONS

1. San Vicente Geothermal Prospect is structurally controlled by a central graben, which has vertically displaced the tertiary basement. This graben strikes WE and is 8 Km wide. It seems to continue to the East of this study area.

2. Residual gravity anomalies indicate the South and north upthrow blocks of the graben. Results of 2D modelling of the residual gravity data along two profiles in the NW-SE and N-S directions provide some information about the gross characteristics of the graben structure. The maximum depression occurs along the central axis at the graben beneath main cities in the San Vicente area. The depression has been infilled by andesite-basalt lava flows erupted during Pleistocene and Holocene epochs.

3. *Scarps* of circular walls to the West of Chichontepec Volcano could be a result of erosion or weathering on the old volcanic complex.

4. The simple preliminary 2D gravity modelling along the NW-SE profile PQ does not show any evidence of a small horst suggested by the geological study in the surrounding of the Ramirez and Candelaria Hills.

5. A low density body underneath the Chichontepec Volcano, inferred from the preliminary 2D gravity modelling along the NS profile AB, could represents rocks with high porosity. If this interpretation is true, such porous body at rocks could allow a passage for hot magmatic gases.

6. Interpretation of Schlumberger resistivity sounding supports that the vertical resistivity structure in the whole of the San Vicente Prospect is almost uniform except in the surroundings of the hydrothermal manifestations. In this zone a vertical electrical discontinuity is observed near the San Francisco Agua Agria.

7. Hot (250oC) chlorine water was encountered within the tertiary basement to 1000 m deep by SV-I well. Schlumberger sounding, however, probably did not indicate a low resistivity Tertiary basement because of the "masking effect" by the upper low resistivity layers. An alternative result of 2D gravity modelling along profile **AB** (Fig. 10), using resistivity interpretation results **as** a constraint, suggests the presence of a low density body above the containing hot Tertiary basement which could be interpreted as fractured lava containing hot fluids.

**8.** Schlumberger traversing show the low resistivity areas associated with the two surface hydrothermal manifestations. **A** high resistivity zone lies between both hydrothermal manifestations. The low resistivity zone expands to the North and east from the main hydrothermal activities. The north path is limited by Acahuapa River where it bends to the East. This east boundary cannot be completely defined due to lack of data.

9. Two outflows can be inferred in the study area. One to the South of the Ramirez Hill and the other to the North between Verapaz and Tepetitan Villages. Both contain mixing bicarbonate water: the one to the North is discharging into Acahuapa River; the other one to the San Cristobal and Amapupulta Rivers. In the three rivers warm thermal activities are observed.

10. The prospect areas for future exploration feasibility studies and drilling are: a) First Priority: 1.5Km radius around the San Francisco Agua Agria. b) Second priority: Infiernillos Ciegos 2 Km to the SE of the secondary fault. Both areas have been shown low resistivities. High temperature and fractured zone exist in the San Francisco Agua Agria and accompanied by acid conditions.

It is suggested to complete the gravity measurement over the areas to the South of the volcano, and at least 3 Km to the North of the graben. This should also be accompanied by density measurement of rock samples. A 3D gravity modelling should provide more information about the gross structure of the San Vicente geothermal field. A directional hole near SV-1 well may be drilled to intercept the inferred body of low density under the north slope of the Chichontepec Volcano. On the basis of the shallow resistivity interpretation, MT measurement around the hydrothermal manifestations, could reveal reliable results of the deeper electrical structure. A study of gases, isotopes, and hydrology is also suggested in order to get a hydrogeology model and fluid composition in the San Vicente area. Detailed vulcanology study and daiting of rocks should also be made in this area to obtain better understanding of the volcanic evolution and its relationship with the formation of the San Vicente Geothermal system.

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