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Application of the Head On Resistivity Method in Geothermal Fields of El Salvador, Central America

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ABSTRACT

In order to identify mapped and hidden geological faults, the Head On profile electric method has been applied in geothermal fields of El Salvador. In this country, there are two geothermal fields currently under production, in which many wells have been drilled, and two fields in development with the application of the Head On resistivity method. Wells were directed to fractured zones suggested by the structural map and by alignments seen by the Head On method. The goal of this method is to identify the most fractured zones, making perpendicular profiles to the main direction of the faults system. Several alignments at the structural geologic map have been identified, and others have been suggested by this method. The results have indicated that several zones have good permeability and could be intercepted with the drilling of successful wells. The fractures delineated with this method have been of great help to define the drilling targets in the deep geothermal exploration programme. The cases of Ahuachapán and Berlin geothermal fields will be presented.

1. INTRODUCTION

Ahuachapán and Berlin geothermal fields (AGF & BGF) are located about 100 Km West and 110 Km East from San Salvador (SS), the capital, respectively. See Figure 1. The geothermal resource used in El Salvador is the AGF, which has around 57 wells and a power station summarising 95 MWe using 2x30 and 1x35 Mw units and started to generate electricity in 1975. In another hand, the BGF, which started to generate electricity in 1992 using 2 x 5 MW backpressure units, has about 38 wells and a power station summarising 109.4 MWe using 2x28, 1x44 and a Rankine binary cycle plant of 9.4 MWe. The BGF has around 38 wells, 14 are producers. The first two units (2x28 MW) started to generate in 1999, then in 2007 and 2008 the reminder two units.

In total, with the two-power geothermal plant, the geothermal installed capacity in El Salvador is 204.4 MWe, which represents about 24% of the total El Salvador energy demand. There are two more geothermal development, San Vicente and Chinameca fields. See in Figure 1 the location of four projects and Head Office. In Figure 2, the installed capacity of Ahuachapán and Berlin power station is shown.

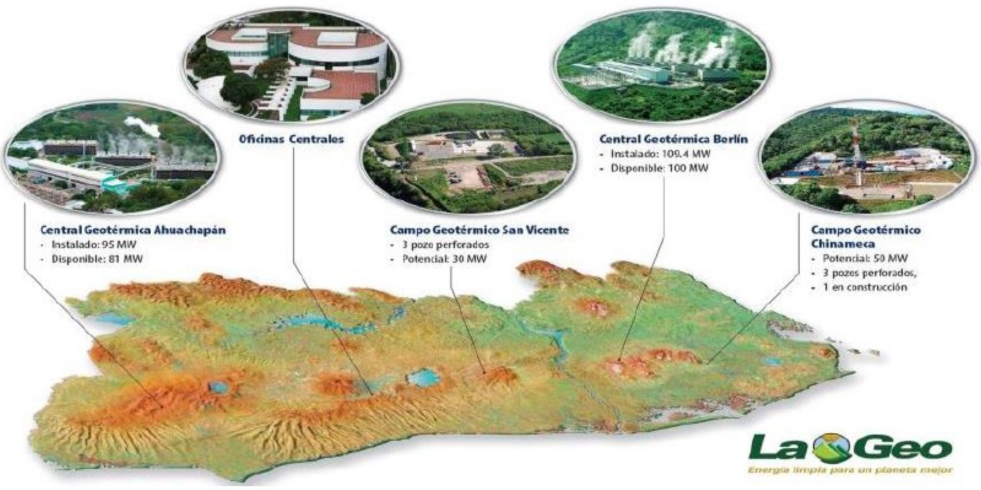

Figure 1: Location of the Ahuachapán and Berlin geothermal power stations and ongoing projects San Vicente and Chinameca. LaGeo Head Office located in Santa Tecla city, La Libertad, close to the capital city of San Salvador (Taken from Castillo, 2017).

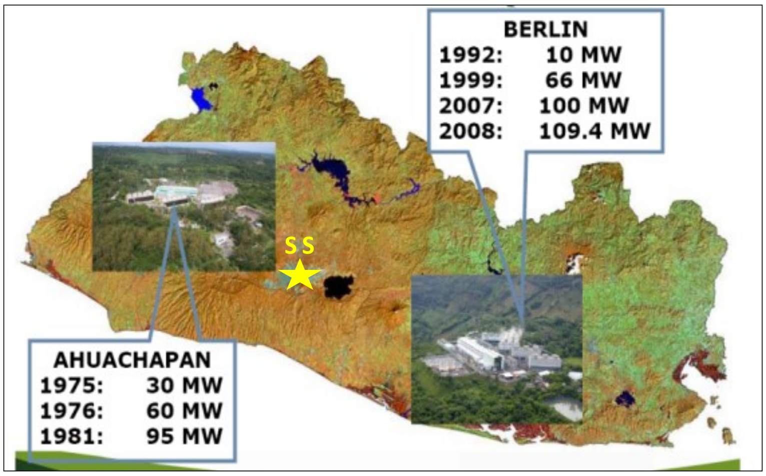

Figure 2: Location and installed capacity of the Ahuachapán and Berlin geothermal fields (Modified from Santos & Rivas, 2015).

To develop these geothermal fields, several exploration geophysics methods have been applied (resistivity, gravity, seismic, CSAMT, MT, Dipole-dipole) and the Head On method have been used at the drilling stage to identify fractured zones to target the wells (Santos, P., 2000).

One of the most important and difficult tasks in geothermal exploration is to identify and determine the fractures (faults) pattern governing the movement of geothermal fluids. Geophysics methods like gravity, magnetic and Head On methods, together with structural geological survey, provide information on the definition of the faults. The advantage of Head On method over other methods is the resolution on vertical resistive discontinuities associated with permeable faults.

The Head On resistivity method was developed in China in 1958. It has been successful in locating conductive fracturing in fields of low temperature in Iceland and has proved to be very useful in detecting faults in high-temperature geothermal areas in Kenya and Indonesia (Flóvenz, 1984). Essentially, the Head On is a fault detection graphic method.

Head On method has been successfully applied in the Ahuachapán and Berlin geothermal fields. About 60% of known faults have been confirmed, and new alignments have been inferred from the conductive sub-vertical stripes identified by this method. Some drilling has proven the presence of these inferred faults.

2. METHODOLOGY

Head-on resistivity is a modified Schlumberger (VES) technique designed to detect narrow conductive zones in a resistive background (PB Power, 2000). The method uses a half-Schlumberger electrode layout, with the other electrode removed to infinity. The penetration depth is similar to that obtained with a full Schlumberger electrode array with the same maximum AB/2 value. This means that investigation is restricted to the shallow surface layer.

The advantage of the Head On method, in fault detection and location, is the resolution on the vertical conductive subsurface contrasts, typically associated with faulting. The configuration of the field array is a typically Schlumberger method plus a third current electrode named “C” besides the well-known “A & B for current electrodes” and “M & N for the potential ones”. The configuration is shown below in Figure 3. The array is moved along a profile, and the electrode "C" remains perpendicular to the profile. “C” electrode is located at a distance of at least four times the semi spacing of the current electrodes (OC > 4OA). In practice, the electrode “C” is considered at the infinite when it is located at a distance of about 4OA. The potential difference between electrodes MN is measured independently when current is passed between AB, BC and AC dipoles. Subsequently, the values of apparent resistivity ρ_{AB}, ρ_{BC}, ρ_{AC} are calculated, see eq. 1. These resistivities are determined by (Hersir and Bjornsson, 1991):

$$\rho_{AC} = [\Delta V_{AC}\, \pi\, (S^2 - P^2)]/[IP] \;; \qquad \rho_{AB} = [\Delta V_{AB}\, \pi\, (S^2 - P^2)]/[2IP]; \qquad \rho_{BC} = [\Delta V_{BC}\, \pi\, (S^2 - P^2)]/[IP] \qquad \text{eq. 1}$$

Where S=distance between the current electrodes (m); I = injected current (Amp); P = distance between potential electrode (m) ΔV_{AC} = potential difference between electrodes M and N, when current is passing between electrodes A and C.

The electrode C is held fixed while the array AMNB gradually moves on the profile for the next reading. The position of “C” at infinity theoretically maintains the perpendicularity between OC and the profile.

After the computation of ρ_{AC}, ρ_{AB} and ρ_{BC}, the differences ρ_{AC}-ρ_{AB} and ρ_{BC}-ρ_{AB} are calculated, and a plot of both differences is made. When the curves intercept themselves reflect an electric discontinuity. This electric discontinuity is interpreted as the array passed through a geological structure that can be an alignment, a fracture or fault, a lithologic contact, etc. This result can be correlated with the structural map to confirm mapped or identify hidden structures and propose new features for the structural map.

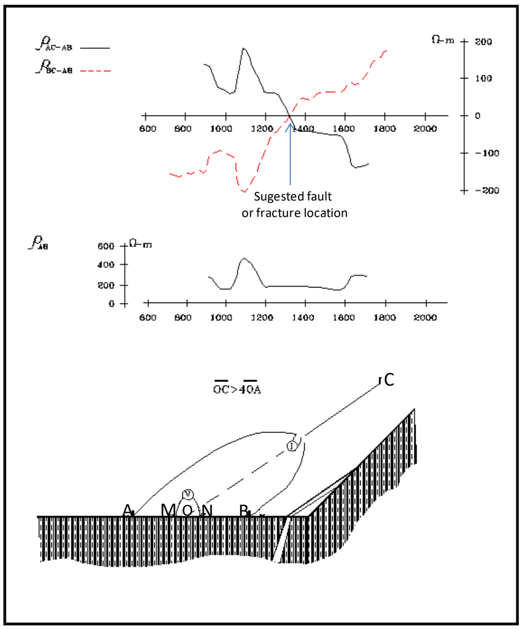

Figure 3: Electrodes configuration of the Head On resistivity method. (Modified from Flovenz, 1984).

In the isotropic and homogeneous medium, resistivity values are equal. Given a vertical conductive contrast (connected to faulting) potential changes because the current tends to flow in the conductive fracture. If the potential electrodes (M and N) and current (A and B) are on the same side of the conductive fracture (left side) ρAC- ρAB always be positive. When the same configuration of electrodes is on the opposite side of the conductive ρAC- ρAB is negative. The opposite occurs in the case of ρAC- ρAB. Just above the conductive fracture ρ_{BC} y ρ_{AC} are the same and curves ρ_{BC}-ρ_{AB} y ρ_{BC}-ρ_{AB} mutually cross (see Figure 2). The direction of the fault can be easily determined from the correlation of this intersection point in several profiles perpendicular to it (Hersir and Bjornsson, 1991). It is possible the data may be influenced by metal such as pipelines and well casings. Also, the noise from the power plant, pumps, power lines, etc. may alter the resistivity values but not the intersections of the curves.

One example of a curve and interceptions is shown in Figure 4. In this example (the profile P2 traced in Figure 6) three interceptions were observed suggesting three alignments. Green arrows indicate graphic interceptions which means possible fracture zones or structural alignments. The strong interceptions at the right of the graphics could mean strong fracture zones. This result has been compared with the structural map and seismic hypocentres distribution.

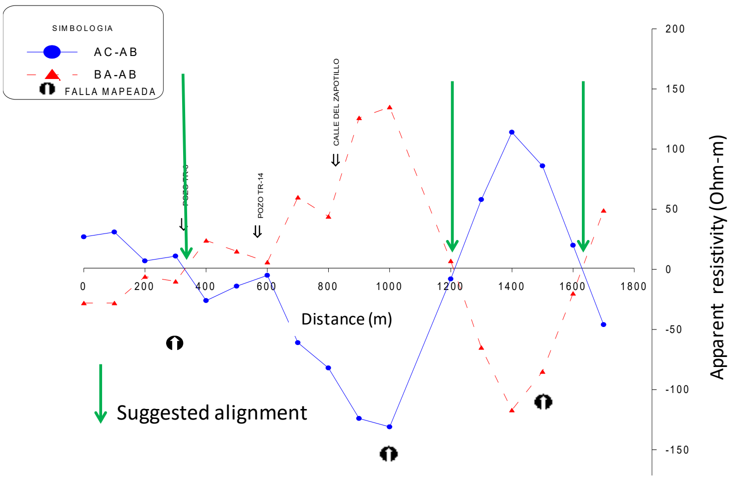

Figure 4: Head On profile P2 in BGF traced in Figure 6.

Conductive zones in this layer could be caused by warm geothermal fluids, rising closer to the surface along more permeable paths (Figure 5), and forming conductive clays. This enhanced permeability could be associated with some fault or fracture that may not form a detectable trace on the surface. If this faulting is the shallow extension of a fault or fracture that penetrates the conductive layer into the reservoir, then head-on resistivity anomalies could help to delineate likely permeable zones at deeper levels. (PB Power, 2000).

The Head On method has some limitations. In high-temperature geothermal fields resistive contrasts are weak, those contrasts are much smaller and therefore more difficult to identify. The depth exploration of the method is relatively shallow (depends on the separation AB/2). If the fault is under a layer of a thickness exceeding 300 m, could hardly be identified.

In densely fractured areas, the curve can take complex forms, which are not necessarily considered resistivity intersections. In such a case, a thorough analysis of them with the help of a specialised program for interpretation is required.

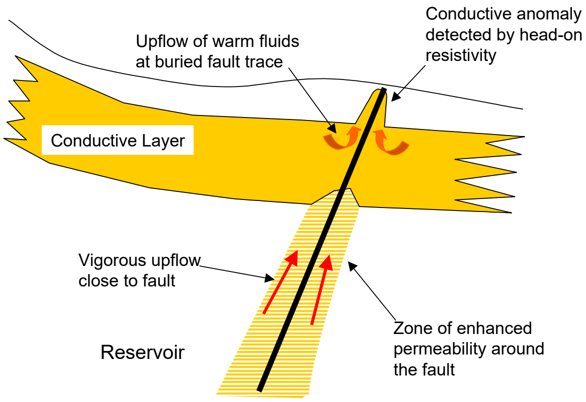

Figure 5: Possible cause of conductive zones detected by head-on resistivity. (Taken from PB Power, 2000).

3. HEAD ON SURVEY RESULTS

The equipment used for the application of the Head On method consisted of a current transmitter Scintrex, model TSQ-3 and a motor-generator, both of 3kV and a receiver Scintrex model IPR-10A. After following the described methodology, the obtained results in both geothermal fields are summarised below.

3.1 Results in Ahuachapán Geothermal Field

Figure 6 shows the structural map of the Ahuachapán geothermal field and over this seven (7) profiles at the production zone, located in the southwestern part of the area (brown rectangle in Figure 6) and four (4) profiles at the reinjection zone, in the north-eastern part of the area (red circle) have been measured with Head On method. The profiles are drawn and measured perpendicular to the alignments or faults to confirm or identify them. The pink dashes mean resistivity curves interceptions along blue lines profiles in the geothermal field, these interceptions can be correlated with the structural map.

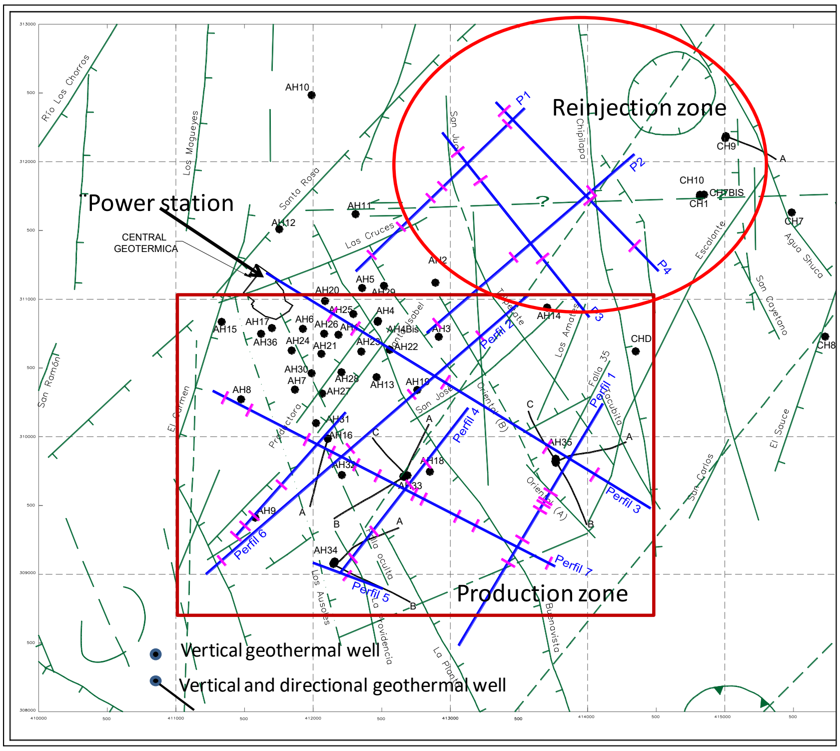

Figure 6: Head on profiles over the Ahuachapán structural map. (Blue lines are the profiles. Green lines are faults and alignments). Brown rectangle is the production zone and inside the red circle is located reinjection zone.

From Figure 6, it can be observed that there is a good correlation between resistivity curves interception (pink dashes) and the geologic alignments. It indicates that the area is fractured, and this suggests good permeability, especially at the south at the production zone. It is obvious that many interceptions do not correlate with mapped faults, but probably they are indicating hidden faults or fractured zones. The AGF has proven to be of good permeability at both, production and reinjection zones. i.e. three wells at the north absorb the total mass coming from the power station.

3.2 Results in Berlin Geothermal Field

A total of thirteen (13) profiles with lengths ranging from 1 to 3 km were executed. The profiles were drawn a perpendicular to the main structural systems responsible of fluid circulation. The profiles location and the resistivity curves interceptions observed with Head On method is presented in Figure 7. The pink dashes over blue lines, which represent the resistivity curves interceptions and profiles, are abundant and this means a high density of fractures, especially at the south of the area where the production zone is located (black rectangle). On the other hand, inside the red rectangle, at the north, is located the reinjection zone and this is characterised by less density of resistivity curves interceptions, that is to say, there are fewer density fractures and consequently less permeability. The reinjection at BGF is very critical because of low permeability at the north. The dots, crosses and stars represent epicentres (Rivas, 2000) and some alignments correlate with Head On interceptions at the north of reinjection zone (red rectangle).

In Figure 7, the Head On method results have been correlated with the structural map and microseismicity distribution in order to confirm the resistivity curves interceptions and its relationship with faults. Faults extension have been possible suggested, based on the correlation of Head On and seismic events alignment and following the fault traces (see yellow dashed lines). It is quite obvious the predominant NW-SE faults trend. Many Head on curves interceptions correlate with faults; others indicate how fractured is the area because of the density of interceptions. The accuracy in these correlations ranges in the range of 25-100 m. This is due to the inaccuracies associated with the application of the method, location of faults and profiles on the map, etc. The best matches correspond to intracalderic faults, possibly because they are responsible for the conduction of geothermal fluids (Santos and Handal, 1996).

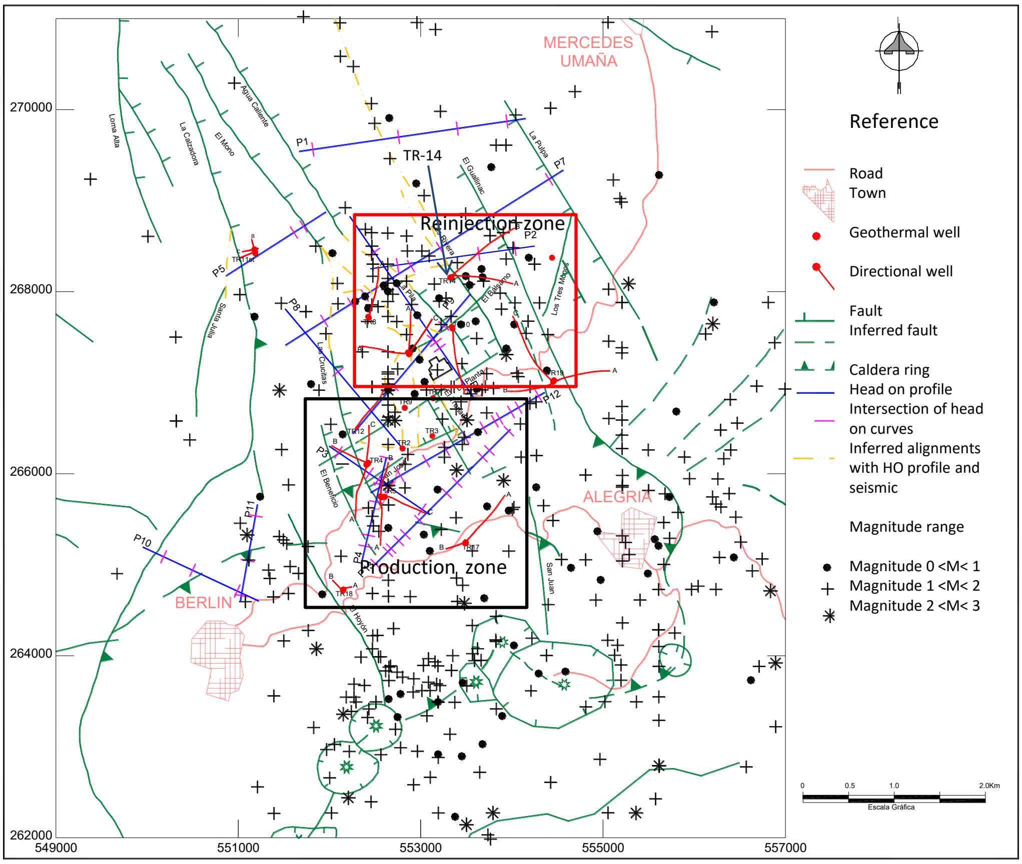

Figure 7: Head on profiles correlated with microseismicity and structural map at Berlin geothermal field. Green traces are faults and structural alignments. Pink dashes over blue lines are Head On resistivity interceptions. Dots, cross and stars are epicentres. Faults extensions suggested are represented with orange lines.

On Figure 8, an interpreted structural map of faults is presented based on Head on profiling, and the pink bands represent the error of the method which are intercepted by the cuttings of the Head On curves mainly north of the area. (Santos, P. and Rivas, J. 1999). It is possible to extend some faults to the northwest with the help of profiles interceptions. The NW-SE trending is predominant in the area.

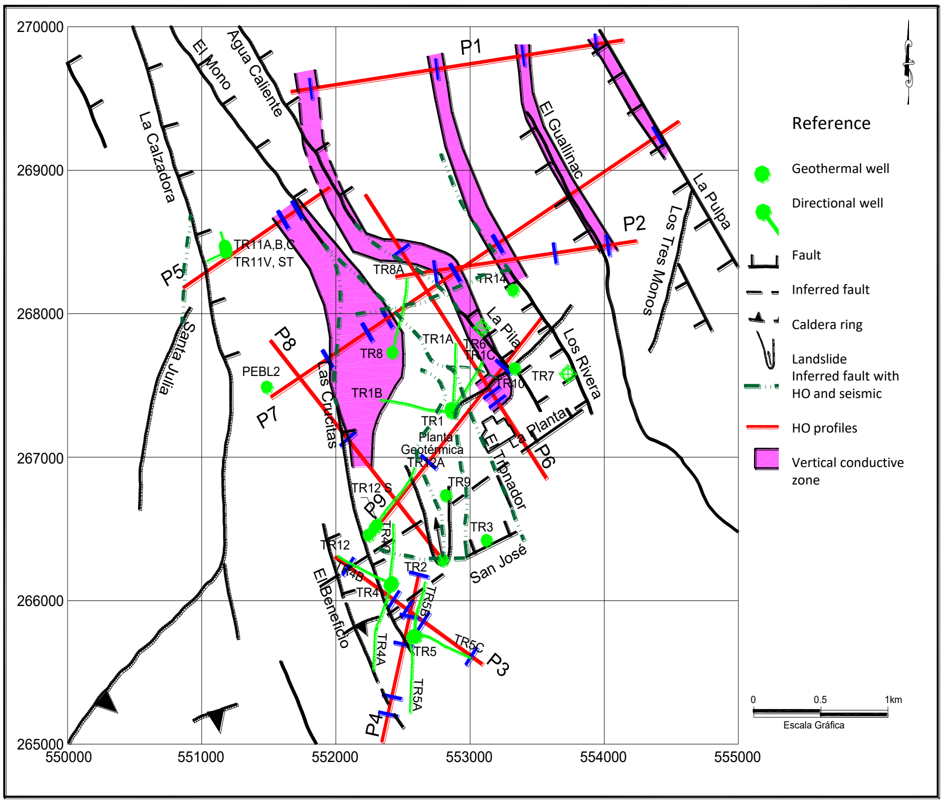

Figure 8: Interpreted structural map from Head On profiling method.

4. CONCLUSIONS

The Head On method has proven to be an important tool in the detection and location of faults in low and high-temperature geothermal fields. Its main advantage over other structural methods is its resolution to the presence of conductors associated with aquifers confined to failures.

The method has detected much more permeability in the south, in production zones, than north, in reinjection zone. This is confirmed by the density of interceptions over profiles in both geothermal fields.

The effectiveness of the Head On method was verified by performing two profiles at the north end of the field, intercepting the Berlin local graben fault system, in the NNO-SSE direction. As a result, a good correspondence was obtained between the failures suggested by the method and those identified in the structural map (known).

The accuracy in these correlations ranges in the range of 25-100 m. This is due to the inaccuracies associated with the application of the method, location of faults and profiles on the map, etc. The best matches correspond to intracalderic faults, possibly because they are responsible for the conduction of geothermal fluids.

The results of the profiles made in the production area of the wells, in BGF, near the TR-4 and TR-5, suggest the existence of the northern edge of the Blanca Rosa boiler identified by GENZL. The accuracy in the correspondence between the faults intercepted by profiles P3 and P4 ranges between 25 and 100 m.

The results suggest the existence of some unidentified faults which can be confirmed by making other profiles transversal to the same, using a larger opening in the current electrodes.

5. ACKNOWLEDGEMENT

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