Exploration of the geothermal reservoir of Cerritos Colorados, Jal., Mexico, using 1-D and 2-D inversion of resistivity data

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Abstract

The Cerritos Colorados geothermal field is located inside the forest of La Primavera, 20 km to the west of Guadalajara, State of Jalisco, Mexico. In this work we have carried out 1-D and 2-D inversions based on the least squares method with smoothness constraints for a Schlumberger Vertical Electric Sounding (VES) data set measured at 95 VES stations. The objective of this work is to find the low resistivity zone and structures that control the movement of the geothermal fluids. The result is ambiguous at depth because the apparent resistivity curves seem not to reach the minimum values at even the maximum electrode spacing, that is why we only consider the resistivity structure at relatively shallow depth (less than 750 meters above the sea level) as a reliable structure. The inverted resistivity distribution at relatively shallow depth shows an important low resistivity zone that probably reflects the hydrothermal alteration zone in the central portion of the study area where some production wells are located. The low resistivity zone is located in the western part of a resistivity discontinuity trending NW-SE, which is also detected in the inverted resistivity distribution. Therefore the resistivity discontinuity trending NW-SE possibly reflects a fault-like structure controlling the movement of the geothermal fluids.

Keywords: Mexico, Cerritos Colorados, geothermal exploration, resistivity.

Exploración del yacimiento geotérmico de Cerritos Colorados, Jal., México, utilizando inversiones 1-D y 2-D de datos de resistividad

Resumen

El campo geotérmico de Cerritos Colorados se localiza dentro del Bosque de La Primavera, 20 km al oeste de Guadalajara, Estado de Jalisco, México. En este trabajo se realizaron inversiones de una y dos dimensiones con base en el método de mínimos cuadrados con restricciones de suavizado para una serie de datos de Sondeos Eléctricos Verticales (SEV) Schlumberger obtenidos en 95 estaciones. El objetivo fue hallar la zona de resistividad mínima y estructuras que permitieran definir el movimiento de los fluidos geotérmicos. El resultado es ambiguo a profundidad porque las curvas de resistividad aparente no parecen alcanzar los valores mínimos, incluso con el máximo espaciamiento de los electrodos, por lo que aquí se considera confiable sólo la estructura resistiva a profundidades relativamente someras (menos de 750 metros sobre el nivel del mar). La distribución de la resistividad inversa a profundidad relativamente somera muestra una importante zona de baja resistividad que probablemente refleja la zona de alteración hidrotermal en la porción central del área de estudio donde se localizan algunos pozos productores. Esta zona de baja

resistividad se ubica en la parte occidental de una discontinuidad resistiva de orientación NW-SE, la cual se detecta también con la distribución de la resistividad inversa. Por lo tanto, la discontinuidad resistiva NW-SE indica probablemente una estructura tipo falla que controla el movimiento de los fluidos geotérmicos.

Palabras clave: México, Cerritos Colorados, exploración geotérmica, resistividad.

1. Introduction

The geothermal zone of Cerritos Colorados is located inside the forest of La Primavera, 20 km to the west of the city of Guadalajara, the second largest city in Mexico (Fig. 1). This geothermal field lies in the south-central part of the Quaternary volcanic caldera of La Primavera, which is a part of the Mexican Volcanic Belt and was formed near the intersection of three major structures: the grabens of Chapala (E-W), Colima (N-S) and Tepic (NW-SE), (Sánchez, 2003).

Geothermal exploration uses different geophysical techniques to interpret measurements of physical properties of the Earth and thus determine subsurface conditions. Some of these techniques are, among others, seismic, geo-electric, electromagnetic, gravity, and magnetic surveys (Telford *et al.*, 1990).

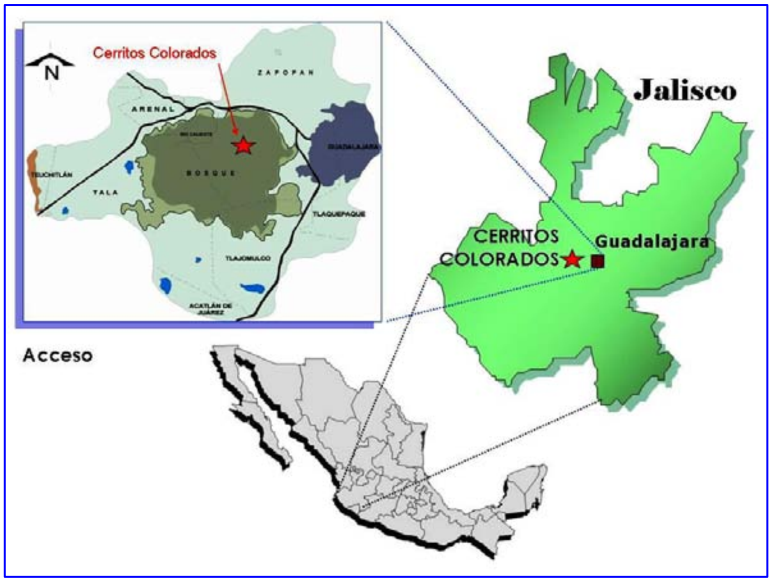

Fig. 1. Schematic location for the geothermal field of Cerritos Colorados.

Geo-electrical methods, specifically DC resistivity, have been used with great success for locating geothermal aquifers, especially in a resistive environment. However, it has been unsuccessful in outlining the reservoir of vapor-dominated systems hosted in sedimentary rocks. With the increased availability of faster computers, it is now practical to employ numerical modeling techniques to invert resistivity data for an actual geologic structure (El-Qady *et al.*, 2000). In this study, we have carried out a 1-D and 2-D inversion based on the least squares inversion with smoothness constraints for a Schlumberger VES data set measured at the Cerritos Colorados field.

2. Geological framework

The topography in the Cerritos Colorados area is complex, because of the presence of several local mountain areas where the altitude varies from 1450 to 2230 meters above the sea level (masl).

The La Primavera caldera has a geomorphologic structure almost circular with a diameter of 12 to 15 km. Within the caldera, and in its surroundings, there are numerous vitreous and rhyolitic domes distributed in an annular way. The highest domes (2200 masl), known as Las Planillas, are located by the south of the caldera.

The drilling of several deep wells allowed to know the subsurface structure of the central part of La Primavera caldera to a depth of about 3 km. Regional structural profiles of La Primavera were presented by

Yokoyama and Mena (1991) with information of the wells PR-1 to PR-13. According to Gutiérrez-Negrín (1988) and JICA (1989), the outcropping layer is composed by lake-sediments and pumice post-caldera deposits with an average thickness of 33 meters and Quaternary age (<70,000 years). Underlying those sediments there is an ignimbrite formation, known as Toba Tala, with an average thickness of 370 m; this lithologic unit was formed 95,000 years ago by pyroclastic flows from the caldera events. Below the Toba Tala is a unit of rhyolites, which present an average thickness of 64 meters and an age of 120,000 years. Underlying the rhyolites is a unit composed of a sequence of andesites and tuffs with minor basalts and a thin layer of rhyolites (69 meters), with a combined thickness of 2,300 meters, and an age from Late Miocene to Early Pliocene. This unit can be related to the early basement of the Mexican Volcanic Belt or the late volcanic activities of the Western Sierra Madre. All of these units rest over a granodiorite basement, cut only by the deepest well, PR-9, at 2986 m depth, with a radiometric age of at least 7.3 Ma (Late Miocene) (Gutiérrez-Negrín *et al.*, 2002). For more details on the subsurface lithology of the wells see Santoyo-Gutiérrez *et al.* (1991).

Like many young silicic centers, the Sierra La Primavera is the site of an active hydrothermal system (Mahood, 1980). La Primavera presents surface thermal manifestations in the form of fumaroles and hot-water springs with considerable discharge volumes, such as the Rio Caliente stream with 73 m3/s (Santoyo-Gutiérrez *et al.*, 1991).

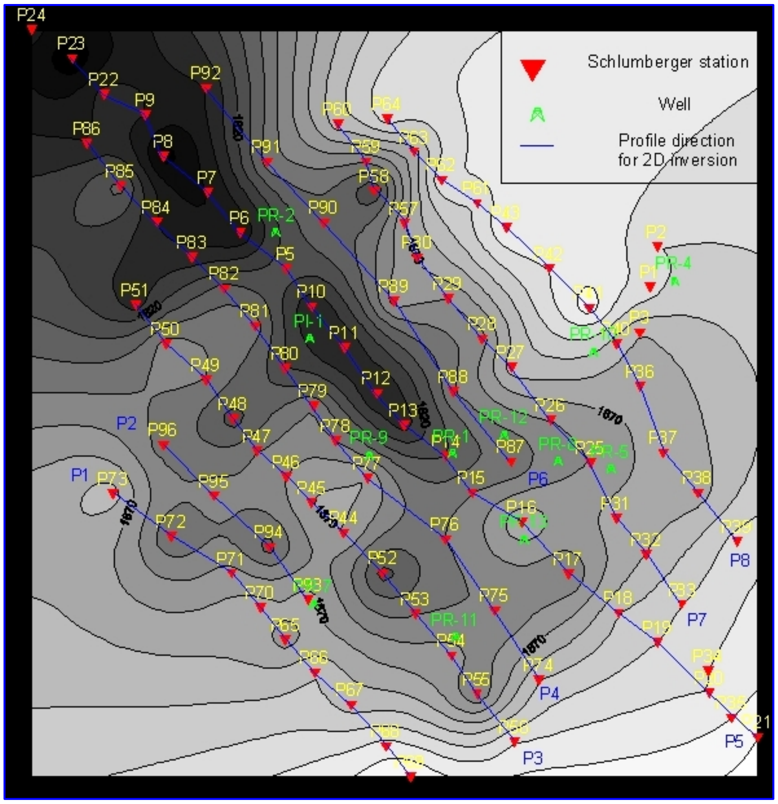

Fig. 2. *Topography contour map and location of the wells.*

Large-volume springs averaging 65° C that discharge at the Rio Caliente are the source of the Rio Salado stream. Other springs at Balneario Primavera and Agua Caliente emerge near the contact of pre-caldera lavas and the overlying Toba Tala. Dozens of wispy fumaroles emanate from the bounding faults of the graben atop the Mesa El Nejahuete, where the ground is strongly acid altered. Where the southwest end of the graben intersects the contact of the Toba Tala and the overlying lake-sediments, hundreds of small fumaroles rise from the silicified tuff. One kilometer north are the sulfur-depositing steam vents of La Azufrera. Feeble fumaroles issue near the top of Cerros Las Planillas (Mahood, 1980).

3. Geophysical data

Geo-electric resistivity studies are widely applied in hydrogeological and geothermal field surveys (Majumdar *et al.*, 2000). The geophysical survey described in this work consisted in DC resistivity soundings with a Schlumberger array. Data from 95 VES stations in the Cerritos Colorados field (Fig. 2) were used for 1-D and 2-D inversion, using electrode spacing started from AB/2 = 9 m up to 3496 m in a successive steps. The field sites were chosen on the basis of the accessibility and applicability of the Schlumberger method. The distance between stations varied between 100 to 350 meters according to the topography.

As a first step, a 1-D inversion analysis was conducted using the least square method. Although the deduced information from 1-D inversion was correlated with the geological studies (Fig. 3), it was not fully matched with the 3-D geological structures. To get a better solution we have to use 2-D or 3-D inversion. Then we created a 1-D plan-view resistivity maps (Fig. 4) at different depths (750, 1000, 1250 and 1500 masl) and compare them with the 2-D inversion results to assure the consistency of the technique.

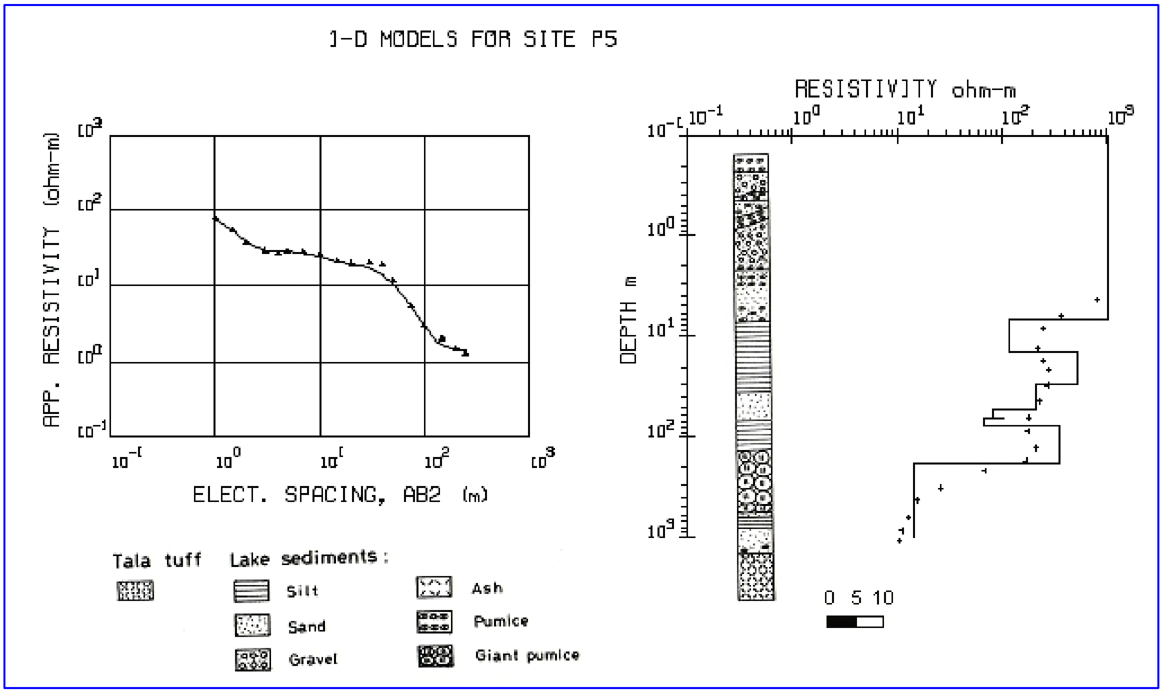

Fig. 3. Correlation between resistivity and lithology.

In general, the resistivity structure derived from 1-D inversion is fairly consistent with that derived from 2-D at shallow depths. The 2-D inversion analysis has also been conducted with the same data used for the 1-D inversion analysis, because the results of 2-D inversion are usually more reliable than those of 1-D inversion, especially at depth. The algorithm utilized in this work is based on the smoothness constrained least squares method with a Finite Element calculation. The basis of the code had been extensively discussed by Uchida (1991) and El-Qady *et al.* (1999).

With this algorithm we seek a model which minimizes both the data misfit and the model roughness, so we have to run the inversion process until the best fit is attained. Then we select the best model according to the smoothing factor and the root mean square (RMS-misfit). In this case, the curve became nearly stable and attained the convergence after the iteration number 5, for 8 profiles trending a NW–SE direction (Fig. 2).

In the Figure 5 we can see how the measured data fit with the calculated data, and we can conclude that these models are acceptable for sub-surface resistivity structure in the area. On the basis of the resistivity values obtained from the 2-D inversion, we created some plan-view maps at different depths (750, 1000, 1250 and 1500 masl). These maps are shown in the Figure 6.

5. Data interpretation

From the results obtained after the 1-D and 2-D inversions, it is found that the tendency of the resistivity distribution has a NW–SE direction in the plan-view maps at different depths. Therefore the inverted resistivity distribution of the analysis mentioned before intends to show the sub-surface resistivity structure at shallow depths (shallower than 750 masl, approximately). Nevertheless, in all the stations the apparent resistivity curve does not seem to reach the minimum values at the maximum electrode spacing. Then the inverted resistivity distribution at depth (approximately deeper than 500 masl) is ambiguous (Fig. 7).

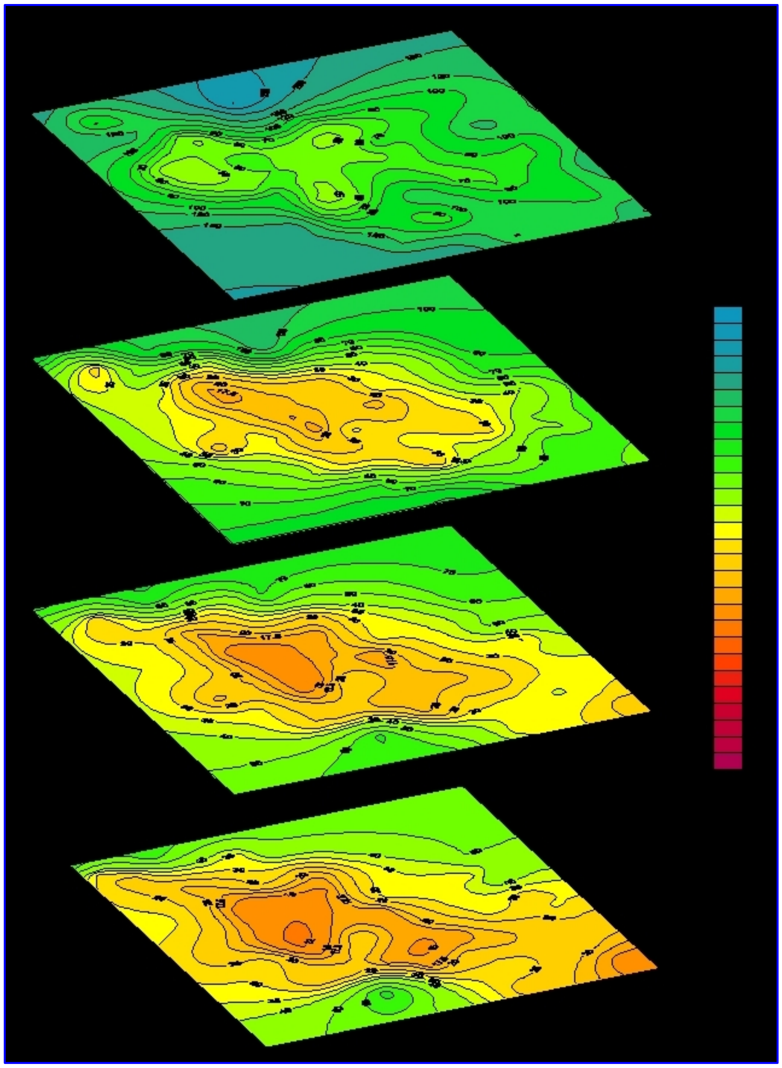

Fig. 4. True resistivity maps obtained from 1-D inversion.

In the plan-view generated from the results of the 2-D inversion (Fig. 6), specifically in the resistivity maps at 1250, 1000 and 750 masl, we can observe a very low resistivity area of less than 20 ohm-m near the central portion of the maps. More precisely, in the 750 masl resistivity map the low resistivity area seems to be distributed along a direction NW–SE. In many geothermal areas, because of the presence of conductive clay-minerals, such as smectite, or zeolites, low resistivity areas are generally distributed on the top of the geothermal reservoir. Therefore, this could be an indicative of a hydrothermal alteration zone at relatively shallow depths in the area.

On the other hand, it is found a relatively high resistivity zone in the direction northeast of the study area. With the resistivity contrast between the low and high resistivity areas, we can say that a resistivity discontinuity exists with a NW-SE direction. In the JICA´s report (1989), some lineaments trending NW-SE appear in the Bouguer anomaly map (ρ = 2.20 g/cm3) and one lineament seems to be near the resistivity discontinuity obtained in this work. Even the position of the resistivity discontinuity slightly differs from the gravity lineament compared in the JICA´s report, the directions of both trends are almost the same. Moreover, the intervals of the gravity stations are very separate from each other (approximately 500 m or more), so accurate position of the gravity lineaments can not be determined. Therefore the resistivty discontinuity and the gravity lineament possibly reflect the same fault-like structure.

Additionally, in the western part of the resistivity discontinuity, the low resistivity area is distributed and seems to be extended along the discontinuity. Therefore the fault-like structure deduced from the Bouguer anomaly and the resistivity distribution may play an important role to control the movement of the geothermal fluids.

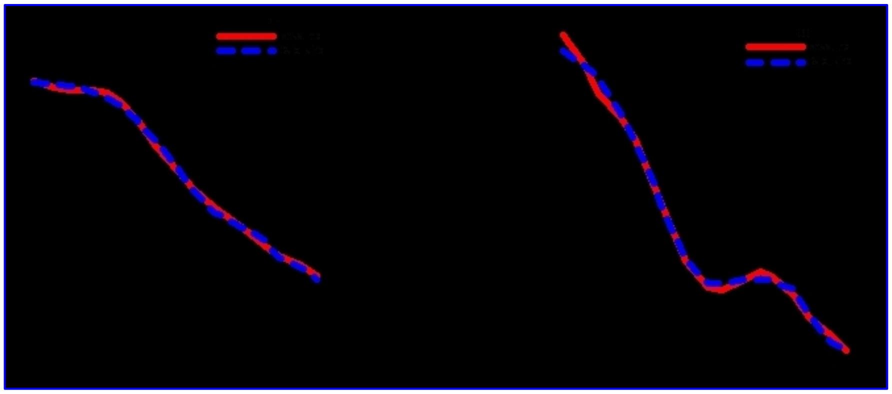

Fig. 5. Matching calculated apparent resistivity data to observed data.

6. Conclusion

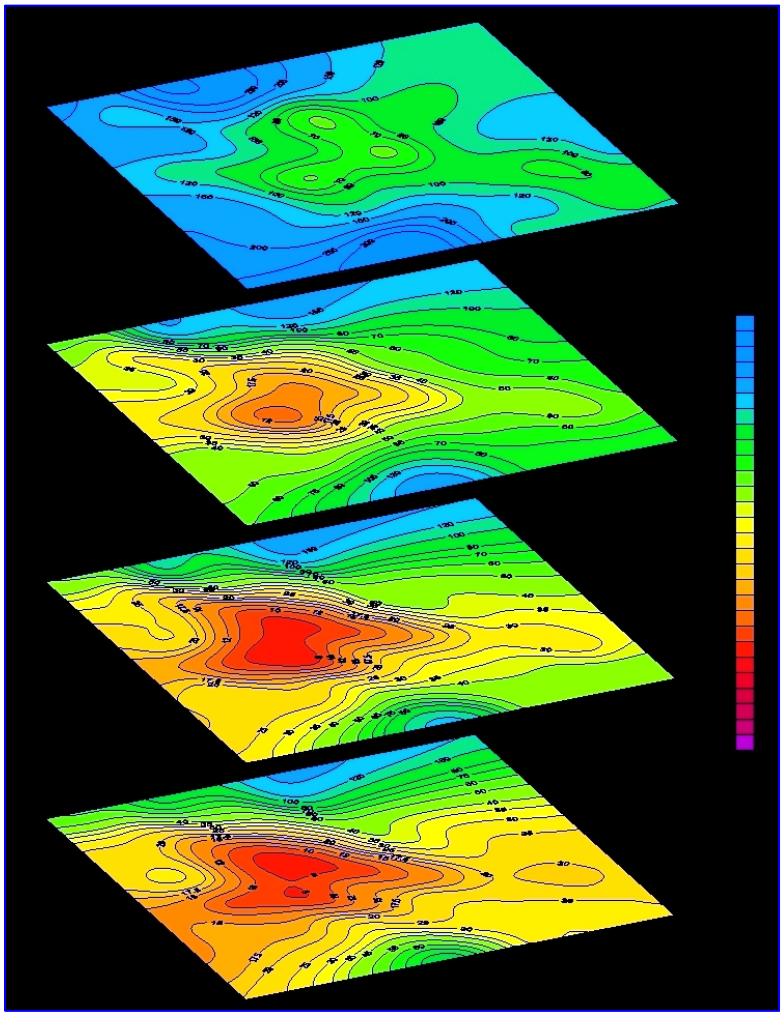

Fig. 6. Resistivity maps obtained from 2-D inversion at different depths.

In the data interpretation mentioned before, the resistivity discontinuity tendency has a NW-SE direction, and it is possible that this discontinuity reflects some fault-like structures. Besides, we found a low resistivity zone in the western part of the discontinuity where the wells PR-1, PR-9, PR-12 and PR-13 are located, showing less than 20 ohm-m in the resistivity map at 750 masl. According to the geochemical analysis, the deep-seated geothermal hot water originates in the deep formation near the well PR-1 (Sánchez, 2003).

Accordingly, we can conclude that the up-flow of the geothermal fluids near to the well PR-1 probably move along the fault structure trending NW-SE (resistivity discontinuity) and form the hydrothermal alteration zone (low resistivity zone) in the western part of the discontinuity at relatively shallow depths.

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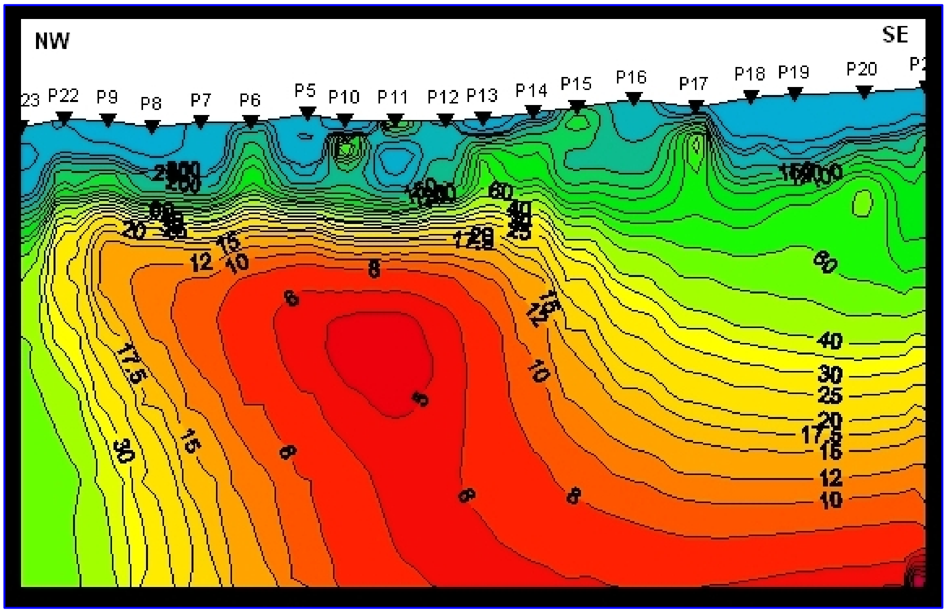

Fig. 7. Geo-electrical cross- section resulted from 2-D inversion for Profile 5.

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