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DC Resistivity at the Ahuachapán Geothermal Field, El Salvador

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ABSTRACT

Deep dc resistivity surveying has been performed at the Ahuachapán Geothermal Field in western El Salvador. The field lies on the north base of the volcanic range that runs the length of the country and is the site of a significant active geothermal powerplant. The technical purpose of the surveying was to assess the geophysical properties of the geothermal regime around the existing field. The survey was carried out as a colinear dipole-dipole survey using dipole spacings of 500m and 1000m, and dipole separations of up to fourteen dipole lengths. Results included (1) the observation that the geothermal reservoir was not readily detectable due to surface lithologic changes and extensive cultural effects, (2) the hydrothermally altered areas are readily recognized by their low resistivities, (3) local lithologies appear to be mappable based on their *in situ* resistivities, (4) the greater field logistical convenience of the shorter 500m dipole spacings is negated by the increase in topographic effects, and (5) if appropriate dipole separations are used, there is no need to run surveys of both 500 and 1000 meter dipole spacings to gather shallow and deep information.

INTRODUCTION

A deep resistivity geophysical survey was performed at the Ahuachapán geothermal field (AGF), the site of a 90 megawatt powerplant, in western El Salvador between November 1987 and May 1988. The survey was part of a project of geothermal resource evaluation and technology transfer program sponsored by Los Alamos National Laboratory (LANL) and funded by the United States Agency for International Development (USAID). The results of two survey lines are presented in this paper; however, two additional lines have recently been completed and will be presented in a future report.

OBJECTIVES

The technical objectives of the resistivity program were designed to study particular aspects of the geothermal resources of the Ahuachapán region by defining the electrical characteristics of the known geothermal reservoir such that adjacent areas may be investigated and compared. Specifically,

1. identifying and mapping the relevant physical properties related to shallow geothermal production so that the Chipilapa area to the east may be better evaluated, and
2. determining the deep electrical characteristics beneath the volcanic mountains to the south of Ahuachapán to evaluate the geothermal and recharge potential in that area.

LOCATION

The AGF, as shown in Fig. 1, is located at the western end of El Salvador immediately north of a chain of volcanic mountains that run the length of El Salvador. Site elevation is approximately 800 meters. The mountains to the south rise to approximately 1800 meters. None of the volcanoes is active but some are young enough to have well defined craters. The geothermal field is named after the nearby town of Ahuachapán in the state of Ahuachapán.

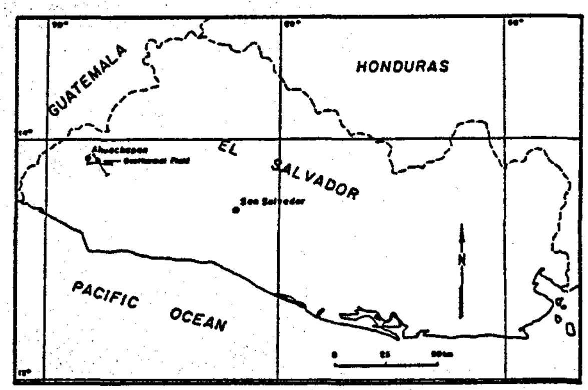


Fig. 1. Location map of the Ahuachapán Geothermal Field, El Salvador.

METHOD

Resistivity Surveying

The method of electrical resistivity surveying employed a dipole-dipole array with dipole spacings of 500 and 1000 meters. Lines 1 and 2 shown in Fig. 2 consisted of 24 line kilometers.

In order to assure adequate shallow resistivity information, dipole separations of 0.1, 0.5, 1.0, 1.5, 2.0, 3.0, 4.0, 5.0, and 6.0 were used to collect the 1000 meter dipole data, and the 500 meter dipole data were gathered using separations of 0.2 and integer intervals of 1 through 14. The reduced data are presented in logarithmic pseudosection format. The objectives of using two dipole spacings were to enhance the lateral and near-surface resolution with the shorter dipole spacing (500m) and to allow deeper penetration with the larger spacing (1000m). Both of these objectives were achieved successfully. Indeed, the combination of field logistics and resultant data suggest that future work may be satisfactorily performed with only the 500m spacing, *if adequate current is injected into the ground.* In situations where adequate current is not achievable, larger dipole spacings must be used.

Previous resistivity work performed by CEL included Schlumberger array vertical electrical soundings (VES's) in a grid covering the Ahuachapán area and extending to the northeast towards Turin. This grid is outlined in Fig. 2. Qualitative and quantitative data comparisons between the dipole-dipole array work and the VES's are quite good. The dipole-dipole data, because of instrumental design, allowed deeper penetration with minimal interference from electromagnetic (EM) response, whereas the VES data, because of instrumental design limitations, appeared to suffer from EM response at the larger spacings. The data for the larger current-electrode spacings for the VES's were qualitatively corrected for the EM response but the quantitative interpretation for those spacings was still questionable.

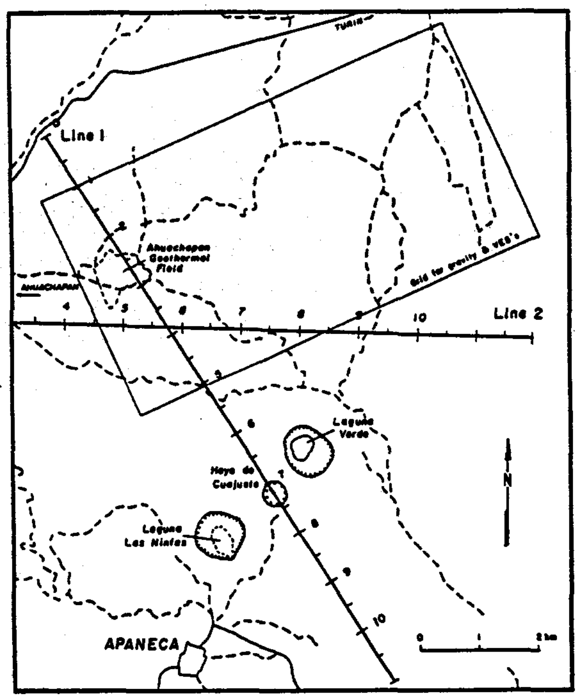


Fig. 2. Location map of Lines 1 and 2 for the dipole-dipole dc resistivity program of 1987-1988.

Survey Program

The survey consisted of four lines, three of which were oriented due east-west, approximately parallel to each other, and eight kilometers long. These lines were one-half kilometer apart and located so that they would connect the known area of the AGF to the Chipilapa area by crossing the southwestern corner of the grid of existing VES data. This would then extend the resistivity information to the south of the grid. The fourth line (Line 1) was oriented approximately N25°W so that it would cross the western end of the VES grid, cross the established limits of the AGF, and extend to the south over the mountains.

Data Presentation

Dipole-dipole data are generally presented in pseudosection format. This method of data presentation displays the collected data in a manner such that the horizontal scale is linear distance and is scaled in units of dipole length and the vertical scale is in units of dipole separation and may be either linear or logarithmic. The vertical axis is positive downward. Although the appearance is that of a geologic section, we must emphasize that the location of the plotted points is not necessarily representative of depth.

Topographic Modeling

The effects of topography on a resistivity survey are well known. These effects are due mostly to two causes: lack of collinearity of the four electrodes represented by any given data point, and compression or expansion of the equipotentials observed on the earth's surface related to the transmitting dipole.

For the work herein, the method of Schwarz-Cristoffel conformal transformation was used to approximate the topographic effects. This method allows the topography along the survey line to be modeled as if it were a two-dimensional structure. In the case of Line 1, where it crosses the Hoyo de Cuajuste crater, there are severe topographic effects and they are not two-dimensional. However, the 2-D model results give a qualitative idea of the trends and magnitudes of effects anticipated from the modeled structures.

Topographic effects are determined by the severity of the topography relative to the dipole size. At Ahuachapán, topographic effects were maximum where the line crossed the highest elevation and the Cuajuste crater. Ridges produce an increase of the observed apparent resistivities, in this case with 1000m dipoles, up to fifty percent greater than a flat surface. Valleys, or flanks of ridges, reduce the observed apparent resistivities, approximately twenty-five percent less using 1000m dipoles. In spite of the large topographic effects present, the general patterns present in the uncorrected 1000 meter apparent resistivity pseudosection were still present after removing the topographic effects suggesting that lithologic changes occurred sympathetically with the topography. Prior to geologic modeling, the modeled 2-D topographic effects were subtracted from the observed field data.

Geologic modeling

Modeling of apparent resistivity due to complex earth structures is more computationally intensive than the topographic modeling. For this work, 2-D geologic models using a finite element algorithm were used to approximate the observed data. The finite-element routine used is a commercially available program.

Drilling has shown that the AGF reservoir is limited in lateral extent and therefore three-dimensional. Nevertheless, 2-D approximations are the most readily available and should suffice to guide the interpretation of the observed data. Physical property values for the model were based on reported laboratory-measured physical properties performed by CEL and estimated physical properties from short-dipole-spacing field data. The laboratory resistivity measurements were made for a frequency range of 5 to 10,000 Hz and three pressures of 100, 500, and 1000 psi. The laboratory results show reservoir rocks (andesite and breccia) to have true resistivities in the range of 5 to 50 ohm-meters, whereas overlying tuffs and lavas range from 10 to 1000 ohm-meters. The reported trends of increasing resistivity with decreasing frequency are acknowledged, but extrapolation to dc is not prudent as induced polarization effects are also inferred to be present in the laboratory data. The inverse relationship of resistivity with pressure at the lower frequencies is also acknowledged. This would only tend to decrease the observed apparent resistivities in the field data. Although there appears to be a tendency for the tuffs and lavas to be of moderate to high true resistivity, hydrothermal alteration of any of the lithologies present will produce low resistivities.

INTERPRETATION

LINE 1 (a = 1000m)

Observed values ranged from 2.3 to 250 ohm-meters. In general, the apparent resistivities fall into two groups, low (2 to 20 ohm-meters) and moderate (20 to 200 ohm-meters). The low values correlate with the surface expression of hydrothermally-altered lithologies and with deeper stratified lithologies, most likely those of the andesites and saturated agglomerates in the lower Quaternary San Salvador Formation. There is no evidence in the resistivity data that older lithologies such as the Pliocene Balsamo Formation were detected. The moderate apparent resistivities correlate with the shallower tuffs and lavas where they appear to form cap-rock and in the high-topographic-relief area where the survey line crosses the mountains.

Line 1 (a=1000m) data are shown in logarithmic pseudosection in Fig. 3. Increased data density was desired in the immediate vicinity of the AGF, so the received data were collected with half-dipole moves for the transmitter resulting in double density coverage. The portion of the AGF crossed by the line is between stations 2 and 3. Blank spaces occurring beneath dipoles 4-5 and 6-7 indicate unreliable or unreadable data.

A qualitative investigation of the data in Fig. 3 indicates considerable variation in the near-surface apparent resistivities. The lowest values (3.8 ohm-meters) for the shallowest data occur at station 5 which was located among fumaroles. Low values also occur at the AGF (5.5 ohm-meters) and next to Cerro Blanco (another hydrothermally altered area) at station 6 (4.0 ohm-meters). In the high-density portion of the pseudosection these low apparent resistivities are flanked by slightly higher values ranging from 5 to 17 ohm-meters.

Moderate-valued near-surface apparent resistivities occur to the extreme northern and southern ends of the line and midway between stations 3 and 4. The northern end of the line is in a cultivated area. Generally, shallow data are artificially low due to the increased soil moisture content typical of cultivated areas. Consequently, the slightly-higher-valued shallow data seen in this area demonstrate that the lower-valued shallow data seen elsewhere are not due solely to surface moisture. The moderate-valued apparent resistivities occurring in the southern end of the line are in the area of outcrop and high topographic relief. Therefore, they would be expected to be higher-valued than data in lower, cultivated areas. The significance of the very low values mentioned previously is that they occur where extensive hydrothermal alteration is quite evident at surface. With increasing depth (pressure), saturation, and temperature, the true resistivities should decrease considerably. Therefore it is expected that lower apparent resistivities should appear for larger dipole separations, especially in the vicinity of the geothermal field where extensive hydrothermal alteration has taken place.

Of particular interest is the moderately-valued shallow data between stations 3 and 4. These data are flanked by lower values. Therefore, this local, moderately-resistive area probably represents a near-surface, relatively unaltered lithologic block that may be representative of caprock material. The block is likely 100 to 200 meters thick and perhaps up to a kilometer wide in the direction of the survey line and is restricted to the area between stations 3 and 4.

The lowest values occur immediately beneath this localized, near-surface, moderately-resistive block. Model data show that the low closure for the 3 ohm-meter contour is a constructive interference phenomenon and that more representative true resistivities would be around 5 to 10 ohm-meters. The interference phenomenon results from the lower near-surface resistivities which modeling suggests to be around 5 ohm-meters or less.

With increasing dipole separation the apparent resistivities appear to increase (for example, between stations 4 and 5) perhaps suggesting a deep, resistive medium. The presence of a deep resistive body or layer is unresolvable due to the fact that surface resistivities also increase to the south which, as already indicated, will produce constructive interference for the larger spacings.

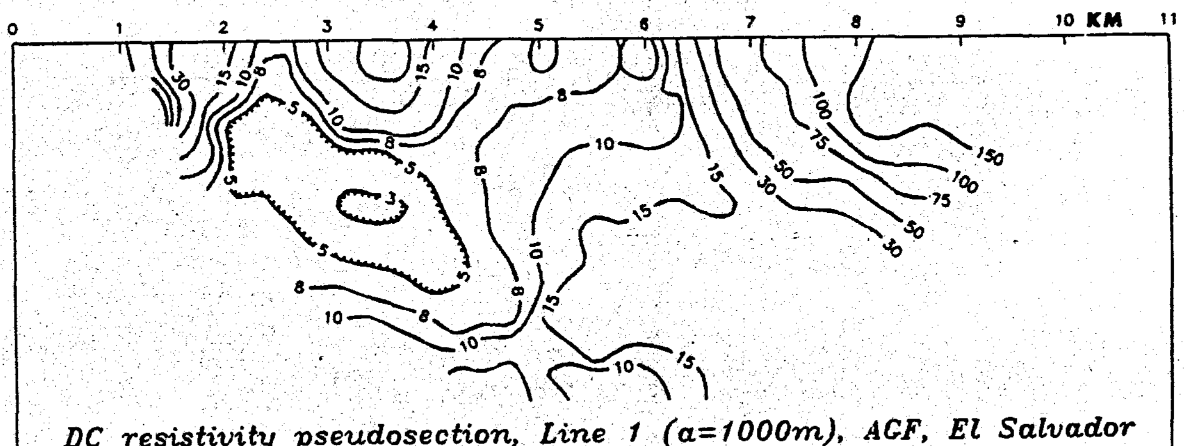


Fig. 3. Pseudosection of Line 1 showing the apparent resistivities logarithmically contoured in ohm-meters for 1000 meter dipole spacing.

The gradient indicated in the contoured data between stations 6 and 7 suggests a lithologic change occurring on the north slope of the mountains. This gradient location coincides with the contact between the Laguna Verde volcanics and the central graben pyroclastics. The moderately resistive material likely represents the unaltered Laguna Verde mountain-building volcanics. This is supported by the constancy of the shallower apparent resistivities to the south of the gradient that suggest the lithology remains the same within the vicinity of the survey line.

Geologic model

A geologic model for Line 1 is presented in Fig. 4. This model is based on the 1000 meter dipole data. Four media of different true resistivities were used to generate the model: medium 1 (100 ohm-meters); medium 2 (10 ohm-meters); medium 3 (500 ohm-meters); and medium 4 (5 ohm-meters). In the immediate vicinity of the AGF only media 1, 2, and 4 are relevant for the purpose of defining reservoir characteristics.

Model medium 1 (100 Ω-m)

Medium 1 is intended to represent the unaltered (or only partially altered) surface pyroclastics and lavas of younger San Salvador age. The moderate resistivity of 100 ohm-meters suggests limited hydraulic permeability and good potential for caprock formation. Medium 1 is vertically limited to the upper 600 meters. Laterally, medium 1 is modeled at the north end of the line, between stations 5 and 9, and in the previously-discussed isolated block between stations 3 and 4. In general, the base of medium 1 corresponds to the contact between reservoir lithologies and overlying lithologies. The depth to this contact in well AH-12 is reported at 550 meters, whereas in wells AH-1 and AH-20 the depth is 450 to 500 meters. In an area of variable lithology this is considered good agreement.

Model medium 2 (10 Ω-m)

Medium 2 represents lower resistivity material occurring from 300 meters to depth (greater than 1000 meters) and forming a vertical "plume" between stations 3 to 5. This plume-like vertical extension of lower resistivities corresponds very well with the shallow depths to high temperatures between stations 3 and 4. The northern extent or contact of the plume-like low resistivities occurs at station 3 and is coincident with a vertical fault. To the south, the plume-like feature contacts lower resistivity material (medium 4) at station 5 beneath the soccer-field fumaroles. Two lesser blocks of medium 2 are modeled at surface near station 7 to the south and between stations 1 and 2 to the north. These lesser blocks are regarded as being transitional material, probably less altered, between media 4 and 1. The thickness of these blocks is 100 meters, which corresponds well with the known alluvial thickness.

Model medium 3 (500 Ω-m)

Medium 3 represents a high resistivity medium occurring to the south of station 7 and corresponding to the aforementioned Laguna Verde volcanics of the high plateau in the vicinity of Apaneca. Enough resistivity data are available in that area to suggest that the Laguna Verde volcanics overlie more conductive lithologies represented by medium 2. Although medium 2 shows continuity from the AGF to approximately station 9, there is nothing else in the electrical data to support continuity for the thermal characteristics. Nevertheless, this area should not be disregarded for future geothermal potential.

Model medium 4 (5 Ω-m)

Medium 4 is intended to represent extensive hydrothermal alteration regardless of lithology. The close association of the low apparent resistivities with the fumarolic activity and surface alteration suggest that these low resistivities are likely a result of high porosity and high clay content. Hydraulic permeability is probably higher than the less altered lithologies in spite of the increase in clay content.

Although no medium 4 is presented in the model below 600 meters, a simple trade-off exists from the modeling standpoint. Consider the large, irregular block of medium 4 beneath stations 2 to 3. By removing some of that block of medium 4 and placing it below 600 meters in the same general area would produce similar model results. This exemplifies the inherent non-uniqueness of any modeling procedure. The choice of not modeling medium 4 beneath 600 meters was made to determine the resolvability of a conductive deep body with this particular data set. *In this instance*, a deep body of only moderate resistivity contrast with the overlying material is very difficult to detect, *because of the complexity of the overlying geology*. On the other hand, in an area of less surface complexity such as extensive caprock and minimal surface

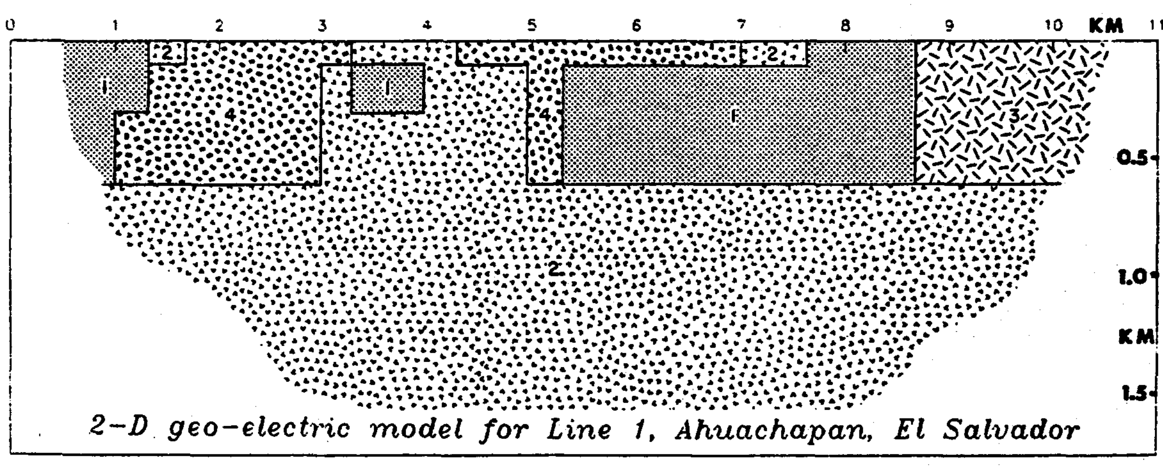


Fig. 4. Two-dimensional geo-electric model for Line 1 based on topographic corrected apparent resistivity data using a finite element program.

alteration, a deep conductive body should be readily mappable.

LINE 1 (a = 500m)

Figure 5 shows the data for Line 1 (a = 500m). As might be expected from the 1000 meter dipole data, the observed resistivities range from 1.8 to 250 ohm-meters. To be as compatible as possible, data were collected for dipole separations ranging from 0.2 to 14. Within the accuracy of the method, the 1000 meter and 500 meter pseudosections are very similar. The same pattern exists for the two sections and consequently the same interpretation would apply. The differences that are observed are not significant enough to warrant modeling changes.

This similarity of results illustrates two important points. First, there is probably no need to collect data at both 1000 and 500 meter dipole spacings as long as; 1. shallow data are collected for the larger dipole spacings, or 2. deeper data are collected for the shorter dipole spacings. The original work plan was oriented towards using the 1000 meter dipole data for deep investigation and the 500 meter dipole data for shallower control. The field work performed at AGF shows that both situations may be satisfied with a single dipole spacing, if appropriate dipole separations are used.

Topographic effects for the shorter dipole spacing are considerably larger and more complex. Figure 6 shows the modeled topographic effects in the vicinity of the Cuajuste crater. In this case the ridge effects may increase the apparent resistivities by up to 100% whereas the valley effects decrease apparent resistivities by approximately 50%. These extremes in topographic corrections suggest that the logistical advantage of shorter dipole sizes may be offset by more complex topographic effects in the resultant data.

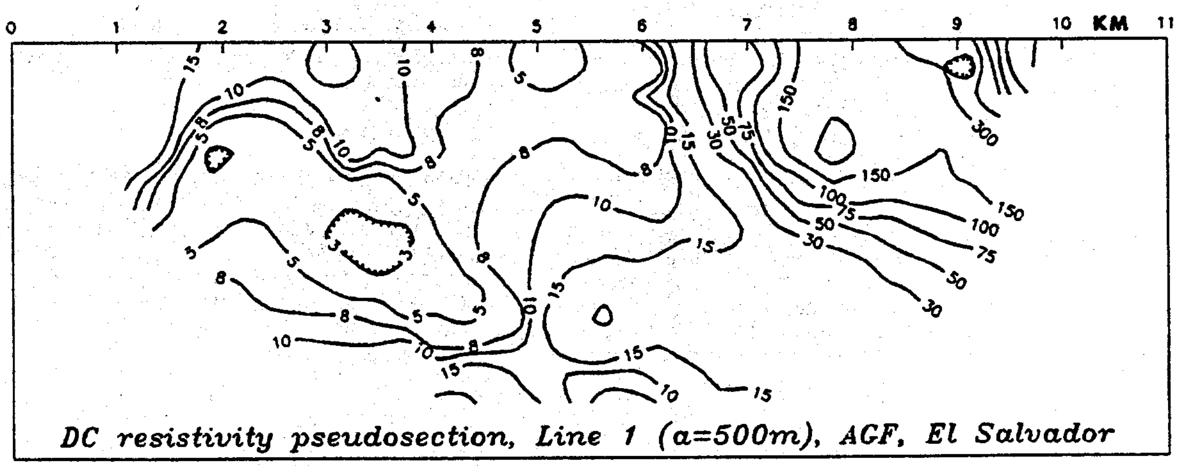


Fig. 5. Pseudosection of Line 1 showing the apparent resistivities logarithmically contoured in ohm-meters for 500 meter dipole spacing.

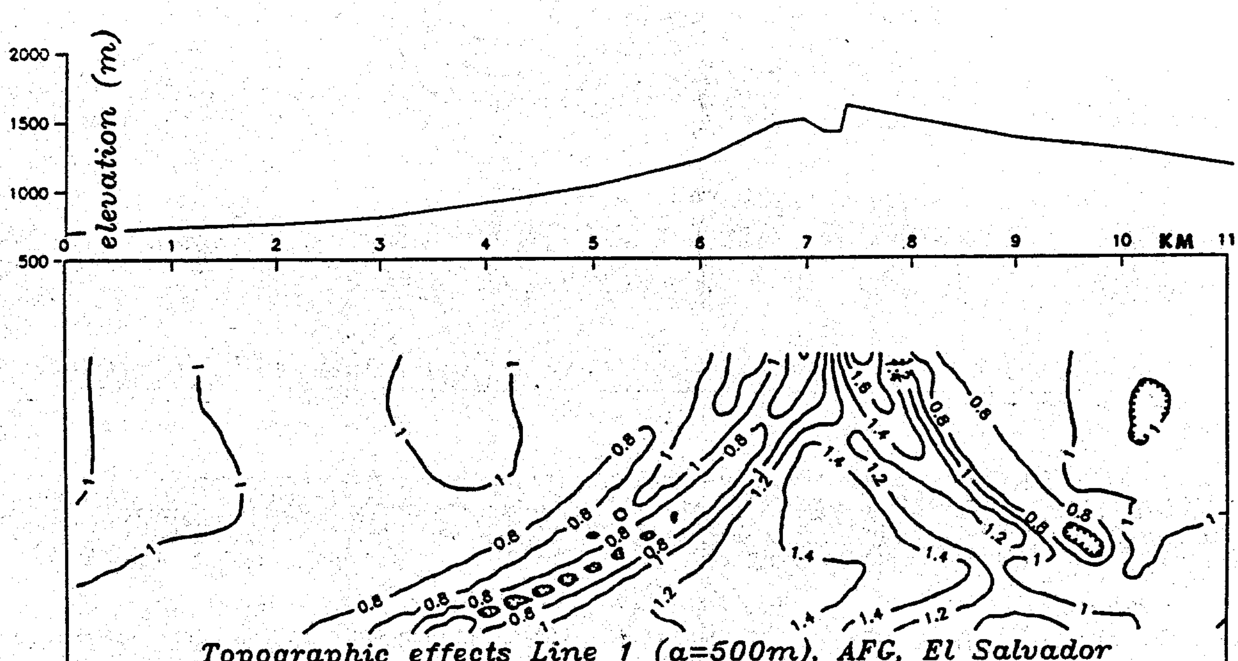


Fig. 6. Logarithmic pseudosection of topographic effects on Line 1 due to the mountains south of the site for 500 meter dipole spacings.

LINE 2 (a = 1000m)

Line 2 is oriented approximately east-west and crosses Line 1 roughly 250 meters north of station 4. The point of intersection on Line 2 is approximately 250 meters west of station 6 (see Fig. 2). Apparent resistivities ranged from 3.4 to 105 ohm-meters. With only a few exceptions, the entire pseudosection shows resistivities less than 20 ohm-meters, however, the general pattern of low-to-high apparent resistivities is surprisingly similar to that of Line 1. The similarity *of pattern would be desirable for two-dimensional modeling if* the features appeared parallel. They do not appear parallel and do demonstrate the three-dimensionality of the area.

The apparent resistivity data are presented in Fig. 7. The lowest near-surface resistivities occur at station 4 near the Agua Shuca fumaroles. The low apparent resistivities appear to extend to station 5, located just east of the Rio Los Ausoles. Higher resistivities are encountered at station 7 and are suggestive of the localized moderate resistivity block occurring on Line 1 between stations 3 and 4. There does not appear to be a direct connection between these two localized resistive blocks. At surface, another low resistivity area occurs to the east around station 10 which is reasonably close to the Cuyanausul fumaroles. These near-surface, apparent resistivity lows further support the previous observation that they are associated with extremely altered lithologies.

Topographic corrections were not determined for Line 2. The eastern end of the line encountered moderate topographic relief but the lack of severe relief and the non-orthogonal two-dimensionality of the topography encountered minimized the necessity and usefulness of topographic corrections, in this instance.

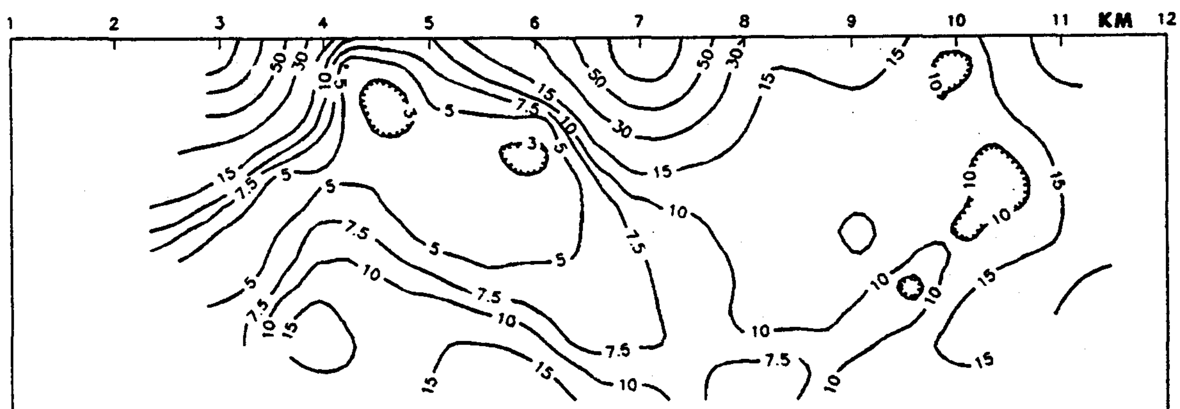
The most salient feature of Line 2 is the presence of an apparent resistivity low beneath stations 4 to 6. It is most likely that this feature is related to the aforementioned hydrothermally-altered lithologies. This feature is quite similar to the apparent resistivity low occurring on Line 1 beneath stations 2 to 4 in the immediate vicinity of the AGF. Interestingly, both wells AH-8 and AH-9 (which bracket Line 2 between stations 4 and 5) are non-productive. The geologic logs indicate that the more permeable agglomerates are missing in these two holes but the temperature logs indicate that relatively high temperatures are still present.

The consistent values of 10 to 15 ohm-meters is suggestive of an elevated thermal environment between stations 7 and 11. The lack of shallow, more resistive material that could serve as caprock is somewhat of a drawback but not so much that the area should be disregarded. *This area lies between the* Chipilapa and Cuyanausul surface expressions.

The deeper appearing localized highs and lows in the apparent resistivities are likely the result of interference effects from surface features.

LINE 2 (a = 500m)

As with Line 1, the shorter dipole data display a pattern quite similar to that of the larger dipoles. Apparent resistivities ranged from 3.3 to 127 ohm-meters. Differences in the observed values do not justify any change in interpretation of the larger dipole pseudo-section. The similarity of the 500 and 1000 meter dipole data on both lines indicates that sufficient information is available with only one dipole spacing if the appropriate dipole separations are used.



DC resistivity pseudosection, Line 2 (a=1000m), AGF, El Salvador

Fig. 7. Pseudosection of Line 2 showing the apparent resistivities logarithmically contoured in ohm-meters for 1000 meter dipole spacing.

SUMMARY

The apparent resistivity data collected for Lines 1 and 2 at the AGF display a three-dimensional complex geologic picture. Two-dimensional modeling demonstrates that known lithologies may be identified (where unaltered) by a limited range of resistivities. Reservoir rocks have interpreted true resistivities of less than 10 ohm-meters. Younger overlying rocks range from 20 to 200$^+$ ohm-meters. Both of these lithologies may be hydrothermally altered to have resistivities below 5 ohm-meters.

The known reservoir at the AGF does not appear to have a sufficiently diagnostic electrical signature to stand out relative to the interference effects of the near-surface altered lithologies and possible cultural effects. It is not unusual for a fracture-flow hydraulic regime to show little or no electrical resistivity contrast with the country rock. One of the results of a magnetotelluric survey performed previously indicated that the reservoir was a high-resistivity body relative to the country rock. These relatively-high resistivity characteristics are not seen in either the VES's or dipole-dipole dc data.

The severe topography encountered on Line 1 does not pose an interpretational problem with 1000 meter dipole data as long as it is taken into account. The 500 meter dipole data suffer more from the topography but should not be left out of consideration for future work because the shorter dipoles have other logistical advantages.

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