FINAL REPORT

**Results of Investigations at the
Ahuachapán Geothermal Field, El Salvador
Part 2: Electrical-Methods Geophysics**

by

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Prepared for:

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Subcontract No. 9-XQO-E8837-1

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April 1990

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1.0 INTRODUCTION

The Ahuachapán Geothermal Field (AGF) is a 95 megawatt geothermal-sourced power-plant operated by the Comisión Ejecutiva Hidroeléctrica del Río Lempa (CEL) of El Salvador. During the past decade, as part of an effort to increase in situ thermal reserves in order to realize the full generation capacity of the AGF, extensive surface geophysical coverage has been obtained over the AGF and the prospective Chipilapa area to the east. The geophysical surveys were performed to determine physical property characteristics of the known reservoir and then to search for similar characteristics in the Chipilapa area. A secondary objective was to evaluate the surface recharge area in the highlands to the south of the AGF. The principal surface electrical geophysical methods used during this period were DC resistivity and magnetotellurics. Three available data sets have been reinterpreted using drillhole control to help form geophysical models of the area. The geophysical models are compared with the geologic interpretations presented by Lawrence Berkeley Laboratories (LBL, 1989), of Berkeley, California and of Electroconsult (ELC, 1984b), of Milan, Italy.

The AGF is located in the western end of El Salvador as shown in Fig. 1.1. Within the general AGF area the emphasis for the electrical methods geophysics has been on a canted rectangular grid that was centered on the Chipilapa area, but also covered the AGF to the

Fig. 1.1. Location map of the Ahuachapán Geothermal Field, El Salvador.

west. The grid and other geophysical survey locations are shown in Fig. 1.2. The grid orientation was $N65^{\circ}E$ and was approximately 4 kilometers wide. The VES coverage extended 3.5 kilometers both northeast and southwest of center. Gravity coverage was also performed concurrently on the same grid but extended an additional 1.5 kilometers both northeast and southwest of the VES sites. Between 1982 and 1985, CEL geophysical personnel observed 135 Schlumberger array vertical electrical soundings (VES's) and 410 gravity sites. A magnetotelluric survey was performed by Geosystem s.r.l., of Milan, Italy in 1984 and 1985. The MT survey consisted of 73 soundings at convenient locations primarily within the VES-gravity grid.

Subsequent to the VES and MT work, a large-scale, dipole-dipole array, DC resistivity (DDR) survey was designed and implemented by Los Alamos National Laboratory (LANL) under a U.S.A.I.D. program during the period 1987 through 1990. During this program, two DDR survey lines were performed under the direction of LANL personnel at which time technology transfer through on-site training took place. Two more lines were performed inde-

Fig. 1.2. Location of the VES sites (open circles), MT sites (stars), DDR survey lines, and drillholes (solid circles). Ahuachapán and Turin are shown for reference.

pendently by CEL geophysical personnel. A total of four of the five originally designed five lines were performed.

The purpose of this report is to present a "final" interpretation of the DDR work. This "final" interpretation includes the evaluation of the previously performed electrical geophysics and a joint re-interpretation of the collective electrical geophysics. All data sets have been reprocessed by hydroGEOPHYSICS (formerly Geophynque International) of Tucson, Arizona to various degrees depending on the level of the original information available. Other previously performed geophysical surveys, much smaller in scope, were not available for this report. The gravity survey and subsequent geophysical surveys, such as microseismic monitoring (Fabriol et al. 1990) and a new magnetotelluric survey performed by Instituto de Investigaciones Electricas (IIE) of Cuernavaca, Mexico (CEL, personal communication, 1990), are not included in the present discussion but are referenced.

The conclusions presented herein differ considerably from the original interpretations, but these differences result in a more uniform geological picture and apparent agreement with the geology as it has been mapped and logged. The most desirable result from the integrated interpretation would be a potential location for additional steam reserves. This objective has been realized and a target has been partially defined. Although the target occurs in a somewhat unlikely location, there is sufficient geophysical evidence to warrant further investigation.

2.0 NOMENCLATURE AND SOURCE INFORMATION

For the purpose of simplifying comparisons and maintaining consistency, the nomenclature used in this report for drillholes, geologic cross-sections, geophysical survey lines, and geophysical survey sites adheres, where possible, to previously encountered nomenclature. Since several references have been cited and used, there are several options available for nomenclature and sections. This section addresses these options in hopes that if confusion arises, this section may be referred to in order to clarify the point.

2.1 Information Sources

Geologic information was derived from internal reports by CEL and contract reports from Electroconsult (ELC) and Lawrence Berkeley Laboratory (LBL). These were the only geologic reports available for this report. Geophysical information was derived from internal reports by CEL and contract reports from Geosystem s.r.l. (GEO) and hydroGEOPHYSICS (HG). Topographic information was derived from 1:50,000 and 1:25,000 topographic maps published by the Instituto Geográfico Nacional de El Salvador. Report references are listed in the section 8.0 REFERENCES AND RELATED PUBLICATIONS.

2.2 Coordinate System

The common mapping coordinate system generally in use in El Salvador is based on the Lambert Conic Conformal Projection. The metric grid locations used are Lambert Metric and not Universal Transverse Mercator (UTM) as is more commonly encountered. The use of both coordinate systems for the presentation of data makes direct comparison difficult. However, if direct comparison is desired, then the correct coordinate conversion method must be used. This point is made because the reference coordinates for El Salvador are unique to El Salvador.

The reference coordinates for the Lambert Origin in El Salvador at 13° 47'N, 89°00'W which is assigned a False Easting of 500,000 meters and a False Northing of 295,809.184 meters. These reference lines for the national grid are shown as the crosshairs in Fig. 1.1. As an example, well Ah-06 is given the location: 310,791.22m latitude, 411,921.01m longitude

(LBL, 1989). The converted, equivalent geographic coordinates for well Ah-06 are 89° 48' 54.05"W, 13° 55' 2.68"N. All plotted data in this report are presented using Lambert Metric coordinates.

2.3 Source Identification

Several reports use similar profile or cross-section labeling schemes. To minimize confusion, this report uses three character prefixes, such as CEL, ELC, LBL, VES, MTS, or DDR to indicate either which report source or which geophysical method is being used. For example, cross-sections presented by LBL are referred to as LBL E₁-E₂, etc.

The terms drillhole and well are used synonymously and are referred to by a five character identifier, e.g. Ah-06, Che-1, etc. Fortunately, this nomenclature has been reasonably uniform throughout the various reports.

2.4 Schlumberger VES Sites

The Schlumberger array, low frequency, vertical electrical soundings (VES's) performed by CEL are referred to by a seven character identifier, e.g. VES-001, VES-002, etc. The VES's were performed in a rectangular grid so that several collinear VES's are referred to as Line-01, Line-02, etc. VES's actually have two sets of identifiers, a single number (indicating the chronological sequence in which the VES's were performed) and a grid location identifier. The grid was used for both resistivity and gravity and was centered on the prospective Chipilapa area. The grid center is 0+000 (approximate coordinates near Ch-01). VES locations are indicated by distance away from center and direction, e.g. VES-001 is at grid center, VES-072 is 1+000SW on Line-8, VES-110 is 2+500NE on Line-14, etc.

Surveyed coordinates were unavailable for the VES sites. Plotted locations have been digitized from supplied location maps. The CEL internal report (Rodriguez, 1985) on the resistivity work also contains profiles referred to as A-A' through J-J'. Profiles A-A' through I-I' are identical to Lines 1 through 14, although, numerically, not all of Lines 1 through 14 exist. The relationship is shown in Table 1. Profiles J-J' through Y-Y' are also collinear sets of VES's within the rectangular grid, but are orthogonal to the first set of profiles. Profiles

A-A' through I-I' are oriented N65°E and profiles J-J' through Y-Y' are oriented N25°W. VES profiles are referred to as VES Line A-A', etc.

Table 1. VES profile nomenclature

Grid line	VES profile	VES grid range
1	E-E'	3+500SW to 3+500NE
2	F-F'	3+500SW to 3+500NE
3*	---	3+500SW to 3+500NE
4	G-G'	3+500SW to 3+500NE
5*	---	3+500SW to 3+500NE
6	H-H'	3+500SW to 3+500NE
7*	---	3+500SW to 3+500NE
8	I-I'	3+500SW to 3+500NE
9*	---	3+500SW to 3+500NE
10	C-C'	3+500SW to 3+500NE
11**	---	3+500SW to 3+500NE
12	B-B'	3+500SW to 3+500NE
13*	---	3+500SW to 3+500NE
14	A-A'	3+500SW to 3+500NE

* doesn't exist in VES or gravity grid **exists only in the gravity grid

2.5 MT Sounding Sites (MTS)

The magnetotelluric soundings performed by Geosystem S.r.l. are referred to in this report by seven character identifiers, such as MTS-001, MTS-002, etc. The MTS's are not grid based, but do lie mostly within the VES-gravity grid. The MT site locations were originally indicated in Geosystem's report by two descriptors, e.g. A20 & MT 020, A80 & MT 080, etc. and apparently were labeled chronologically. Geosystem's descriptors were not used in this report because of the duplication and similarity to the drillhole identifiers.

2.6 Dipole-Dipole Resistivity Lines (DDR)

The four DDR survey lines are referred to as Line-1, Line-2, etc. and only partially correspond to the VES-gravity grid. For example, Lines 1 and 2 cross the grid diagonally near the western end of the grid and do not correspond to any other VES profiles or lines. Line 4 was oriented to correspond to VES Line R-R' for a portion of its length. Line 5 was oriented to correspond to VES Line C-C' (VES Line 10) for a portion of its length. Line-3 was not performed.

3. GEOPHYSICAL METHODS DISCUSSED

The various geophysical methods discussed in this report are briefly described for the purpose of understanding their usage. This description is not intended to explain how, or why, the methods work or how the data are interpreted, but rather, the rationale behind the selection of methods and how the different results compare. The method-to-method comparison is useful in understanding how the final interpretations have been accomplished.

Electrical geophysical methods have proven themselves useful tools in the geothermal environment for the simple reason that elevated temperatures increase the total dissolved solids (TDS) in the reservoir fluid thereby lowering the electrical conductivity of the reservoir rock relative to the surrounding host rock.

There were three different methods used to measure apparent resistivity in the vicinity of the AGF; low-frequency (pseudo-DC) Schlumberger array vertical electrical soundings (VES's), true-DC dipole-dipole array (DDR) traverses and soundings; and magnetotelluric soundings (MTS's). Each method has unique attributes that made it amenable to the purpose for which it was used.

In the AGF and adjacent Chipilapa prospect, the VES's were intended for relatively shallow investigation; the magnetotellurics were intended for much deeper investigation; and the dipole-dipole work was intended to extend coverage to new areas, fill in the intermediate depth range, and have continuous profile coverage of the areas surveyed.

3.1 Schlumberger array VES's

Schlumberger array VES's were started in 1982 by CEL and were interpreted and reported in 1985 (Rodriguez, 1985). The VES's were placed at regular intervals within a 50 square kilometer grid centered on the Chipilapa area. The grid encompasses most of the AGF to the southwest, and extends just beyond the town of Turin to the northeast. Array spacings ($AB/2$) ranged from a minimum of 15 meters to a maximum of 1500 meters. This suggests an approximate homogeneous-half-space-depth-range of 1 meter to 400 meters. Typically, 19 unique spacings were observed for each VES which resulted in a logarithmic sampling density

of approximately ten points per decade. Fig. 3.1 shows the locations of the VES sites within the VES grid.

Fig. 3.1 Location of VES sites within the VES-gravity grid.

The resistivity measurements were made using McPhar Geophysical equipment (Rodriguez, 1985). The most crucial equipment parameter is the fixed operating frequency of 0.3 Hz. Under "normal" operating conditions 0.3 Hz. would be satisfactory. However, due to the low resistivities typical of geothermal fields (and seen at the AGF) and at relatively large AB/2 spacings (e.g. >200m), electromagnetic (EM) or inductive signal contribution becomes significant and may easily dominate the desired resistive contribution to the signal. This problem did occur at the AGF and was recognized (Rodriguez, 1985). The influence of the EM response limited the *effective* depth of investigation to approximately 100 meters in many instances.

EM effects are easily seen in the VES's as a sharp upturn in the sounding curves occurring at large spacings and, as a result, are frequently mistaken as representing resistive basement. The reason that this effect is easily recognized is that the maximum theoretical slope for a resistive basement underlying a horizontally-layered isotropic earth is $+45^\circ$. Whenever this

theoretical slope is exceeded the data are suspect for three reasons: 1. EM effects, 2. lateral or non-layered effects, and 3. current leakage to ground. The EM effects were correctly recognized and ignored by Rodriguez in his interpretation and have been similarly acknowledged in this report. Although it is possible, no attempts were made to model the EM effects because one of the essential parameters necessary for modeling, the offset distance between transmitting and receiving cables, was not (and is not normally) recorded. Furthermore, the purpose of performing the DDR at true DC effectively eliminated the problem.

3.2 Magnetotelluric Soundings

Seventy-five magnetotelluric soundings were performed at accessible locations within the VES-gravity grid by Geosystem s.r.l. of Italy during 1984. The MT soundings generally had 25 to 30 frequencies, ranging from a high of 16.667 Hz. to a low of 0.025 Hz. The depth of investigation or penetration is typically estimated from the plane-wave skin-depth formula where the skin-depth is defined as the depth at which the amplitude of the signal has been attenuated to $1/e$ of its surface value for a homogeneous, isotropic earth. The approximate half-space skin-depth range for these frequencies, and for a range of resistivities typical for the AGF, is a minimum of less than 150 meters (for 1 ohm-meter at 16.667 Hz.) to greater than 100,000 meters (for 1000 ohm-meters at .025 Hz.).

As with the VES's, the MTS's show numerous examples of lateral (non-one-dimensional) effects. These effects are most easily seen as gradients steeper than can be obtained by any realistic layered-earth model, regardless of resistivity contrast between layers.

MTS's may also suffer from what is called "static shift". Static shifts result from placing the MT site over a laterally discontinuous medium of resistivity different from that of the surrounding near-surface host rock. The entire resulting sounding curve may be shifted in absolute value of apparent resistivity because the effect is independent of frequency. The qualitative characteristics of the MTS's may or may not be affected, and true resistivities cannot be satisfactorily obtained through interpretation or modeling without an ancillary electrical (preferably electromagnetic) sounding method performed at the same site. Neither ancillary methods nor remote referencing was performed as part of the MT survey. Specific VES's should not be used for static shift correction because they were not performed at the same locations

and because the apparent resistivities for VES's are measured and calculated differently from those of MTS's.

Geosystem used computer inversion methods to model the MTS's. By comparing the two orthogonal E-field responses, Geosystem determined that if the skew were small enough, then the sounding could be modeled using the one-dimensional approximation.

Geosystem presented the data and model results in a variety of formats: 1. printer plots showing field data, model data, and the layered-earth model parameters; 2. tabular listings of the frequencies used, observed apparent resistivity (assumed to be the X-Y E-field orientation), calculated apparent resistivity for the model, difference between field and model results, calculated model phase, and the relative standard deviation between the model and field results; 3. log-log plots of both E-field apparent resistivity with smoothed curves drawn through them; 4. cross-sections showing MT interpretations, temperature logs, and lithologic logs; 5. profiles of MT interpretations and lithologic logs; and 6. plan maps of contoured results based on the MT interpretations. Fig. 3.2 shows the location and numbering of the MT sites.

Fig. 3.2. Location and numbering of the Electroconsult MT sites.

Some of Geosystem's interpretations involved layered-earth models with up to eight layers, but most of the interpretations are limited to five layers. Interpretations with less than five layers are considerably more reliable than those with five or more. Reliable resolution of eight layers is unlikely.

Table 3.1 MT Model Layered-Earth Parameters (ELC, 1984b)

MTS	R1	T1	R2	T2	R3	T3	R4	T4	R5	T5	R6
MT-001	300.0	200.	2.8	350.	1000.	900.	1.0	300.	1000.		
MT-002	100.0	360.	1.5	230.	500.	600.	1.0	280.	3000.		
MT-003	30.0	150.	4.0	250.	500.	650.	1.5	600.	1000.	9000.	3.0
MT-004	200.0	500.	2.0	100.	1500.	3500.	2.0	350.	5000.		
?>MT-006	10.0	150.	1000.	400.	2.3	450.	5000.				
MT-008	3.8	120.	0.8	230.	5000.	700.	0.8	280.	5000.		
MT-009	80.0	350.	0.8	300.	100.	2000.	3.0	400.	50.		
MT-010	4.5	180.	0.8	650.	9999.	3500.	10.0				
MT-011	13.0	300.	1.0	200.	1000.	200.	1.0	300.	5000.		
MT-012	500.0	520.	1.0	60.	500.	800.	1.0	220.	5000.	6000.	5.0
MT-013	30.0	500.	0.8	80.	120.						
MT-014	10.0	360.	1.0	220.	100.	300.	1.0	5000.			
MT-015	2.5	140.	0.8	240.	5000.	400.	0.8	9999.			
MT-016	15.0	150.	0.8	280.	500.	2500.	1.0	5000.			
MT-017	100.0	215.	0.8	170.	500.	390.	0.8	9999.			
MT-018	10.0	70.	0.81	240.	10.	300.	3.0	900.			
MT-019	70.0	95.	0.8	340.	5000.	2700.	0.8	220.	9999.		
MT-020	40.0	125.	0.8	350.	100.	4000.	3.0	600.	1000.		
?>MT-021	1.0	70.	500.	270.	0.8	320.	1000.				
MT-022	500.0	170.	0.8	230.	500.	1350.	2.0	520.	1000.		

Although there are only half as many MTS's as VES's, the MTS's are still amenable to statistical evaluation. Table 3.1 shows layered-earth-model parameters for the first twenty MTS's as reported by Geosystem. Columns headed R1, R2, etc. indicate the resistivity for that layer. Columns headed T1, T2, etc. indicate the thickness for that layer. Visual inspection of column 3 (R2) reveals a tendency for that layer to have a very low resistivity. This tendency persists throughout the entire 75 soundings. However, in this sampling, MT-006 and MT-021 clearly are anomalous in that they show quite high values for R2. These two soundings are also at odds with the tendencies in columns R3 and R4. This type behavior may be acceptable in an area where significant structural offsets exist, which could be the case for the AGF. However, an alternative viewpoint is that the computer modeling may not be representative of the local structure. Both possibilities are valid.

A simple experiment of shifting the model parameters of MT-006 and MT-021 two columns to the right (the equivalent of a vertical shift of one layer) shows that the model parameters have a much better consistency in the parameters in the noted columns. Table 3.2

shows the appearance of the shifted models. Casual inspection of Table 3.2 reveals much better parameter correlation than Table 3.1 and suggests that the overall modeling deserves a second look.

Table 3.2 Shifted MT Model Layered-Earth Parameters (ELC, 1984b)

MTS	R1	T1	R2	T2	R3	T3	R4	T4	R5	T5	R6
MT-001	300.0	200.	2.8	350.	1000.	900.	1.0	300.	1000.		
MT-002	100.0	360.	1.5	230.	500.	600.	1.0	280.	3000.		
MT-003	30.0	150.	4.0	250.	500.	650.	1.5	600.	1000.	9000.	3.0
MT-004	200.0	500.	2.0	100.	1500.	3500.	2.0	350.	5000.		
>MT-006			10.0	150.	1000.	400.	2.3	450.	5000.		
MT-008	3.8	120.	0.8	230.	5000.	700.	0.8	280.	5000.		
MT-009	80.0	350.	0.8	300.	100.	2000.	3.0	400.	50.		
MT-010	4.5	180.	0.8	650.	9999.	3500.	10.0				
MT-011	13.0	300.	1.0	200.	1000.	200.	1.0	300.	5000.		
MT-012	500.0	520.	1.0	60.	500.	800.	1.0	220.	5000.	6000.	5.0
MT-013	30.0	500.	0.8	80.	120.						
MT-014	10.0	360.	1.0	220.	100.	300.	1.0	5000.			
MT-015	2.5	140.	0.8	240.	5000.	400.	0.8	9999.			
MT-016	15.0	150.	0.8	280.	500.	2500.	1.0	5000.			
MT-017	100.0	215.	0.8	170.	500.	390.	0.8	9999.			
MT-018	10.0	70.	0.81	240.	10.	300.	3.0	900.			
MT-019	70.0	95.	0.8	340.	5000.	2700.	0.8	220.	9999.		
MT-020	40.0	125.	0.8	350.	100.	4000.	3.0	600.	1000.		
>MT-021			1.0	70.	500.	270.	0.8	320.	1000.		
MT-022	500.0	170.	0.8	230.	500.	1350.	2.0	520.	1000.		

The lack of correlation between the original MT interpretation and the mapped geology prompted the decision to perform the 1990 MT survey. For this reason, and the fact that, on Geosystem's contour-structure maps, closures occur around several suspect model parameters, it was felt that reinterpretation of the original MTS's may provide a better correlation between mapped geology and the MT interpretation, as well as assist in the overall electrical methods modeling.

3.3 Dipole-dipole resistivity

The dipole-dipole resistivity survey and related technology transfer were performed at the AGF during the period of November 1987 through May 1988. Equipment used for the survey was designed by LANL personnel and manufactured under sub-contract. Two high-powered DC resistivity transmitters were built, one of which was consigned to Central America for the U.S.A.I.D. funded technology transfer program.

The purposes of using dipole-dipole resistivity were: 1. to evaluate new areas and concepts not investigated by previous methods; 2. to collect continuous data between the AGF and

Chipilapa areas; and 3. to better evaluate the range of depths between those of the Schlumberger array VES's (i.e. those unaffected by EM effects) and those of the highest frequencies in the MTS's. Two dipole sizes were used, 500 and 1000 meters. Inter-dipole spacings ranged from 100 meters ($0.1 \times 1000\text{m}$) to 6 km ($6 \times 1000\text{m}$) giving a homogeneous-half-space-depth range of less than 40 meters to greater than 1500 meters.

Fig 1.2 shows the four dipole-dipole survey lines that were performed for a total of forty-eight kilometers of surface coverage. Two, near-parallel, lines (1 and 4) were run approximately north-south through the AGF and Chipilapa areas. Line 2 ran from the southwest to the northeast skirting the AGF to the south and through the center of the Chipilapa area. Line 5 ran east-west through the southern part of the AGF and close to the region of surface manifestations south of the Chipilapa area.

As one of the principal objectives of the technology transfer program, the dipole-dipole resistivity data were modeled using one-dimensional and two-dimensional methods. These results were both based on, and combined with, the interpretations of the VES's and MTS's.

4. LABORATORY PHYSICAL PROPERTY MEASUREMENTS

Prior to, and concurrent with, the field studies, core samples were tested in the laboratory for several physical properties. Three CEL internal reports on laboratory measurements were made available (Larios, 1984a?; 1984b; & 1985). The properties measured were: 1. electrical (Larios, 1984a?), 2. magnetic susceptibility (Larios, 1984b), and 3. texture and thermal (Larios, 1985). The last report was a synthesis of a more comprehensive report that was not available.

4.1 Electrical properties

In an undated internal report from CEL (Larios, 1984a?) laboratory electrical resistivities were reported on nine core samples from the Ahuachapán field. Complex resistivities were reportedly measured but only vector resistivities were actually included in the report. Complex resistivities were measured as functions of confining pressure and artificially-supplied electrolyte conductivity. The samples included most of the typical lithologies observed in, above, and off the reservoir. Unfortunately, the limited number of samples precludes forming any statistical conclusions.

Nine or ten test frequencies were used which ranged from 5 Hz to 100,000 Hz at logarithmically spaced intervals, all of which are above any reported frequencies used for field measurements. Ordinarily, this would not be of any consequence because broadband measurements can reveal interesting and perhaps useful electrical characteristics. Indeed, in this instance, a noticeable in-phase induced polarization response was suggested in the data at the lowest frequencies, but, because there are no in-phase data below 5 Hz, nor quadrature data at any frequency, spectral characteristics or even a qualitative estimate of true polarization response remains undefined. The ranges of observed resistivities at low-frequencies (5 Hz or 10 Hz) was from 5 ohm-meters to 800 ohm-meters.

Test pressures were 100, 500, and 1000 psi for all but one isolated test where three additional intermediate pressures were used to better define the pressure-resistivity relationship. The core samples were saturated with a brine solution of composition similar to that of the AGF and of two resistivities, 0.3 and 0.6 ohm-meters.

According to conventional thought, the non-reservoir, unaltered lithologies would be expected to have high resistivities and the altered lithologies occurring within the reservoir, low resistivities due to increased permeability, porosity, and clay content. The results of the nine laboratory-tested core samples showed no such pattern. Further, the resistivity of the saturating solution showed little effect on the resultant matrix resistivity indicating that, even when altered, the primary factor controlling the bulk resistivity (at least within the constraints of the laboratory measurements) is the rock matrix and not the contained electrolyte. This is typical of a fracture-controlled reservoir.

Changing the confining pressure had negligible effect at high frequencies, but an inverse relationship was observed at low frequencies, i.e. low pressures produced noticeable increases in resistivity. This effect was most pronounced for the lowest pressure (100 psi) and at the lowest frequency (5 Hz). It can be inferred from these results that induced polarization (IP) may be a useful geophysical method for observing this same effect *in situ* if care is taken to avoid, or correct for, electromagnetic effects. Based on the original temperature logs and the limited number of samples, there does not appear to be a reliable inverse temperature-resistivity relationship. This does not mean that the main geothermal reservoir can be claimed to be electrically resistive or conductive. Rather, it reflects on the statistically insignificant number of tested core samples and on the small size of the core samples in relationship to the overall volume of the reservoir. The lack of a definable relationship must be considered tentative until further laboratory samples are tested and a larger statistical base is established.

Collectively, the laboratory observations are in accord with the fractured character of the reservoir. The suggestion is that, on a local basis (e.g. a few meters), there might not be a characteristic electrical signature, i.e. a resistivity low, related to desirable geothermal conditions. Consequently, one might conclude that the reservoir should appear as electrically resistive. However, the large volume, or gross, electrical characteristics may be very different from the extremely small volume laboratory core sample observations because the core selection process usually results in samples without fractures. On a large scale, increased fracture density offers numerous electrical pathways which usually lowers the electrical resistivity.

Only field measurements can offer large volume electrical characteristics. It was with this understanding that field measurements were made and, indeed, the results suggest that the

thermally elevated areas appear to have lower resistivities. From the field resistivity measurements, it may be inferred that there is a greater fracture density in the reservoir area.

4.2 Magnetic susceptibility

Approximately 100 core samples and 10 hand specimens were run for magnetic susceptibility using a Scintrex CTU-2 Physical Property Testing System in 1983. Samples were taken from most of the wells to represent the various lithologies. Hand specimens were taken from various outcrops of the surface tuffs and lavas. A summary of the results was presented by Larios (1984b).

Susceptibility values ranged from less than 0.1 to 7.0×10^3 c.g.s. units. As might be expected for volcanics, no definitive correlation could be established between the measured susceptibilities and either the lithologies recognized at that time or the location of the samples within the geothermal environment. This does not preclude the possible utility of surface magnetics, but the probability of defining specific horizons on the basis of magnetic susceptibility is low. The susceptibility measurements have no other bearing on the thrust of this report.

4.3 Texture and thermal properties

The textural and thermal properties reported by Larios (1985), referenced in this report, were summarized from a previous comprehensive report by Larios. The parameters measured and calculated were maximum horizontal permeability, porosity, apparent density, grain density, and thermal conductivity. Unfortunately, the comprehensive report was unavailable and the summary did not show some of the sample characteristics for the hydraulic parameters that would have been useful, e.g. the number of samples and depths of the samples. The hydraulic parameter results were averaged on a hole-to-hole basis and on a formation basis. Although the averaged values are interesting, they pose a problem when trying to relate them to newer information. For example, with a possible reinterpretation of the drillhole lithologies (LBL, 1989), the previous formational referencing makes it difficult to relate the physical properties to the new interpretation. Also, the absence of depth information makes the data unrelatable to other depth indexed information.

The range of the averaged permeabilities was from 0.035 to 1.36 milliDarcies. The range of averaged porosities was from 19 to 28 percent. The range of averaged bulk densities ranged from 1.99 to 2.25 g/cc, which is typical for volcanics and relevant to the gravity surveying. The thermal conductivities ranged from 5.8 to 8.9×10^{-3} cal per centimeter-second-°K.

5. GEOLOGY OF THE AHUACHAPAN GEOTHERMAL FIELD

The geology of the Ahuachapán Geothermal Field has been discussed extensively in several reports that are listed in section 8.0 REFERENCES AND RELATED PUBLICATIONS. The intent of the present section is not to discuss the general geology *per se* but rather to present the aspects of geology relevant to the geophysics discussed in this report.

5.1 Regional Setting

El Salvador is situated adjacent to the Middle America Trench, a subduction zone created by the collision of the Cocos Plate with the Caribbean Plate. The subduction gives rise to volcanic activity from Mexico to Costa Rica. El Salvador is characterized by relatively young volcanism (Tertiary) and has no surface exposure of rocks older than younger Mesozoic.

The AGF is located on the south side of the Great Interior Valley (or Central Graben), a major morphological feature that extends the length of El Salvador. Considerably greater volcanic activity is related to the southern boundary of the Great Interior Valley compared to the northern boundary. The Great Interior Valley has been proposed as an extensional graben related to post-plate-collision, crustal relaxation. The southern boundary of the proposed graben may be a major structural zone of weakness that offers favorable pathways for ascending magmatic material.

5.2 Local Geology

The geology of the AGF and surrounding area has been characterized as a block-faulted, stratigraphic, volcanic sequence. The relevant stratigraphic sequence (from surface down) is made up of two main formations; the Quaternary San Salvador Fm. and the Pliocene Bálsamo Fm.

The San Salvador Fm. is separable into three members; Holocene Colluvium (altered pyroclastics and lavas) referred to as Elluvials (EL), Pleistocene pyroclastics and andesites referred to as Young Agglomerates (YA), and Plio-Pleistocene andesites referred to as Ahuachapán Andesites (AA). The underlying Bálsamo Fm. is made up of breccias and andesites and

is referred to as Older Agglomerates (OA). The two deepest lithologic groups, i.e. the AA and OA represent the most favorable horizons for the reservoir zone.

5.3 Geophysical Characteristics

The principal structural and textural geologic features favoring geophysical investigations are:

1. lithologic differences resulting in physical property contrasts across stratigraphic horizons (vertical contrasts),
2. structural offsets in lithologies with detectable physical properties (vertical and lateral contrasts),
3. thermal alteration of physical properties (vertical and lateral contrasts), and
4. lateral differences in texture, and due to texture, occurring within any given horizon resulting in physical property contrasts (lateral contrasts).

Of the various physical properties studied in the laboratory, none showed sufficiently consistent characteristics such that the known lithologies could be uniquely identified by only those characteristics. This observation is not unusual for laboratory studies and is not totally negative. As stated in section 4.0 LABORATORY PHYSICAL PROPERTY MEASUREMENTS section, the physical properties represent a micro-lithology and are not representative of the *in situ*, large-volume, physical characteristics that are detected by field geophysical techniques. A good example of why this is important is in the case of columnar jointing in basalt and the "true" physical properties of basalt. Columnar jointing would allow extensive hydraulic connection within a basaltic horizon, yet the basalt itself may be impermeable. The gross characteristics of columnar jointing would be irrelevant in laboratory tests but would dominate the field measurements. Certainly, within the AGF, samples have been measured with very low permeability and high electrical resistivity. Nevertheless, the gross, *in situ* measurements indicate the reservoir is fracture controlled and likely of low electrical resistivity.

6. SURFACE GEOPHYSICS

6.1 Overview

All three electrical-methods geophysical surveys were performed during the 1980's decade. There is substantial overlap in their respective areas of coverage, but the methods are discussed individually. The general AGF area can be characterized as layered volcanics. There are sufficient VES's and MTS's to allow a statistical evaluation of the original modeling and the modeling revised for this report.

6.2 Schlumberger Array VES's

The Schlumberger array VES's performed by CEL were selectively modeled and presented by Rodriguez in an internal CEL report (Rodriguez, 1985). Rodriguez presented data for 135 VES's and model results for 70 VES's. The apparent resistivity data and model results were presented in profile (section) format relative to the surface topography. The apparent resistivity data were also presented in contoured plan maps of selected AB/2 spacings.

Those model results have been evaluated statistically for the present report to determine the consistency between sounding interpretations, using the assumption of a reasonable degree of consistency in the horizontal layering as indicated in the drilling. Histograms of the various model resistivities and layer thicknesses are presented in their respective sections. Unfortunately, not all model parameters were presented in the CEL report. Where discernible, missing parameters were estimated from the profiles given in the CEL report. The statistics are summarized in Table 6.1.

The Schlumberger array VES's were modeled a second time for this report. All 135 VES's were modeled. These revised model results have also been evaluated statistically, using the same assumptions mentioned above. Whereas, originally up to five layers were used in the modeling, the present work constrained the modeling to three layers in order to test the consistency of a new geologic model. Histograms of the revised model resistivities and layer thicknesses are presented in their respective sections. Although on an individual basis, some VES's may be better fit with more than three layers, substantial reductions in variances of the average resistivities and layer thicknesses for the constrained three-layer models indicate that

Table 6.1 One-dimensional Schlumberger array VES modeling by CEL

	Number of models	Arithmetic average	Standard deviation	Normal variance	Geometric mean	Maximum	Minimum	Log range
Res-1	70	68.6	76.1	5788	55	400	4.0	2.0
Thick-1	70	43.7	85.0	7222	15	500	7.0	1.9
Res-2	70	208.6	235.9	55656	150	1200	1.0	3.1
Thick-2	62	142.1	130.4	17009	100	650	1.0	3.1
Res-3	62	26.4	48.5	2352	8	200	1.0	2.3
Thick-3	23	230.0	191.4	36627	200	750	50.0	1.2
Res-4	23	11.8	30.9	952	4	150	1.0	2.2
Thick-4	2	327.5	102.5	10513	400	400	255.0	0.2
Res-5	2	3.0	1.4	2	4	4	2.0	0.3

Table 6.2 One-dimensional Schlumberger array VES modeling by hydroGEOPHYSICS

	Number of models	Arithmetic average	Standard deviation	Normal variance	Geometric mean	Maximum	Minimum	Log range
Res-1	135	39.6	50.4	2539	22	360	1.0	2.6
Thick-1	135	9.4	8.3	69	8	50	1.0	1.7
Res-2	135	169.7	152.7	23308	130	950	1.3	2.9
Thick-2	135	108.1	63.0	3967	100	300	10.0	1.5
Res-3	135	10.3	7.5	56	8	40	1.0	1.6

the three-layer model is *statistically* more representative of the survey area. The statistical results of the second modeling effort are presented in Table 6.2. The highlighted entries show the parameters and their respective statistics with the greatest changes between the two modeling efforts. In general, the modeling results are depth limited to the near surface (probably less than 200 meters) and correlate with LBL's classification of EL (LBL, 1989), but previous geologic mapping suggests other alternatives that are discussed in the following sections.

6.2.1 Interpreted Surface Layer (VES)

The following comments and comparison between the statistics of the original and revised modeling of the surface layer in the VES's may seem to have little bearing on the purpose of detecting deeper targets. However, the primary reason for elaborating on the first layer of the modeling is that all subsequent layer parameters are affected by the values of the first

layer. Indeed, the characteristics of the near-surface resistivities in the field similarly affect the acquired data. Intuitively, the first layer in the VES modeling should represent soil. Modeled resistivities and thicknesses should reflect this. Unusually high resistivities may be reasonable in areas of negligible soil cover, but excessive soil thicknesses are unlikely, based on drilling results and frequent occurrences of outcrop. Histograms of the original and revised layer-one resistivities and thicknesses are presented in Figs. 6.2.1 and 6.2.2.

Fig. 6.2.1 Histograms of the original and revised modeling for layer one resistivities.

Fig. 6.2.2 Histograms of the original and revised modeling for layer one thicknesses.

With nearly twice the number of modeled VES's, the three-layer constrained models show less than half the variance in average resistivities of the unconstrained modeling. The average and mean resistivities for the first layer are suggested to be 40 and 22 ohm-meters, respectively for the constrained model, compared to the previous average and mean of 69 and 55 ohm-meters, respectively for the original modeling. The range of the revised modeling is from 1 to 360 ohm-meters, compared to the previous range of 4 to 400 ohm-meters. The original and revised model layer-one resistivities are well within reasonable limits for volcanic soil.

The revised models show a significant increase in the consistency of the thickness of the first layer. The variance for the layer-one-thickness in the revised modeling is 69 compared to 7222 in the original modeling. This substantial gain in the statistics of the revised modeling strongly supports the justification of using a constrained three-layer model. The average and mean layer-one-thicknesses for the revised modeling are 9 and 8 meters, respectively, compared to 44 and 15 for the original modeling. The range of revised thicknesses is from 1 to 50 meters. The original model thicknesses ranged from 7 to 500 meters. This latter range of thickness for the soil seems highly unlikely. A range of thickness of 1 to 50 meters seems more appropriate for soil cover in the Ahuachapán area.

The similarity of the revised model thickness values, as well as the small variance, suggests that the revised average thickness for layer one is more geologically plausible if it represents soil. The difference between the average resistivities for first layer (40 revised vs. 69 original) is of little consequence for soil. Contour maps of the resistivities and thicknesses for layer-one of the revised modeling are presented in Figs. 6.2.3 and 6.2.4 (next page).

Although the surface layer is not of exploration significance, the general trend of the model resistivities is to increase toward the northeast and somewhat to the north. These slightly higher model resistivities roughly correlate with the area mapped as undifferentiated San Salvador Fm. (ELC, 1984), suggesting that the soil derived from the San Salvador Fm. may be less moisture retentive.

6.2.2 Interpreted Second Layer (VES)

Geologically, the second layer should represent weathered, in-place, lithologies as shown on the surface geologic maps. The resistivities should be higher than those of the

Fig. 6.2.3. Contour map of the layer-one resistivities from the revised modeling.

Fig. 6.2.4. Contour map of the layer-one thicknesses from the revised modeling.

overlying soil, but probably not as high as unweathered lithologic equivalents. Thicknesses should reflect lithologies seen in the drillhole logs, if electrical property contrasts exist between the various horizons. More importantly, if the lithologies are reasonably persistent over a large area (within the grid), then subtle decreases in the resistivities and-or thicknesses may be indicative of shallow thermal activity. These effects would be the result of modestly elevated temperatures in the ground water as a result of the proximity to much higher thermal source material. The elevated temperatures would tend to increase the rate of alteration which would be manifested as a decrease in resistivity and-or a decrease in thickness.

Fig. 6.2.5. Histograms for the original and revised modeling for layer-two resistivities.

Histograms for the original and revised resistivities and thicknesses are presented in Figs. 6.2.5 and 6.2.6. The comparison between the original and revised results for the second layer shows a nominal improvement in the resistivities and a significant improvement in the thicknesses. Original modeling produced average and mean resistivities of 209 and 150 ohm-meters compared to 170 and 130 ohm-meters for the revised modeling. Although the variance for the revised resistivities is half the original (23308 vs. 55656), the range of values does not differ significantly (1 to 1200, original vs. 1.3 to 950, revised). The values of average and mean resistivities are consistent with in-place, weathered volcanics.

The average and mean thicknesses for the original modeling are 142 and 100 meters compared to 108 and 100 for the revised modeling. Original variance is 17009 versus 3967 for

Fig. 6.2.6. Histograms for the original and revised modeling for layer-two thicknesses.

the revised. As with the surface layer, the improved statistics are a result of a narrower range of thicknesses (10 to 300 meters, revised vs. 12 to 650, original) and similarity between the revised average and mean. Contour maps of the revised model resistivities and thicknesses are presented in Figs. 6.2.7 and 6.2.8.

Fig. 6.2.7. Contour map of the layer-two resistivities from the revised modeling.

Fig. 6.2.8. Contour map of the layer-two thicknesses from the revised modeling.

The general trends seen in the resistivity contour map show an area of relatively high values occurring due north of the Ahuachapán Field and an increasing trend in the east portion of the grid, reaching a maximum in the extreme northeast corner of the grid, in the vicinity of Turin. These two areas correlate well with what has been mapped as pyroclastics and valley fill of the upper San Salvador Fm. (ELC, 1984). The central area shows a relative low that correlates well with the pyroclastics and lavas mapped as the Cerro San Lazaro event within the San Salvador Fm. A second area of low resistivity occurs within, and to the south of, the AGF. It is suspected that the resistivities are lower in this area due to the widespread, near-surface, thermal activity. These relationships are not well defined, but the areal correspondence is certainly suggestive. No two-dimensional structures are inferred from the layer-two modeling.

6.2.3 Interpreted Third Layer (VES)

Although the Schlumberger array VES's were intended to investigate deeper zones, the conductive environment/fixed frequency limitation of the equipment prevented that goal from being realized. Consequently, the revised modeling uses only three layers, the third layer being the equivalent to a homogeneous, isotropic half-space underlying the shallower layers. The third layer is the most conductive and, ostensibly, represents lithologies significantly altered by thermal activity. Histograms of the original and revised model resistivities are presented in Fig. 6.2.9 and the contoured results are shown in Fig. 6.2.10.

Fig. 6.2.9. Histograms of the original and revised modeling for layer-three resistivities.

The original model average and mean resistivities are 26 and 8, respectively. Revised model equivalents are 10 and 8, respectively. The comparison of variances between the two modeling efforts shows a significant improvement in the revised model resistivities (2352 original vs. 56 revised). The improved statistics are the result of a smaller range of resistivities (1 to 40, revised vs. 1 to 200, original) and similarity between average and mean values.

The effective depth of investigation for the revised modeling is indicated by the sum of the layer thicknesses (approximately 110 meters) overlying the bottom layer of indefinite thickness. This figure is considered a "no less than" estimate and correlates well with the theoretical depth of investigation for the Schlumberger array for a maximum AB/2 spacing of 300 to 400 meters.

The sum of the thicknesses for the original modeling indicates an effective depth of investigation of approximately 725 meters. This depth equates to a Schlumberger array AB/2 spacing of 3000 meters. None of the VES's were performed using a spacing this large and it is doubtful that layers modeled are valid for this depth. The maximum AB/2 spacing reported was 1500 meters. For reasons already stated, the useful data are estimated to be limited to AB/2 spacings around 200 meters.

Fig. 6.2.10. Contour map of the layer-three resistivities from the revised modeling.

It should be mentioned that the temperature contours for a depth of 100 meters presented by LBL in their Fig. 7.3 (LBL, 1989; p. 97) derived from Jiménez and Campos (1976) show an excellent relationship to the layer-three resistivities. The "coolest" area (i.e. $< 40^{\circ}\text{C}$) within the grid occurs in the southeast corner of the grid where the resistivities are the highest (> 30 ohm-meters). Otherwise, the remainder of the grid shows temperatures above 40°C and below 10 ohm-meters.

6.2.4 Interpreted Subsequent Layers (VES)

The subsequent layers interpreted during the original VES modeling are not discussed here. Those results have been adequately presented in Rodriguez' report (CEL, 1984). As stated before, some VES's are amenable to modeling with more than three layers but the depth of investigation limitations and near-surface geology suggest that four and five layer models are probably not justified.

6.3 Magnetotelluric soundings

Modeling, interpretation, and reporting were performed by Geosystem s.r.l. of Milan, Italy in 1984. The MTS's were computer modeled using an inversion process whereby the user selected the number of layers and the computer automatically adjusted layered-earth resistivities and thicknesses until an optimal fit was obtained between the model and field curve. Geosystem used models with layers ranging from three to eight layers. Although automatic inversion is supposedly objective and fast, in cases where the sounding curves are affected by non-one-dimensional changes in geology, the computer artificially produces exaggerated resistivities and thicknesses in an attempt to fit the two or three dimensional effects with one-dimensional models. The original model results show such effects in that the layer resistivities range from 0.3 to 10,000 ohm-meters yet may be immediately adjacent. Similarly, layer thicknesses range from 45 to 9000 meters which are plausible, but unlikely, values when their trends are uncorrelated.

An important point to stress here is that an interpretation is always subjective whether it is done automatically by a computer or interactively by a person. Also, an interpretation is simply an opinion based on relevant data. Any given interpretation can be criticized or complimented for a variety of reasons. A re-interpretation of data does not imply incorrectness of a former interpretation, only that an alternative opinion is offered. A reasonable explanation should always be offered for a re-interpretation and perhaps why the new opinion differs from the former. For that reason, a statistical evaluation has been performed on the Geosystem s.r.l. magnetotelluric interpretation to quantify the trends presented by Geosystem and for comparison to a re-interpretation.

Histograms calculated for the Geosystem modeling are presented in their respective sections. A statistical summary of the original Geosystem modeling is presented in Table 6.3.

Table 6.3 One-dimensional MT modeling by Geosystem s.r.l. (1984)

	Number of models	Arithmetic average	Standard deviation	Normal variance	Geometric mean	Maximum	Minimum	Log range
Res-1	75	60.2	180.9	32712	5	1000	0.8	3.1
Thick-1	75	244.2	217.4	47276	170	1200	45.0	1.4
Res-2	75	331.9	866.1	750143	1	5000	0.3	4.2
Thick-2	75	294.9	189.6	35966	250	1300	60.0	1.3
Res-3	75	957.0	1879.3	3531785	500	9999	0.8	4.1
Thick-3	71	1549.5	1892.6	3581960	700	8000	70.0	1.2
Res-4	71	668.3	1833.4	3361377	2	9999	0.3	4.5
Thick-4	57	948.9	1423.6	2026499	340	8000	80.0	2.0
Res-5	57	1765.2	2707.1	7328357	1000	9999	0.8	4.1
Thick-5	20	1635.8	2724	7420356	430	9000	85	2
Res-6	20	1085.7	2142.2	4589220	1000	9999	1	4
Thick-6	5	1902	1840.3	3386520	3000	4500	210	1.3
Res-7	5	502.4	497	247019	1000	1000	2	2.7
Thick-7	1	1000	0	0	1000	1000	1000	0
Res-8	1	1000	0	0	1000	1000	1000	0

A cursory review of the statistics of the model parameters shows extremely large variances and over four orders of magnitude in the range of some parameters. The items of excessive range are highlighted in the table. Such large values may be indicative of quality control problems in the computer-inversion procedure, or a geologic environment that is simply not suited to one-dimensional modeling. As shown in section 3.2 Magnetotelluric Soundings, listing the model results in columnar format and reviewing the consistency of values in any one column shows where computer inversion problems may have occurred.

The one-dimensional modeling performed for the revised interpretation of the magnetotelluric data used the data available in the Geosystem s.r.l. report (ELC, 1984b). The data included in the report were limited to the apparent resistivity for only one of the orthogonal E-field components E(x-y) and no phase information for either component was available. The re-interpretation was performed interactively on a computer using a general five-layer model and statistical feedback.

6.3.1 Statistical Discussion (MT)

Generally speaking, where two distinctly different layered environments exist, large variances may be expected because the overall parameter averages assume a single environment model. Consequently, large variances alone are not necessarily a problem. Indeed, the histograms suggest the possibility of a multi-environment model. However, this effect may also be obtained by shifting layers in the model, either up or down, by one or more layers. The lateral persistence of the various lithologies in the general Ahuachapán area suggests that a single-layered environment would be more appropriate for the geologic model.

Another statistical characteristic of concern is the range of resistivities for layers two through six. Ranges of four orders of magnitude and greater are highly suspect for a reasonably consistent layered-earth environment. One would hope to see variations in the resistivity that may lead to drilling targets, but such a large spread in the original model resistivities suggests an unlikely situation for the Ahuachapán area.

A simple experiment was performed to test the effect of shifting layers in the Geosystem models. The layers were shifted in the table and the statistical characteristics recalculated. These results are shown in Table 6.4 on the next page. The result was a significant improvement in the variances in layers two, four, and six, and a corresponding decrease in the ranges of resistivities for nearly all layers. The experiment also demonstrated that the contour maps presented by Geosystem of layer thicknesses and resistivities are strongly affected by the presence of the wrong layer in the contoured parameter set. One of the major concerns regarding the magnetotelluric survey was the lack of correlation of the interpreted structure (based on the MT contour maps) with what has been mapped in the field. The "shifted layers" may explain this particular interpretation problem.

As a consequence of the "shifted layer" problem, the entire set of MT soundings was re-interpreted. As previously stated, the revised modeling was constrained to five layers and the layer parameters were constrained to values consistent with Schlumberger array and dipole-dipole data. This did pose a problem with the lower limit of resistivities because MT suffers from the "static shift" problem. If the MT apparent resistivities start from a low value because of local near-surface effects and then go lower because of the stratigraphic sequence or lateral

Fig. 6.4 One-dimensional MT modeling by Geosystem s.r.l with shifted layers.

	Number of models	Arithmetic average	Standard deviation	Normal variance	Geometric mean	Maximum	Minimum	Log range
Res-1	48	70.6	175.7	30882	8	1000	0.8	3.1
Thick-1	48	282.2	247.7	61369	200	1200	45.0	1.4
Res-2	74	22.4	44.5	21	1	35	0.3	2.1
Thick-2	74	227.9	135.3	18296	220	770	50.0	1.2
Res-3	75	1287.9	1908.0	3640626	1000	9999	2.0	3.7
Thick-3	71	1526.5	1875.9	3519073	650	8000	80.0	2.0
Res-4	71	1.3	1.6	3	1	10	0.1	1.5
Thick-4	67	305.5	158.6	25154	290	770	70.0	1.0
Res-5	67	2208.6	2828.9	8002784	1000	9999	20.0	2.7
Thick-5	22	3310.9	2407.8	5797732	3000	9000	110	1.9
Res-6	202	1.6	1.2	1	1	5	0.8	0.8
Thick-6	19	366.1	364.5	132857	230	1500	85	1.2
Res-7	19	1326.3	2116.1	4477750	1000	9999	200	1.7
Thick-7	2	3750	1060.7	1125000	4500	4500	3000	0.2
Res-8	2	6	5.7	32	10	10	2	0.7

effects, then resistivities less than one ohm-meter may be encountered in the field data. Certainly, true resistivities below one ohm-meter are possible, especially in an elevated temperature environment. However, any electrical geophysical method has difficulty reliably resolving resistivities below one ohm-meter. Furthermore, computer modeling falsely suggests that subtle differences in resistivities below one ohm-meter are resolvable.

Without corrections for the static-shift problem, which cannot be done without supporting information at the same location, the resistivities derived from the modeling of the MT soundings will not appear to correlate with those of other methods. This aspect of the MT method simply has to be accepted and any comparisons made with results of other methods must be qualitative. A summary of the statistical evaluation of the revised MT modeling is presented in Table 6.5 on the next page. Histograms calculated for each layer parameter of the modeling are presented in their respective sections. MTS-071 was not included because it singularly represented several statistical extremes.

Fig. 6.5 One-dimensional MT modeling by hydroGEOPHYSICS

	Number of models	Arithmetic average	Standard deviation	Normal variance	Geometric mean	Maximum	Minimum	Log range
Res-1	73	31.5	3.3	11	30	40	30.0	0.1
Thick-1	73	39.6	15.6	244	40	90	10.0	1.0
Res-2	73	1.3	0.6	0	1	3	0.4	0.9
Thick-2	73	44.1	38.5	1479	30	180	5.0	1.6
Res-3	73	104.5	11.0	122	100	150	80.0	0.3
Thick-3	73	253.4	222.9	49669	190	900	100.0	2.0
Res-4	73	1.0	0.5	0	1	3	0.3	1.0
Thick-4	73	297.9	127.7	16300	300	600	50.0	1.1
Res-5	73	64.7	45.7	2088	60	250	5.0	1.7

6.3.2 Interpreted Surface Layer (MT)

A significant difference in the method of modeling between the Geosystem interpretation and the revised interpretation is that the revised model emphasizes shallow layering. Although the Schlumberger array VES's should adequately resolve shallow layering, the influence of shallow layers may be profound in the MT soundings. Indeed, the presence of very low resistivity material can profoundly affect the depth of investigation of the MT method. As the revised modeling demonstrates, very conductive layers can limit the depth of investigation to less than one kilometer. Also, the resultant models of the two methods may appear quite different even in the shallow layers. The primary purpose for emphasizing the shallow layers is to develop an adequate understanding for the near-surface effects in both methods in order to better compare the models with the known geology and to evaluate the influence of the shallow layers on the interpretability of deeper layers. The results are anticipated to be different in detail. The average effects were the objectives of the revised modeling.

Histograms of layer-one parameters for the original Geosystem and revised modeling are presented in Figs. 6.3.1 and 6.3.2 on the next page. The average and mean resistivities for the Geosystem layer-one are 60 and 5, respectively, compared to 32 and 30 for the revised modeling. The difference between the modeling results is not of major importance, but a comparison of the respective variances shows 11 for the revised modeling versus 32712 for the original modeling. The minimum-maximum range for the original modeling is 0.8 to 1000 ohm-meters, versus 30 to 40 ohm-meters for the revised modeling.

Fig. 6.3.1 Histograms for the original and revised modeling for layer-one resistivities.

Fig. 6.3.2 Histograms for the original and revised modeling for layer-one thicknesses.

The average and mean thicknesses for the original layer-one modeling are 244 and 170 meters, respectively, versus 40 and 40 meters, respectively, for the revised modeling. The agreement between the average and mean thicknesses for the revised modeling are not indicative of accuracy in modeling, but rather that the shallowest layer is poorly defined (shallower than the data can detect) and can be fixed at nearly any value within a reasonable range. This was necessary to maintain the five-layer constraint throughout the modeling and the resistivity and thickness values used were based on nominal values derived from the Schlumberger array modeling. Contour maps of the layer-one parameters are shown in Figs. 6.3.3 and 6.3.4.

Fig. 6.3.3. Contour map of layer-one resistivities from the revised MT modeling.

Fig. 6.3.4. Contour map of the layer-one thicknesses from the revised MT modeling.

Magnetotelluric soundings are insensitive to layers as thin as the surface layer modeled in the Schlumberger array VES's. However, the surface layer used for the revised MT modeling includes the influence of the soil layer and a portion of the underlying more resistive layer. This combination produces average resistivities in the 30 to 60 ohm-meter range. Although the layer-one resistivities are essentially fixed in the revised MT modeling, there is a reasonable correlation between the layer-one MT model thicknesses and the combined thicknesses of the first two layers in the VES modeling.

In the eastern part of the grid the model thicknesses increase significantly. Between the Chipilapa area and the eastern part of the grid is an area that can be modeled with relatively thin layers. In the immediate vicinity of the AGF, there is generally an increase in model layer thicknesses. This thickening appears to carry on to the north of the AGF. The most salient disagreement occurs to the southeast of the AGF near the edge of the grid. In this area the VES modeling suggests thickening of the first two layers, but the MT modeling suggests a thinning effect.

6.3.3 Interpreted Second Layer (MT)

The second layer for both the original and revised MT modeling efforts is very conductive. The average and mean resistivities for the shifted original modeling are 2.4 and 1.0, respectively, and 1.3 and 1.0 ohm-meters, respectively, for the revised modeling. In contrast, the unshifted original modeling had 232 and 1.0 ohm-meters, respectively, as shown by the bimodal distribution in the left histogram in Fig. 6.3.5, which illustrates the effects of including other layer parameters. Layer-two could just have easily been modeled with a fixed value of 1.0 ohm-meter allowing for some incompatibilities in model curve gradients. Histograms for the original and revised layer-two parameters are presented in Figs. 6.3.5 and 6.3.6 on the next page.

Perhaps the single biggest discrepancy in the entire multidisciplinary interpretation exists in the explanation of the presence of a very conductive layer in the MT modeling where it cannot be justifiably placed in the VES modeling. This layer is necessary for most of the MT soundings to explain the downturn in apparent resistivities at the highest frequencies.

Fig. 6.3.5. Histograms for the original and revised MT modeling for layer-two resistivities.

Fig. 6.3.6. Histograms for the original and revised MT modeling for layer-two thicknesses.

A severe incompatibility exists between the VES modeling and the MT modeling when the thicknesses for this layer are considered. For the shifted original modeling, the average and mean thicknesses for the second layer are 135 and 220 meters, respectively. The corresponding values in the unshifted modeling are 295 and 250 meters, respectively, which shows a considerable difference in the averages due to the presence of the unshifted layers. The revised modeling average and mean thicknesses are 44 and 30 meters, respectively, substantially less than those of the original modeling. A conductive layer as thin as 30 to 40 meters at a typical depth of 40 meters should be readily detected in the Schlumberger array VES data. The closest

Fig. 6.3.7. Contour map of the layer-two resistivities from the revised MT modeling.

Fig. 6.3.8. Contour map of the layer-two thicknesses from the revised MT modeling.

corresponding conductive layer in the VES modeling is the third layer. Typical depths to the conductive third layer in the VES modeling are from 80 to 100 meters. This disparity in the interpretations may be deliberated over at great length. However, a subsequent MT survey performed by IIE in 1990 will produce full tensor impedance information from which a more tenable interpretation may be derived and which should eliminate any concerns over the single E-field modeling.

Contour maps of the layer-two parameters are presented in Figs. 6.3.7 and 6.3.8 on the previous page. Any discernable trends in the resistivities are more likely representative of static-shifts than true values. It is interesting to note that there is a tendency for layer-two to thicken to the southeast and to be at its thinnest over the AGF. If the low resistivity indicated by layer-two is representative of elevated temperatures, then a reverse relationship would be expected.

6.3.4 Interpreted Third Layer (MT)

Histograms of the layer-three parameters for the original and revised MT modeling are presented in Figs. 6.3.9 and 6.3.10. The average and mean resistivities for the original and shifted original modeling are 957 and 500 ohm-meters, and 1290 and 1000 ohm-meters, respectively. The differences are not significant. The revised modeling shows average and mean resistivities of 105 and 100 ohm-meters, respectively, a substantial decrease compared to the

Fig. 6.3.9. Histograms of the original and revised MT modeling for layer-three resistivities.

Fig. 6.3.10. Histograms for the original and revised MT modeling for layer-three thicknesses.

original modeling. This difference is primarily attributable to the computer inversion process forcing the resistivity of this intermediate, poorly-resolved, resistive layer to be much too high in some cases. For example, the maximum value attained is 9,999 ohm-meters. In MT modeling, increasing or decreasing a layer's thickness has a much greater effect on raising or lowering the model curve than increasing or decreasing the layer resistivity. The layer resistivity is the least correlated of the two parameters.

The layer-three thickness statistics in Tables 6.3 and 6.4 show a similar average and mean for both the shifted and unshifted original modeling, 1530 and 650 meters shifted, respectively, and 1550 and 700 meters unshifted, respectively. The average thicknesses are substantially greater than the mean thicknesses due to the very large values used in some cases, as indicated by the maximum thickness of 8000 meters. More judicious average and mean values of thickness are presented in the revised modeling as 253 and 190 meters, respectively. Although the first two layers showed substantial parametric differences between the original and revised modeling, this third layer is even more unusual in that the difference between the thicknesses is nearly an order of magnitude. The average thickness of the top four layers of the revised models may be included in the total thickness of the first three layers of the original modeling. Differences beyond these first three layers are so great that only the revised models are discussed.

The contour maps of the layer-three parameters are presented in Figs. 6.3.11 and 6.3.12 on the preceding page. The resistivity contours might be suggestive of a desirable trend related to the distribution of lower values over the AGF and leading to the north. However, the thicknesses are highly variable and do not show any discernable trend, although, the revised model average thickness corresponds very nicely with the upper part of what has been identified as the YA. An enticing aspect of this correlation is that the saturated ground water aquifer occurs in the YA and for the water to be palatable, it must support lower TDS than the underlying saline aquifer. The lower TDS level is directly related to higher average electrical resistivities.

6.3.5 Interpreted fourth and fifth layers (MT)

Regardless of the inconsistencies in the first three layers between the original and revised modeling, the primary interest is in ascertaining whether or not a major, low resistivity response can be related to the Ahuachapán reservoir and hopefully elsewhere in the survey area. Such a target can only exist beneath the surface layers if one of the layers is sufficiently impermeable to act as a cap or seal for an underlying reservoir. Indeed, a deeper, conductive layer has been modeled as layer-four in both modeling efforts. Histograms of the layer-four parameters for the original and revised MT modeling are presented in Figs. 6.3.13 and 6.3.14. The contoured results are shown in Figs. 6.3.15 and 6.3.16.

The average and mean resistivities for the fourth layer in the original and shifted original modeling are 668 and 2.0 ohm-meters, and 1.3 and 0.8 ohm-meters, respectively. The large difference in the original modeling is another manifestation of the out-of-sequence layers, the shifted values are more characteristic of the modeling scheme. The revised modeling produced average and mean resistivities for the fourth layer of 1.0 and 0.9 ohm-meters, respectively, in agreement with the shifted values of the original modeling. There is good parametric agreement between the modeling efforts. However, the big difference occurs with the thickness (and depth) of the fourth layer. The original and shifted original layer average and mean thicknesses are 950 and 340 meters, respectively, compared to 253 and 190 meters, respectively, for the revised modeling.

Fig. 6.3.13. Histograms of the original and revised MT modeling for layer-four resistivities.

Fig. 6.3.14. Histograms of the original and revised MT modeling for layer-four thicknesses.

The accumulated depth to the top of the conductive fourth layer in the original modeling is on the order of 1000 to 2000 meters. The equivalent accumulated depth to top of layer-four for the revised modeling is approximately 250 to 350 meters. This latter depth estimate compares favorably with the depth to significantly elevated temperatures in the vicinity of the Ahuachapán reservoir as determined by temperature logging. The former depth correlates with the depths of the highest measured temperatures in the reservoir area and, in general, the average thickness of 300 meters brackets the most productive horizon within the reservoir. The average thickness of the original modeling is 3000 meters and extends well beyond the depths of logged temperatures. For these reasons, viability of the models may be favorably argued

Fig. 6.3.15. Contour map of the layer-four resistivities from the revised MT modeling.

Fig. 6.3.16. Contour map of the layer-four thicknesses from the revised MT modeling.

both ways, but the desired target horizon correlates better with the revised modeling results.

Unfortunately, neither modeling effort shows an anomalously conductive or any well defined response that correlates with the limits of the Ahuachapán reservoir as determined by temperature gradients. Furthermore, the layer-four resistivities show very little variation across the survey area because they are in the very limited range of 0.5 to 1.5 ohm-meters. The primary hope would be for a significant thickening of layer-four in the reservoir area. However, this does not occur. Indeed, the variation in thicknesses of layer-four across the survey area is quite variable, with the most interesting exploration areas (Ahuachapán reservoir area and Chipilapa area) showing up in a generally thinner zone. This "thinner" zone is approximately 200 meters thick and appears to be reasonably persistent across the western and central parts of the survey area. It also extends northeasterly towards Turin. The thicker portions occur north of Chipilapa and in the extreme east end of the survey area. The non-uniqueness of layered-earth parameters may allow a focused reinterpretation on the thinner areas to see if there might be a trade-off in resistivity versus thickness such that the reservoir area may appear to be thicker. However, the IIE MT survey should offer better parametric resolution with the full tensor data and any further efforts spent on the Geosystem data are not justified.

Histograms of the layer-five resistivities are presented in Figs. 6.3.17. The lowest layer in the revised modeling shows average and mean resistivities of 65 and 60 ohm-meters, respec-

Fig. 6.3.17. Histograms of the original and revised MT modeling for layer-five thicknesses.

tively. The lowest values occur in the northeastern area toward Turin and beneath the Ahuachapán and Chipilapa areas. The resistivities in these areas are around 5 to 30 ohm-meters compared to greater than 100 ohm-meters for the highest values. Although, an encouraging correlation appears to be present, it is difficult to put much weight into it because the lowest-layer resistivities are very poorly defined in the MT sounding curves. The values used for the revised modeling were "best guesses" that were based on characteristics of the MT sounding curve at the lowest frequencies. Fig. 6.3.18 shows a contour map of the revised layer-five resistivities.

Fig. 6.3.18. Contour map of the layer-five resistivities from the revised MT modeling.

6.4 Dipole-dipole array profiles

Interim results of the DDR data were reported (Fink, et al; 1989) when the first two lines of completed coverage were modeled and discussed. The present report completes the discussion of the four lines that were subsequently completed. Lines 1 and 2 were originally discussed and the modeling performed at that time has since been revised and extended to include Lines 4 and 5 (Line 3 was never surveyed). The locations of the DDR lines relative to the VES grid and the MT soundings is shown in Fig. 1.2.

Lines 1 and 2 were oriented to obtain as much information over the AGF as possible. Line 1 was oriented $N34^{\circ}W$, started at the Ahuachapán-Turin highway, crossed through the middle of the AGF, went over the high terrain to the south, and terminated just east of Apaneca. Line 1 length was 12 kilometers. Line 2 was oriented approximately east-west, started at the Ahuachapán-Ataco highway, crossed Line 1 on the south side of the AGF, and terminated on the north slope of Montaña de la Laguna. Line 2 length was 13 kilometers.

Lines 4 and 5 were oriented to cross the Chipilapa area. Line 4 was oriented $N15^{\circ}W$ and extended to the north almost to El Salitre. Line 4 was approximately orthogonal to the long axis of the VES-gravity grid and offset approximately 500 meters to the northeast of the center (zero point) of the grid. Line 4 also crossed over the volcanic high terrain to the south. Line 5 was oriented $N65^{\circ}E$ and crossed Line 4 near well Che-1. Line 5 was coincident with Line 10 of the VES grid for all but the last sounding to the northeast. Line 5 also crossed Lines 1 and 2 near well Ah-08 and close to the intersection of Lines 1 and 2.

Although Lines 1 and 4 were nearly parallel, qualitative inspection of their pseudosections shows that a single two-dimensional model will not suffice. Actually, the large distance between the lines is sufficient reason alone to use different models. Qualitative inspection of the pseudosections for Lines 2 and 5 shows that a single two-dimensional model is adequate for both lines, even though the lines intersect. The angle of intersection is small enough, and the pseudosections similar enough, to allow for a single model.

None of the four dipole-dipole lines were truly parallel. Consequently, the effectiveness of two-dimensional modeling might be considered somewhat diminished. However, the lateral variations (non one-dimensional effects) are so pervasive that line to line continuity is difficult to assess except in the vicinity of the line intersections. Indeed, the quasi-continuous profiling

accomplished by the particular manner in which the dipole-dipole was implemented at the AGF very nicely illustrates why there is great difficulty in performing one-dimensional modeling for the other sounding methods. The lateral contrasts observed in the near-surface data are impressive and clearly indicate why the VES's and MTS's show strong lateral effects.

In particular, in the vicinity of the intersection of the three lines south of the AGF, each line shows significant lateral variations in all directions relative to the area of intersection. In places there are changes of up to one order-of-magnitude within one dipole spacing (500 to 1000m). Changes this large make it extremely difficult, if not impossible, to correlate soundings from one site to another when they are near the discontinuity. This further illustrates the importance of orthogonal pairs of soundings when the Schlumberger array is used and static correction techniques when MT is used.

The DDR data are presented in pseudosection format for both 500m and 1000m dipoles with the corresponding topography in their respective. A contour map of the optimal depth of investigation is also presented. Both one-dimensional and two-dimensional modeling methods were used for the DDR data depending on the applicability. The one-dimensional modeling used an industry standard, digital-filter convolution method. The two-dimensional modeling was performed using an industry standard, linear-basis, finite-element method. Terrain corrections were performed during the preliminary evaluation (Fink et al, 1989), but subsequent modeling suggested that the gain in performing terrain corrections is lost in subsurface model detail in the areas of primary interest because of computer memory limitations. The choice was made to enhance the subsurface detail in the areas of interest (displaced from the topographically affected data) and ignore the extremities of the lines where the topographic effects are most pronounced.

Prior to discussing the one-dimensional modeling results, a brief comment is warranted. To present sounding results from two different arrays on the same plot, a common abscissa must be used. In the present work, the "half-space depth" abscissa was chosen. The "half-space depth" is a theoretically-derived, common basis that applies to all grounded electrode arrays (but not magnetotellurics for which the skin-depth formula is used).

6.4.1 One-dimensional Modeling (DDR)

Visual inspection of the pseudosections shows that the only portion of the DDR surveying that is clearly amenable to one-dimensional modeling is in the northern half of Line 4. Fortunately, this portion of the line also crosses the area of Schlumberger VES's and MTS's and allows comparisons between the various methods.

A plot of the comparison between proximal DDR and Schlumberger VES-062 and an appropriate three-layer model for the north end of Line 4 is presented in Fig. 6.4.1. The Schlumberger data show better near-surface resolution because of higher data point density but cannot define the resistivity or thickness of the conductive layer because of EM effects. On the other hand, the DDR data define the conductive layer very well in both resistivity and thickness but have less resolution of the near-surface layering than the VES, again due to differences in data point density.

Fig. 6.4.1. Comparison of VES, DDR, and three-layer model curve for DDR Line 4.

The depth limitation of VES's due to the presence of EM effects is well illustrated in Fig. 6.4.1. The sharp departure of the VES curve from the DDR curve and the model curve shows where the onset of EM effects for this particular environment occur. The slope is also in

excess of 45° (log-log) which immediately eliminates any possibility of the upswing representing the presence of a deeper, resistive layer, regardless of the cause of the upswing. DDR data could also be similarly contaminated if the same fixed-frequency equipment limitations were imposed. The ability of the LANL-built equipment to operate at effectively DC reduces the problem to a negligible level. However, even at the large spacings in the DDR data an upswing in excess of 45° is present. In this case, the probable cause is a lateral effect, which is most likely the severe topographic relief at the southern end of the line.

The three-layer model suggests a 200 meter thick surface layer of 40 ohm-meters which correlates well with the temperature logs of wells Ch-1 and Che-1. Both wells show a reasonably constant temperature of 100°C to a depth of 150 meters. Below the low temperature region is a transitional zone 250 to 300 meters thick within which the temperatures increase to 200°C . The modeled depth to the low resistivity layer occurs within this transitional zone, as might be expected. The low resistivity model layer is 600 meters thick and is underlain by more resistive material suggesting a possible bottom to the elevated temperatures, or perhaps a vapor dominated regime.

The nearest equivalent MT soundings are MT-67 and MT-81. Both of these MT soundings show a sharp downturn at the highest frequencies indicating a shallow conductive layer. The MT soundings cannot be modeled without this shallow conductive layer. Consequently, there is a fundamental disagreement between the DC resistivity results from both Schlumberger and DDR and those of MT.

No other portions of the DDR lines are amenable to one-dimensional modeling because of the strong lateral inhomogeneities.

6.4.2 Two-dimensional Modeling (DDR)

A non-reservoir model was presented (Fink et al, 1989) for Line 1 showing that a single DDR line does not contain adequate information to reliably form a two-dimensional model. A concern at the time of the earlier modeling was that too much optimism was being put into DDR surveying and that an apparent success in a very difficult logistical situation might be misconstrued as far as the resolving capabilities of the method were concerned. A model was generated to show that the observed response could easily be the result of an

Fig. 6.4.2. Topography and log pseudosections of DDR Line 1 at the AGF.

electrically conductive reservoir. However, an alternative model was actually presented that demonstrated that the same response could be derived from near-surface lateral

inhomogenities without a conductive reservoir body being included in the model. Subsequent modeling was deferred to the completion of the remaining lines.

The present two-dimensional modeling was purposely constrained by attempting to use the least number of unique bodies with a consistent, but limited, number of true body-resistivities in the range of values already demonstrated by other surface electrical resistivity methods and laboratory measurements. Model body resistivities were limited to 1, 3, 10, 30, 100, and 300 ohm-meters. The pseudosection data clearly show three-dimensional effects in the vicinity of the intersection of Lines 1, 2, and 5. For this reason, it is anticipated that similar geologic characteristics occur elsewhere within the area of coverage. Consequently, the two-dimensional modeling can only be considered a best approximation. Three-dimensional modeling methods would require much more data coverage and were not considered reasonable for the present modeling effort.

6.4.3 Line 1 (DDR)

Line 1 topography and the two pseudosections for dipole sizes of 1000 and 500 meters are shown in Fig. 6.4.2. The corresponding two-dimensional model and related model pseudosection are presented in Fig. 6.4.3. The various bodies in the model are shaded according to their resistivity, dark being lowest and light highest.

Line 1 modeling shows that a conductive reservoir may be placed beneath stations 3 and 4 with an intrinsic resistivity of 1 ohm-meter. The top of the known reservoir in this area occurs at approximately 650 meters below surface (see section C-C', LBL-1990). The model reservoir, represented by the dark shaded body in Fig. 6.4.3 best fits between 800 and 1300 meters below surface, with a narrow feeder to the base of the reservoir and a narrow feeder from the reservoir nearly to the surface. The model level of 800 to 1300 meters satisfactorily corresponds with the Ahuachapán andesite and the upper portion of the OA. At reservoir depth, the modeled reservoir is bounded to the north by resistivities gradually increasing to 30 ohm-meters. This corresponds to the gradually diminishing temperatures logged to the north in drillholes Ah-20, Ah-12, and Ah-10. The DDR data require a much sharper southern boundary to the reservoir model and is in contrast to the temperature gradients measured in the general area.

Above the modeled reservoir, a large volume of low resistivity material (3 ohm-meters) is modeled to represent altered volcanics of all types. At the depth range of the upper AA, this modeled volume is bounded on the north by material of a slightly higher resistivity (10 ohm-meters) than the extensively altered volcanics and appears to correspond to the top of the

Fig. 6.4.3. Schematic drawing and log pseudosection of the 2-D model for Line 1.

AA although the boundary may instead correspond to the fault proposed between drillholes Ah-12 and Ah-10 (either fault 1 or fault 3, LBL, 1990, p. 34). This fault suggests a termination of the AA to the north of the AGF and could occur anywhere in the one-thousand

meter distance between the drillholes. The DDR data agree with this geologic interpretation, but almost necessitate that the fault be very close to station 2, which would suggest fault 3.

At the depth of the AA, a large volume of 30 ohm-meter material is modeled to extend to the south, well beneath the volcanics forming the Cerro Las Ninfas-Cerro Laguna Verde mountain complex. Unfortunately, two-dimensional topographic corrections are inadequate for the range of elevations and extreme gradients to also allow for any reasonable resolution beneath the mountain complex in the modeling. For that reason, a well-defined southern boundary for this layer, which is probably related to the AA and OA, is indeterminate. It may, or may not, continue beneath the mountain complex.

The near-surface modeling shows a series of small features occurring between stations 2 to 7 that are probably related to various degrees of thermal alteration as indicated by their range of intrinsic resistivities. Individually, these features do not represent anything significant as far as the deeper reservoir is concerned. However, they are very significant in that they demonstrate the near-surface complexity of the electrical characteristics and may lead to artificially high or low resistivity features at depth in the pseudosection data due to constructive and destructive interference (surface masking) (Fink et al, 1989). The range of resistivities as well as the volume of each block, or feature, determines how well any electrical geophysical method will perform in the local environment. It is this type of nearly random variation of surface resistivities that make the use of discrete sounding methods extremely difficult. Clearly, sounding placement is of major concern.

Relative to the entire line, the series of small features appears to be localized. That is, beyond the features to the north and south, the surface resistivities appear to be less variable and much higher. Hence, it may be concluded from the geophysical modeling that the thermal alteration may be confined to the area in the general vicinity of the reservoir, as surface geologic mapping and temperature information already suggest.

6.4.4 Lines 2 and 5 (DDR)

Topography and two pseudosections each for Lines 2 and 5 are shown in Figs. 6.4.4 and 6.4.5 for their respective dipole sizes of 1000 and 500 meters. The corresponding model

Fig. 6.4.4. Topography and log pseudosections of DDR Line 2 at the AGF.

representative of both Lines 2 and 5. The 2-D model and resultant pseudosection is presented in Fig. 6.4.6. As with Line 1, the model bodies are shaded according to their resistivity.

Fig. 6.4.5. Topography and log pseudosections of DDR Line 5 at the AGF.

The most salient feature is the high resistivity boundary occurring to the west on both lines (Line 2 station 4 and Line 5 station 4). This boundary is modeled as a fault contact

between unaltered volcanics to the west and the altered volcanics in the vicinity of the AGF. This may correspond to a reported transverse graben fault (ELC, 1984a, and LBL, 1990, fault

Fig. 6.4.6. Schematic drawing and log pseudosection of the 2-D model for Lines 2 and 5.

11, p. 34). The low, near-surface resistivities immediately to the east of this contact (for approximately one kilometer) represent the altered surface volcanics over the southern-most portion of the AGF.

A localized, high-resistivity block occurs at Line 2 station 7 and Line 5 station 6. This block may be represented in the lithologic logging as a greater thickness of the YA which has

also been reported as a repeated sequence (LBL, 1990). It is probably the same feature as seen on Line 1 station 4.

A large volume of 3 ohm-meter material is included in the model, but a smaller volume of lower resistivity that might directly represent possible reservoir material could not be incorporated, but a deep feeder was included to test the resolving capability of the data. It could easily be removed without affecting the model results. This inability to place a substantial volume of one ohm-meter material in the Line 2-5 model tends to indirectly substantiate the modeled reservoir material on Lines 1 and 4.

The 3 ohm-meter material appears to extend well into the Chipilapa area and is assumed to represent a moderate to relatively high temperature regime. Considerably less surface variation is evident on Lines 2 and 5 which may suggest less fracturing and faulting near surface. This could be regarded as a benefit if the more consistent resistivities indicate a better cap or seal for an underlying reservoir. However, the associated underlying resistivities are not as low as those of the AGF.

Very little can be resolved at depths greater than 1500 meters, but it appears that the deeper material is generally more resistive (100 ohm-meters) and may correlate with the OA.

6.2.5 Line 4 (DDR)

Topography and Line 4 pseudosections are shown in Figs. 6.4.7 for dipole sizes of 1000 and 500 meters, respectively. The corresponding model is presented in Fig. 6.4.8. The model bodies are shaded according to their resistivity.

The general appearance of Line 4 shows less overall variation in the resistivities than Lines 1, 2, and 5. Similarly, the corresponding model is slightly less complex. The most important feature in the modeling is the presence of a large volume of low resistivity material that may be representative of significantly elevated temperatures, as is seen in the reservoir model for Line 1. This low resistivity body is perplexing because it is located in an area of projected lower temperatures to the north of Chipilapa en route to the probable outflow area at El Salitre. Interestingly, the model resistivities in the immediate vicinity of Chipilapa are higher and a low resistivity body of similar volume cannot be modeled there. The suggestion is

The possible presence of a significant volume of low resistivity material, such as that modeled in the north end of Line 4 cannot be easily dismissed as a spurious anomaly. It can be

Fig. 6.4.8. Schematic drawing and log pseudosection of the 2-D model for Line 4.

argued that the feature may be modeled by more complex near-surface bodies as was initially done for Line 1, but, the fact remains that both Lines 1 and 4 show significant low resistivity features, one of which corresponds very well with the known reservoir. Regardless of how this model does not fit the present consideration of temperature distribution, it should not be ignored. What may also be of significance is that this feature lines directly between the AGF reservoir and the area of deep microseismic events reported to occur beneath Turin (Fabriol, et

Fig. 6.4.9. Contour map of the DDR average apparent resistivities at the reservoir level.

al; 1990). Fig. 6.4.9, which is a contour map of the averaged apparent DDR resistivities at the reservoir level, shows the spatial relationship between the resistivity lows on Lines 1 and 4 and opens the question as to whether or not they are connected. Fig. 6.4.9 also serves as a simple, graphical summary of the effectiveness of the DDR method. The AGF stands out as a significant low resistivity closure, although it could be open to the northeast. The low resistivity feature in the north end of Line 4 requires further investigation to be properly delineated. And, the gradients to the south and west indicate areas of substantially higher resistivity.

The higher resistivity material occurring in the southern portion of the model corresponds with the mountain complex discussed under Line 1. It may be of significance that the low resistivity material surrounding the possible reservoir does not appear to extend

beneath the mountain complex to the south. However, this may be a result of the topography and depth to the layer beneath the mountain complex.

7.0 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The overall electrical resistivity modeling of the AGF general area shows a moderately layered environment with high potential for additional thermal resources. Each method modeled shows a different aspect of the volume of earth investigated in the area, but the combined modeling and interpretation is substantially enhanced by the various methods. The magnetotelluric data are the most difficult to reconcile with those of the Schlumberger and DDR arrays. This is most likely because of the lack of full tensor data available for this report, but also because of the lack of compensation for static offsets.

The Schlumberger array and DDR array data complement each other. The Schlumberger array VES's supplied detailed shallow information, which could have been greater had it not been for the fixed operating frequency of the equipment contaminating the larger AB/2 spacings. Orthogonal pairs of Schlumberger VES's would have greatly enhanced the quality of the soundings by determining spatial vector resistivities which would enable lateral resistivity variations to be better defined. Although the most difficult to perform in the field, the DDR data provided information to approximately 1500 meters below surface, as well as quasi-continuous profiling. More DDR lines should be performed.

The DDR data clearly show the lateral variations that would be uncertain if based only on the discrete soundings of the VES and MT methods. These lateral variations are the bane of one-dimensional modeling and render the modeling results unreliable. Confirmation of the presence of lateral variations, their locations, and their relative resistivity contrasts have given significant insight to the general electrical characteristics of the AGF. A limitation of the DDR method is the difficulty in satisfactorily removing the effects of severe topographic relief, although the other two techniques are similarly affected. Fortunately, in the areas of primary interest (i.e. the graben) the terrain is sufficiently flat to all but eliminate the effects. The low resistivities that precipitated the EM contamination problem with the equipment used for the Schlumberger array VES's were satisfactorily measured using the specially-designed, high-powered LANL transmitter. This equipment made possible deep readings that would otherwise be virtually impossible using commercially available, resistivity equipment.

The resultant models derived from the various methods are of limited diagnostic use. That is, too many variables are at play with the electrical methods in this environment to allow specific hydraulic or structural characteristics to be well-defined. Nevertheless, the DC methods, in particular DDR, provide a very effective means for detecting low resistivity targets in this volcanic environment.

The problem of non-uniqueness has been discussed and certainly applies in the Ahuachapán environment. The ability to create coherent models that demonstrate the possible presence of reservoir-grade low-resistivities should be regarded as a strong indication of where to focus further exploration effort.

7.2 Recommendations

DDR Line 4 should be extended 5 to 6 dipoles to the north to ascertain the northern limit of the low resistivity zone and extend beyond, well into background. A fifth DDR line should be performed approximately half-way between Lines 1 and 4. This line should extend from the southern highlands to a similar northern endpoint as the extension of Line 4. A sixth line should then be considered to the east of Line 4 with similar length. These lines should be performed in a manner similar to that of the previous lines.

If at all possible, a significant amount of drill core should be retrieved in sealed plastic bags (to retain natural moisture) for further laboratory tests, regardless of the well location within the general area. A sufficient number of core samples should be tested to form a statistical data base so that the geophysical parameters may be better characterized for future work.

If any further Schlumberger array VES's are to be done, they should take into account the EM problem at large spacings and should be paired with an orthogonal sounding at the same site. This advice extends to all subsequent exploration efforts.

Extensive recommendations for either drilling or other types of geophysics should await the interpretation of the new magnetotelluric survey. However, even if the new MT results are not sufficiently diagnostic in the graben area, the recommendations above should be considered based on the current data review.

8.0 REFERENCES AND RELATED PUBLICATIONS

* publications referred to in text

Alvarez, S.J., Perdida Calórica del Campo Playon de Salitre

Arevalo, M.J. and Campos, T., Perforaciones Geotérmica en El Salvador, simposio Internacional sobre la Energía Geotérmica en América Latina, Guatemala, October 1976.

Aumento, F., Viale, P., Choussy, M. and Santana, A., Alteration Mineralogy of the Ahuachapán Geothermal Field, Geothermal Resource Council Trans., 6, 7-10, 1982.

Bodvarsson, G. and Bolton, R.S., A Study of the Ahuachapán Geothermal Field, UN report, May 1971.

Bolton, R.S., Ahuachapán Geothermal Field, Report on Visit, May 7-18m 1979, June 1979.

Campo geotérmico de Ahuachapán asistencia a la operación del campo y estudio geológico de detalle: Informe geológico-vulcanológico; Report AHU-D-5331, Electroconsult, Milano, Italy, Nov. 1981.

Campo Geotérmico de Ahuachapán asistencia a la operación del campo y estudio geológico de detalle: Estudios geocientíficos; Report AHU-D-5369 (draft copy), Electroconsult, Milano, Italy, March, 1982.

Campo Geotérmico de Ahuachapán asistencia a la operación del campo y estudio geológico de detalle: Informe final; Report AHU-D-5596/Rev.1, Electroconsult, Milano, Italy, Feb. 1984.

Campos, A.R., Reporte de Avance: Monitoreo Químico de las Aguas de la Zona Prospectiva de Chipilapa, CEL, July 1983.

- Campos, T., **Indices de Inyectividad en el Campo Geotérmico de Ahuachapán**, CEL, 1980.
- Campos, T., **Pruebas de Spinner, Pozos de Reinyección, Ahuachapán**, CEL, 1986.
- Campos, T., **Pruebas en Régimen Transitorio en el Pozo AH-26**, July 1979.
- Campos, T., **Pruebas en Régimen Transitorio de Presión, Temperatura y Distribución de Flujo en AH-6, AH-7, y AH-1**, CEL, September 1979.
- Campos, T., **Ten Years of Commercial Exploitation of the Ahuachapán Geothermal Field**, Proceeding 7th NZ-Workshop, pp. 15-20, 1985.
- Carr, M.J., Mayfield, D.G. and Walker, J.A., **Relation of Lava Compositions to Volcano Size and Structure in El Salvador**, Journal of Volcanology and Geothermal Research, Vol. 10, pp. 35-48, 1981.
- CEL, **Comportamiento del Campo Geotérmico de Ahuachapán, Estudios Geoquímicos, Durante 1984** CEL, 1984.
- CEL, **Comportamiento del Campo Geotérmico de Ahuachapán, Estudios Geoquímicos Durante 1986**, CEL, 1986.
- CEL, **Descripción del Modelo Matemático del Campo Geotérmico de Ahuachapán** Elaborado por Electroconsult, CEL, November, 1982.
- CEL, **Estudio de la Reinyección en el Campo Geotérmico de Ahuachapán (Reporte Interno)**, CEL, August 1983.
- CEL, **Isotopos en Estudios Geotérmico, Actividad: Estudios de los Isotopos Ambientales en el Area Geotérmico de Ahuachapán**, CEL, May 1986.
- CEL, **Resultado de Cierre de Pozos en el Campo Geotérmico de Ahuachapán, Junio-Septiembre 1982**, CEL, October 1982.

- Choussy, M. and Escobar, D., Mediciones de Interferencia en el Campo Geotérmico de Ahuachapán, CEL, April 1979.**
- Cuellar, G., Programa de Reinyección en el Campo Geotérmico de Ahuachapán, Simposio Internacional sobre la Energía Geotérmica en América Latina, Guatemala City, October 1976.**
- Cuellar, G., Programas Químicos en Desarrollos Geotérmico, U.S. Environmental Protection Agency, 2nd Workshop on Sampling and Analysis of Geothermal Effluents, Las Vegas, Nevada, February 1977.**
- Cuellar, G., Choussy, M. and Escobar, D., Extraction-Reinjection at Ahuachapán Geothermal Field, CEL, 1979.**
- DiPippo, R., Geothermal Energy Developments in Central America, Geothermal Resources Council Bull., 3-14, November 1986.**
- Durr, F., Perdidas Calóricas Superficiales de los Campos Geotérmicos de Ahuachapán, 1960.**
- Einarsson, S., Vides, R.A. and Cuellar, G., Disposal of Geothermal Waste Water by Reinjection, UN-Symposium, 1975.**
- ELC-Electroconsult, Campo Geotérmico de Ahuachapán, Analisis del Comportamiento del Campo Hasta el Año 1980, CEL, June 1981.**
- ELC-Electroconsult, Planta Geotérmica de Ahuachapán, Optimización de la Explotación del Campo, CEL, November 1979.**
- ELC-Electroconsult, Campo Geotérmico de Ahuachapán, Asistencia a la Operación del Campo y Estudio Geológico de Detalle, CEL, March 1982.**
- ELC-Electroconsult, Campo Geotérmico de Ahuachapán, Optimización de la Explotación del Campo, CEL, March, 1983.**

- *ELC-Electroconsult, Campo Geotérmico de Ahuachapán, Asistencia a la Operación del Campo y Estudio Geológico de Detalle, CEL, February 1984a.**
- *ELC-Electroconsult/Geosystem, Estudios Magnetoteléuricas en Los Campos Geotérmicos Ahuachapán y Chipilapa, CEL-1461, July 1984b.**
- Escobar, C.A., Reservoir Engineering at Ahuachapán, Project for Diploma in Energy Technology (Geothermal), Project Report No. GEOTHERM. 85.07, Geothermal Institute, University of Auckland, New Zealand, October, 1985.**
- Escobar, D., El Campo Geotérmico de Ahuachapán Durante los Años 1979-1980, CEL, April 1981.**
- Escobar, D. and Martinez, J.A.M., Respuesta del Campo Geotérmico de Ahuachapán a la Explotación Durante 6 Años, CEL.**
- *Fabriol, H., Beauce, a., and Le Maxne, D.; Seismic monitoring of the Chipilapa geothermal area(El Salvador), Jrl. Vol. Geother. Res., Vol. 43 pp. 311-320, 1990.**
- *Fink, J. B., de la Fuente, M., Rodriguez, R., Cash, D. J., & Gerety, M.; DC Resistivity at the Ahuachapán Geothermal Field, Ahuachapán, El Salvador, Proc. 14th Workshop Geotherm. Reservoir Eng., Stanford, pp. 111-117, 1989.**
- Glover, R.B., Geochemical Investigations of the Ahuachapán Geothermal Field, UN, October 1970.**
- Grant, M., Simple Modeling of Production and Reinjection at Ahuachapán, DSIR, February 1980.**
- Hanold, R.J., Loose, V.W., Laughlin, A.W. and Wade, P.E., Geothermal Initiatives in Central America, GRC Bulletin, Sept./Oct. 1986.**
- Jimenez, M., Reporte Hidrogeológico del Area Geotermal de Ahuachapán, CEL, July 1971.**

- *Jimenez, M.A. and Campos, T.A.V., Perforaciones Geotérmicas en El Salvador, Simposio Internacional sobre Energía Geotérmica en América Latina, Guatemala, 1976.**
- Jonsson, J. Report on Geological Investigation in Ahuachapán, UN, July 1970.**
- Kurman, M.J., A Regional Blueprint for Geothermal Development in Central America, GRC Transactions, Vol. 9- Part 1, 1985.**
- *Larios, D., Estudio de la Permeabilidad, Porosidad y Densidad de las Rocas del Campo Geotérmico de Ahuachapán, CEL, April 1983.**
- *Larios de Lopez, D. A.; Propiedades eléctricas de las rocas del Campo Geotérmico de Ahuachapán, CEL internal report, San Salvador, El Salvador, 1984a.**
- *Larios de Lopez, D. A., Susceptibilidad magnética de las rocas del Campo Geotérmico de Ahuachapán, CEL internal report, San Salvador, El Salvador, Feb. 1984b.**
- *Larios de Lopez, D. A., Síntesis de las propiedades físicas del Campo Geotérmico de Ahuachapán: Propiedades texturales y térmicas, CEL internal report, San Salvador, El Salvador, Feb. 1985.**
- *LBL; Aunzo, Z., Bodvarsson, G. S., Laky, C., Lippmann, M. J., Steingrimsson, B., Truesdell, A. H., and Witherspoon, P. A.; The Ahuachapán Geothermal Field, El Salvador - Reservoir Analysis; Lawrence Berkeley Laboratory Report LBL-26612 (3 volumes), August 1989.**
- Liguori, P., Jarach, F., Choussy, M., Campos, T. and Escobar, D. Reservoir Engineering of the Ahuachapán Geothermal Field, GRC Trans., Vol. 6 pp. 289-292, 1982.**
- Mahon, W.A.J., Preliminary Report on a Geochemical Assessment Study of the Ahuachapán Geothermal Field, UN, February 1970.**
- Martinez, J.A., Consideraciones Geoquímicas sobre la Prueba de Máxima Extracción, Campo de Ahuachapán, CEL, July 1981.**

- Mendoza, S.A., Behavior of Ahuachapán Geothermal Field, Geothermal Institute, University of Auckland, Auckland, NZ, October 1985.
- Ondrej, F., A Hydrologic study of the Ahuachapán Geothermal Area, UN, February 1970.
- Proyecto: Magnetotelúrica en Ahuachapán-Chipilapa - Informe final (data and maps only); Geosystem S.r.l., Milano, Italy, 1984.
- Quijano, J. E., Re-interpretation of Dipole-dipole Traverses across the Great Ahuachapán Field, El Salvador, Geothermal Institute, Univ. of Auckland, N.Z., Report No. 89.21, Oct. 1989.
- Rivera, R.J., and Samaniego, V.F., Reporte de la Misión sobre la Evaluación de las Condiciones Actuales del Yacimiento Geotérmico de Ahuachapán, CEL, July 1983.
- Rivera, R.J., Vides, R.A., Cuellar, G., Samaniego, V.F. and Neri, I.G., A Status Report on the Exploitation Conditions of the Ahuachapán Geothermal field, Proceedings 9th Workshop on Geothermal Reservoir Engineering, Stanford, CA, pp. 97-105, 1983.
- *Rodriguez, C. E., Reporte final de interpretación de la resistividad eléctrica del area geotérmica de Chipilapa, CEL internal report, San Salvador, El Salvador, Sept. 1985.
- *Rodriguez, C. E. & Rivas, J. A., Reporte de la interpretación de los estudios gravimetricos del area geotérmica de Chipilapa, CEL internal report, San Salvador, El Salvador, June 1986.
- Romagnole, P., Cuellar, G., Jimenez, M., and Ghessi, G., Hydrogeological Characteristics of the Geothermal Field of Ahuachapán, El Salvador, Proceeding 2nd UN-Symposium, pp. 571-574, 1976.
- Santana, A., Analisis Microscopio de Muestra de Canal y Nucleos de 32 Pozos, Campo Geotérmico de Ahuachapán, CEL.

- Santana, A., Distribución Vertical de Minerales de Alteración, Pozos Ahuachapán, CEL, March 1987a.
- Santana, A., Mapa Estructural, Correlaciones Litológicas y Patrones de Distribución de Minerales de Alteración, Campo Geotérmico de Ahuachapán, CEL, March 1987b.
- Sigvaldason, G.E. and Cuellar, G., Geochemistry of the Ahuachapán Thermal Area, El Salvador, Proceedings UN Symposium on the Development and Utilization of Geothermal Resources, Pisa, 1392-1399, 1970.
- Vega, D., Advances de la Geotermia en El Salvador, Proceedings of the International Symposium on Development and Exploration of Geothermal Resource, Cuernavaca, Mexico, October 5-9, 1987, 36-41.
- Verduzco, R., Reporte de la Misión sobre la Evaluación de las Condiciones Actuales del Yacimiento Geotérmico de Ahuachapán, 1983.
- Vides, J.R., Model Simulation of the Behavior of Ahuachapán Geothermal Field, Geothermal Institute, University of Auckland, NZ, 1982.
- Vides-Ramos, A., Ahuachapán Field Management, GRC Trans., 1985.
- Vides-Ramos, A., Desarrollo Actual de la Geotermia en El Salvador, Seminario Latinoamericano de Exploracion Geotérmica, Quito, Ecuador, September 5-6, 1983.
- Vides-Ramos, A., The Current Development of Geothermal Energy in El Salvador, Latin American Seminar on Geothermal Exploration, Quito, Ecuador, September 1983.
- Ward, P. and Jacob, K., Final Report on a a Study of Microearthquakes and Ground Noise in the Ahuachapán Geothermal Field, UN Report, 1971.
- Weyl, R., Geology of Central America, 2nd ed., Gebruder Borntraeger, Berlin, 1980.
- White et al., The San Salvador Earthquake of October 10, 1986 - Seismological Aspects and Other Recent Local Seismicity, Earthquake Spectra, EERI, Vol. 3, No. 3, 1987.

Wieseman, G., Remarks on the Geologic Structure of the Republic of El Salvador,
Central America, Mitt. Geol. Palaent, Inst. Univ. Hamburg, Vol. 44, 557-574, 1975.

Witherspoon, P.A., Analysis of Reservoir Behavior at Ahuachapán Geothermal Field,
CEL, March 1977.

Witherspoon, P.A. Analysis of Reservoir Behavior at Ahuachapán Geothermal Field,
CEL, May 1979.