GL01441

AHUACHAPAN GEOTHERMAL FIELD

AFTER A YEAR OF OPERATION

[redacted]

SUMMARY

This work attempts to report the present conditions of some of the physical-chemical characteristics of the Ahuachapan geothermal field after a year of intensive operation; also presented are some hypotheses about the changes that are taking place in the production characteristics and in the chemical composition of the discharged fluids.

1. INTRODUCTION

The Ahuachapan geothermal field presently being worked covers an area of approximately 3 km2 and is found located to the west of El Salvador on the north limb of the quatenary volcanic range that crosses the whole country almost without interruption following the direction of the main graven. This graven is full of volcanic materials discharged by the quatenary volcanic centers.

The area being worked seems to be only one part of a more complex hydrothermal system that probably extends towards the East for a distance of about 10 kms. Currently exploratory drilling is being conducted with the purpose of investigating this area; temperatures greater than 200°C at 400 meters depth having been found.

The surface manifestations of the Ahuachapan hydrothermal system are characterized by having a fumarolic character in the limbs of the volcanic system, accompanied by extensive areas of hydrothermal alternation and springs of an acidic character, and in the areas below the volcanic mass by hot springs of a $Cl-HCO_3$ type, that drop off in T and salinity in a northerly direction; see Figure 1.

Presently 24 deep wells have been drilled in the area of which 11 are producers, 4 are reinjection and 9 exploratory with some type of production in some of them. The producing wells discharge a mixture of water-steam in proportions of 11 to 46%. The producing stratum that has been found has thicknesses up to 300 M, the maximum measured temperature is 239° C. The production rate is from 102 to 550 ton/hour of mix.

On the basis of the good results in the drill holes 2 units ~~with~~ at an average pressure of 5.5 with a generating capacity of 30 MW each, which are fed ~~with~~ a steam separator from 9 holes with an average of 8.8 MW per hole, have been installed. The operation of the first unit began in June 1975 and the second in June of 1976. Presently the studies for the implantation of the 3rd programmed generating unit ~~are~~ is planned for 1979 with installation a capacity of 35 MW.

In view of the need to study the conditions of the reservoir being worked, a programmed control of measurements and of fluid sampling has been established in order to detect and evaluate any changes in the physical-chemical conditions of the reservoir. This control basically consists of measurements of the pressure head, volume of water flow, volume of steam flow, input of fluid samples, measurements of production, and records of temperature and pressure.

The variations that have been detected have been:
-increase in total salinity
-decrese in the Na/K ratio
-decrease in hydrostatic levels
-variation in the production characteristics of some wells

All these variations have greater incidence in the major operation area.

Presently said changes are being evaluated in order to establish possible causes and effects.

2. GEOLOGICAL FEATURES

The geology of the Ahuachapan geothermal field has been widely studied. For the purposes of this work a vertical cut of the field has been worked in which it is possible to study the stratographic succession that basically consists of:

-lavatic tuffaceous formation	
-young agglomerate	Quaternary
-Ahuachapan andesitic formation	
-old agglomerates	Tertiary

2-1 Lavatic Tuffaceous Formation (Figure 2)

This basically is made up of two components (tuffaceous formation with lavatic intercalations). It does not have importance from the point of view of the internal reconstruction of the reservoir. It shows thicknesses up to 500 meters.

2-2 Young Agglomerate

It has thicknesses along the order of 200-400 M and is a quite impermeable volcanic formation, ~~that~~ by overlaying the Ahuachapan andesitic formation, serves as an effective seal for the reservoir.

2-3 Ahuachapan Andesitic Formation

A formation made up predominantly of wash with intercalations of tuffaceous materials. It constitutes the producing formation of the field. It is quite fractured although not uniformly, showing an increase in its secondary permeability in its contacts with the young agglomerates and with the deep substratum. The condition of the roof of the andesitic formation is presented in the report prepared by Engineers Jimenez and Campos at this symposium.

2-4 Old agglomerate

This forms the base of the andesitic formation. It ~~will occasionally~~ contains intercalations of breccia and ~~wash~~. In some holes this stratum shows certain secondary permeability.

3 Hydrogeologic Condition

On the basis of the in hydrology and geochemistry and with the verification of the results in the deep drill holes it was possible to confirm the existence of 3 main aquifers:

3-1 Shallow Aquifer

This is located ~~on~~ at the surface in recent geological formations made up of tuff, pumice and fluvials that lie on the wash of the Laguna Verde Volcanic Group. It is fed by surface percolation of meteoric water. The chemical composition of the waters of this aquifer show that they are predominantly carbonated, showing high concentrations of sulfates, when they are heated by underground steam.

3-2 Saturated Aquifer

This aquifer circulates in the ~~wash~~ lavas and pyroclastics that make up the lavatic tuffaceous formation and has a bed ~~the~~ highly impermeable young agglomerates. The water that circulates in this aquifer originates from the more or less deep infiltration of precipitation water. This aquifer feeds the domestic wells and gives certain thermality in some areas, produced by conduction by means of young agglomerates, showing waters with high contents of calcium and sodium bicarbonates, or by mixing with the waters of the deep saline aquifer producing waters with a high content of sodium chloride and bicarbonates of Ca and Na.

3-3 Saline Aquifer

Located in the andesitic formation of Ahuachapan, it has an upper seal of the impermeable young agglomerate formation and as a base massive tertiary agglomerates. This aquifer circulates through the zones of secondary permeability which exist in the andesites.

Its actual expanse is to the South and West of the field, its boundaries on the South and East are not known with exactitude, but apparently it stretches in an easterly direction towards the Chipilapa region. The chemical characteristics are high salinity that basically consists of sodium, potassium, and calcium chlorides, accompanied by a wide variety of lesser constituents Li, Sr, Cs, Rb, I, Br, As, B.

The piezometric data and the geological characteristics suggest that the recharging zone of this aquifer is found in the volcanic groups located to the south of the field, where the craters facilitate the deep infiltration of water, that has been shown to be of a predominantly meteoric origin.

The natural outlet of this aquifer seems to be the series of springs located to the north of the field (El Salitre, La Ceiba, San Lorenzo) which show atomic ratios similar to those of this aquifer although the absolute concentrations are less than that of the water of the saturated aquifer. The massive extraction of fluids from this aquifer in the main part of the geothermal field area has produced a flow inversion, in the direction of the major working area, producing a dip in the piezometric level, this is accompanied by an invasion of water than tends to replace what has been extracted; the characteristics of this water seems to have the greatest heat content and saline content.

CHEMISTRY OF THE FLUIDS

4-1 Generalities

The water discharged by the wells of the Ahuachapan geothermal content field are characterized by being predominantly sodium chloride; but also containing as major constituents potassium, silica, calcium, & ~~Horn~~ boron. See table 1.

The material discharged at atmospheric as pressure has a slightly alkaline pH between 7.10 and 7.80 ~~and is~~ found at boiling point. The extension of the saline aquifer that feeds the producing wells of the area is presently undefined, with only 2 of its boundaries known to date: towards the West as indicated by the results of well Ah-15 which does not show salinity and the results of wells Ah-11 and Ah-12 to the north of the field which show a substantially reduced salinity. This rapid decrease in salinity in those directions clearly tells us the limits of the saline aquifer in that direction a fact that has been verified by the low permeability and temperatures in the area of said wells.

In the other directions where the extension of the high temperature aquifer cannot be determined we have a concentration effect in a S-SW direction as indicated in the map of the isocentration of chlorides (Figure 4).

Everything seems to indicate that the saline water of the aquifer being worked has a common source although the possibility of mixes with high temperature water of lower salinity cannot be excluded. To date a salinity gradient in a vertical direction has not been detected since there are nearby wells drilled at the same depth with different concentrations, but the existence of a horizontal concentration gradient in a S-SW direction is evident. The existence of this gradient tells us that the migration of fluids in the producing stratum is horizontal and that the wells with the highest concentrations (wells Ah-7, Ah-16) would be closer to the reservoir feed.

Apparently the fall of the piezometric levels of the producing aquifer caused by the operation are causing a more rapid migration of the water with greatest salinity and temperature towards the center of the field. This fact is verified by the increment of concentrations that have been made in wells Ah-1, Ah-4, Ah-6 as well as by a decrease in the Na/K ratio in some wells (Figure 4).

The atomic ratios of Cl/B, Cl/As, Cl/F, Cl/Br, Cl/I also indicate that the saline water has a common source.

4-2 Na/K Ratio

This ratio, whose importance due to its dependence on temperature is well known, has in the fluid discharged by the Ahuachapan wells a range between 12.5 and 8.76 which corresponds to a temperature range between 222 and 274°C (White 1970) -- that differs in its upper limit with the maximum temperature measured at the reservoir which is 239°C in well Ah-22. We can contend that the Na/K ratio hasn't reached its balance in the area of the field where there are great differences between the T measured and the T calculated by the Na/K ratio; these differences can be observed in the following table in which the values for the maximum temperature measured and the temperature calculated by the Na/K ratio are reported:

Well	Max T°C	T Na/K °C	Difference
Ah-1	232	255	23
Ah-4	234	233	-1
Ah-5	230	222	-8
Ah-6	231	257	26
Ah-7	230	274	44
Ah-20	225	256	31
Ah-21	233	258	25
Ah-22	239	226	-13
Ah-26	232	241	9

From the preceding table and the map of Na/K temperatures compared with the maximum temperatures, it can be seen that these values move away from the temperatures measured in a S-Sw direction culminating in well Ah-7 which shows the greatest difference. This indicates that the sodium potassium hasn't reached its balance with the rocks of the reservoir in that direction and that it reaches the balance when it circulates in a N-NE direction. This fact is important for inferring the possible feeding zone of the reservoir. There is also the possibility that the low ratios reported in that direction are an indication that the water that feeds the reservoir has been in contact with rocks of higher temperature in a deeper zone not necessarily near the reservoir being worked and that the balance in the feeding zone adjoining the reservoir hasn't managed to be established yet. Up to now temperatures greater than 239°C have not been detected in the drilling area.

This ratio also confirms the possible extension of the reservoir in a S-SE direction and its N and NW boundaries coming from the working field.

The map of Na/K temperatures seems to indicate, together with that of maximum temperatures, and with that of the isoconcentration of chlorides, and with that of the concentration of Si02 that the feeding zone is found to the south of the working field and that the circulation of fluids has a lateral direction with a tendency towards the N-NE.

4-3 Concentrations of SiO_2

The concentrations of SiO_2 correspond very accurately to those expected for balanced quartz water to those measured from the reservoir. The map of silica isoconcentrations shows an obvious tendency to increase towards the south of the field, and this correlates with the maximum measured temperatures and with the Na/K ratios. All the evidence indicates that the flow has a N-NE direction previously converging in the center of the area of greatest operation (Figure 5)

If we calculate the heat content of the water in the reservoir using the SiO_2 concentrations in the discharged water, it will be seen that the values are much smaller than those calculated by means of measurements. This fact provides evidence that a certain quantity of steam generated in the reservoir is being expelled with the mix.

4-4 Cl/B, Cl/As, Cl/Br, Cl/I Ratios (Table 2)

This series of ratios show themselves to be quite constant in the waters discharged by the producing wells, confirming only one source for the water that feeds the saline aquifer. It should be noted that the Cl/B ratio stays within the average range even in the Ah-14 and Ah-16 wells, considered to be bordering the working area. This fact is important because it enlarges the extension of the saline aquifer to the S-SE at the same time that it suggests a possible communication with the saline aquifer existing in the Chilapa area.

The Cl/Br, Cl/I ratios are quite low compared to those found in similar fields and the source of the high concentrations of Br (40 ppm) and I (8 ppm) has not yet been explained.

The variation in the absolute concentrations of B, As, Br, and I seem to be related to a process of dilution of the feed water in the reservoir in a N-NE direction although to date it isn't possible to detect this process in ~~another form~~ any way.

5. PHYSICAL STATE OF THE AHUACHAPAN FIELD

Beginning in 1975, an ~~artificial~~ designed ~~operation~~ EXPLOITATION ~~in~~ OF considerable proportions was started in the Ahuachapan geothermal field. To date the total quantity of extracted mass is along the order of 26 x 10^3 ?. This artificial extraction of mass has provoked changes in the physical conditions of the aquifer that supplies caused the Ahuachapan geothermal zone.

The change in the original physical conditions has been detected by a program of routine measurements that include: records of pressure and temperature, measurements of production and control of discharged water.

The original condition of the aquifer, before starting the extraction programs on a large scale for the purpose of generation, as expected ~~was~~ that determined by the saturation condition. The evidence that supports the saturation condition, ~~that~~ is the existence of only one phase; it is possible to get it from the pressure ratios measured in the well together with the saturation pressures for the measured temperatures. Figures 6 and 7 show us these ratios for wells Ah-6, Ah=7, and Ah-20 in 1974. These wells were selected because they are representative of two field sites: Ah-6 and Ah-20 are located in the main working area and Ah-7 because of its being a well quite removed from the area and it has demonstrated not to be sensitive to many of the observed variations.

In said figures we see how the saturation condition was generalized for the 3 selected wells, with only one change in this condition occurring when the hydrostatic pressure surpassed the saturation pressure. The same ratios have been graphed for the current state of said wells, in which one can clearly observe how the saturation condition has been ruptured in the Ah-6 and Ah-20 wells while it has stayed ~~quite similar~~ about the same in the Ah-7 well.

The similarity of the ratios before the extraction process indicates to us a s turation condition in the original aquifer in 1974, while the variations observed for 1976 indicate that in the zone of influence notable changes have occurred in the condition of the aquifer and that these changes have not affected the wells located outside of the major extraction area.

These pressure ratios together with the saturation pressure suggest the probability of a steam phase in the reservoir, that would be explainable on the basis of a decrease in the hydrostatic level.

With the mass extractions, without yet making suppositions about the existence of a recharge mechanism, a decrease in the water level of the reservoir has been produced which necessarily implies a fall in pressure. This fall in pressure should be accompanied by a drop in temperature until the point where the water reaches a balance in the temperature of the rocky formation, The saturation condition will then cause a decrease in pressure until saturated steam pressure corresponding to these balanced temperatures is reached. Below the water level, the pressure will drop with depth until the point where the pressure is greater than the saturation pressure and will dispose of heat from this depth to the water level. This available heat will theoretically cause a steam phase that will fill the formation and will keep the pressure above the water level more or less equal to the pressure of said level.

At this point changes in the heat content of the discharge of individual wells, since the steam produced by the 'flash' in the interior of the well will add to the existing steam in the reservoir; a fact that has already been detected for some wells. Basically, its from this point of view that the hypotheses about the present discharges of the Ah-4 and Ah-6 wells, that are wells located in the center of the working area, the production conditions that are listed in Table 2 have been observed and they have been compared with the characteristics of the discharge of well Ah-7 situated a little further away from the zone affected by the operation; these are characteristics which typify the discharge of a well in which the percentage of steam in the total discharge is only due to the 'flash' process starting with water saturated at 222°C.

A reasonable alternative to the hypothesis of the probability of a steam phase in the interior of the reservoir would be to consider an increase in the interior of the well, that is, a decrease in the 'flash' level. On the other hand, a quite considerable increase would be needed in order to explain the indicated ratios of liquid-steam, an increase that seems to us not to be justified on the basis of given thermodynamic variations.

Some considerations about the hypothesis of a recharge system are left to be done but up to now the only evidence in this direction is qualitative and was obtained during the withdrawal of the first unit in the months of Dec/75 to Jan/76. This was a period in which a recovery in the pressure of the same was observed which exceeded the errors in measurement.

In another part of this report it will be seen that the chemical composition of the waters in the field also lead to establishing the existence of a recharge. Therefore, it remains established that the behavior of the Ahuachapan geothermal field is one corresponding to a field where the discharges of the individual wells are of the water-steam type, that originally it was set up by a liquid phase and has been changed by working to a state of 2 phases: water-steam.

5-1 Temperatures

On the basis of the data obtained from the 24 presently drilled wells, it has been possible to draw a map of the maximum measured temperatures for the reservoir (Fig. 8). On said map one can observe an area of higher temperatures (220-239°C) found situated in an area of 1 km2 that includes all the wells presently in production. The boundaries of the hyperthermal zone are well defined in a northerly direction by the wells Ah-11 and Ah-12 and to the West by well Ah-15. In the South and S-SE the area seems to extend as far as the Chipilapa region, according to what has been shown by the results of the deep well CH-1 and the exploratory wells currently being drilled. This fact would extend the hyperthermal area to approximately 8-10 km2 which gives us an idea of the potentiality of the system.

One fact that has been made clear is that the widening of the area of highest temperatures due to intensive working is probably due to a greater movement of high temperature fluid towards the extraction zone.

Also, it should be noted that the wells located in the high part of the reservoir show the highest temperatures; this probably confirms that the primary feed of the reservoir occurs in a southerly direction.

The vertical distribution of temperatures measured after ~~the~~ thermal stabilization, from the formations, is characterized by a gradual increase in gradient until it reaches the roof of the reservoir, after which there is a notable tendency to maintain values that oscillate between 230-239°C. Generally an inversion occurs upon reaching the massive agglomerates.

PRODUCTION CAPACITY

The present production capacity of the field, considering only the 9 producing wells connected to the Geothermal Station, is around 1630 T/hr of mix which separated at an average pressure of 5.9 kgr/cm2 results in 493 t/hr of steam and 2137 T/hr of water, giving an average ratio of steam/water of 0.23. From the wells previously considered, (Ah-4 and Ah-21) these are found to be restricted due to the smaller capacity of the cyclonic separators.

Later on the production characteristics of the producing wells are reported (Table 3)

The curves of the production characteristics, measured by the critical pressure method, can be seen in graphs 9 and 12. In these we can observe the general production characteristics of each well.

Because of the intensive working of the field, a certain general tendency to an increase in the steam/water ratio has bee noted, that in some wells has been more pronounced, as is the case of well Ah-6, which by its location and depth seems to be the most sensitive to [illegible] ~~[illegible]~~ variations in production.

From the table on production characteristics we can observe 2 significant facts:

1. The production rate of the wells ~~is~~ are quite large, a fact that is intimately related to the distribution of secondary permeability in the field which has been shown to be totally unpredictible. We can see that the wells with greater capacity are those situated in a S-SE direction in the topographically elevated part of the field.

2. A wide range of heat content in the mix that goes from values of 211 kcal/kgr for well Ah-5 to values of 395 kcal/kgr for well Ah-26. This fact seems to indicate that with extensive operation a steam phase has been formed in the central part of the field. This subject was discussed in a previous chapter.

TABLE 2

COMPARISON OF THE DISCHARGES OF WELLS Ah-4, Ah-6, and Ah-7

	Well Ah-4	WellAh-6	Well Ah-7
-Separation Pressure (kg/cm^2)	6.2	5.9	5.8
-Total flow (T/hr)	472	224	228.6
-Water flow (T/hr)	385.92	164.6	198
-Steam flow (T/hr)	85.75	59.4	30.6
-Heat content of the mix (Kgal/Kg)	251.1	291.6	224.87
-Percentage of steam calculated by the separation pressure	18.18	26.55	13.8
-Percentage of separation expected for saturated water*	15.91	15.7	13.9
-Difference (f) - (g)	2.27	10.85	0.1

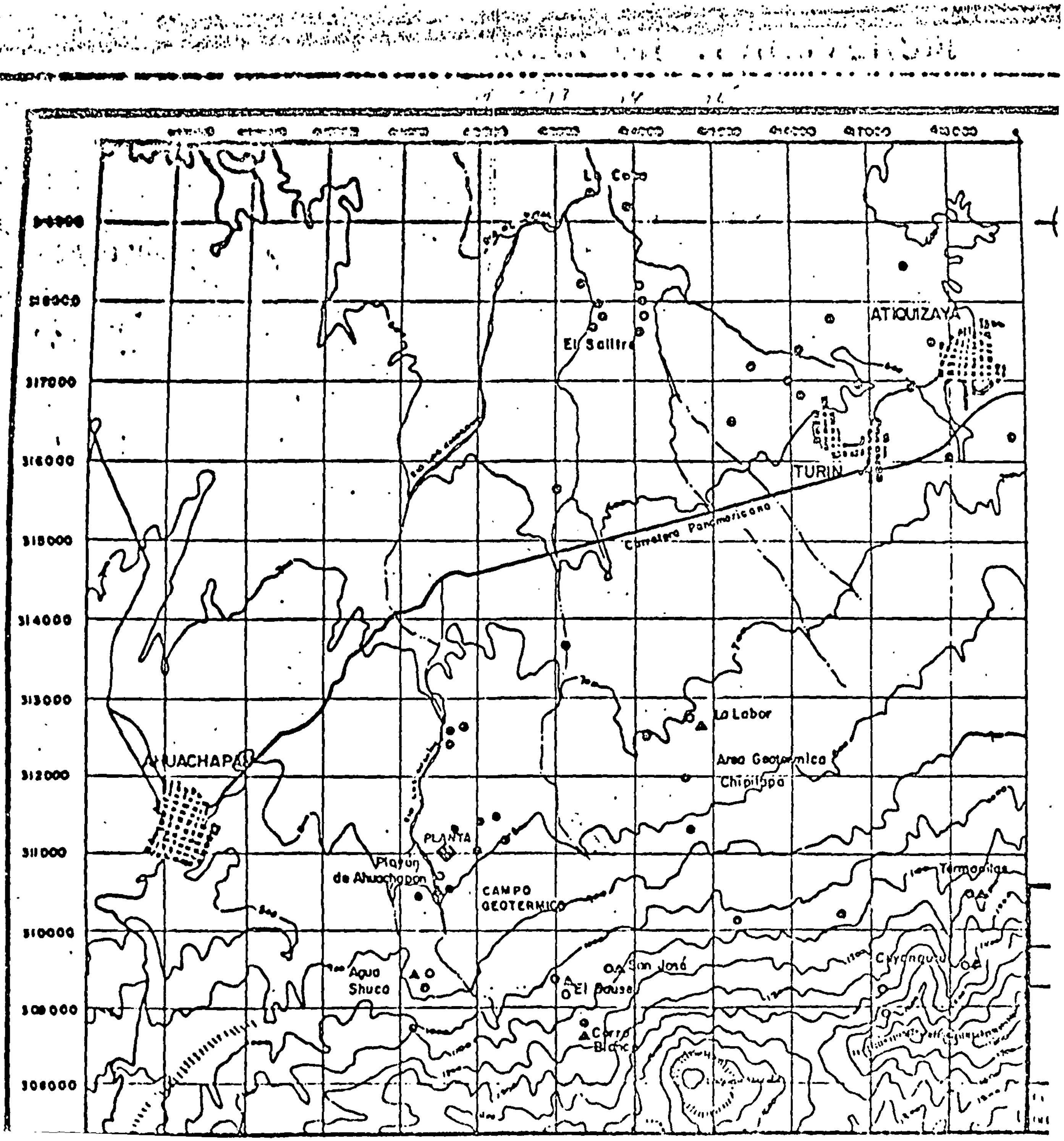
*In order to calculate (g) the heat content of the water at the temperature recorded in the well is taken as a base.

PRODUCTION CHARACTERISTICS

Wells	S.P. Kgr/cm^2	Total Flow T/hr	Water Flow T/hr	Steam Flow T/hr	Percent of separation	Heat Content	Est. MW
Ah-1	5.8	344	298	46	13.37	224	7
Ah-4**	6.2	472	386	86	18.2	251	13
Ah-6	5.9	224	165	59	26.6	291	9
Ah-7	5.8	229	198	31	13.8	225	5.5
Ah-5	5.6	239	213	26	10.8	211	4
Ah-20	5.5	226	183	43	19.0	251	6.5
Ah-21* **	5.9	502	423	82	16.3	220	12.5
Ah-22	5.9	293	221	72	24.5	281	10
Ah-26	5.8	102	54	48	46.8	392	9

*Estimated computation

**Restricted well



LEGEND

- ● Thermal sources
- ○ Fumaroles
- ▲ Gas leak
- Edge of crater

Fig. 1

AHUACHAPAN GEOTHERMAL AREA

CROSS SECTION

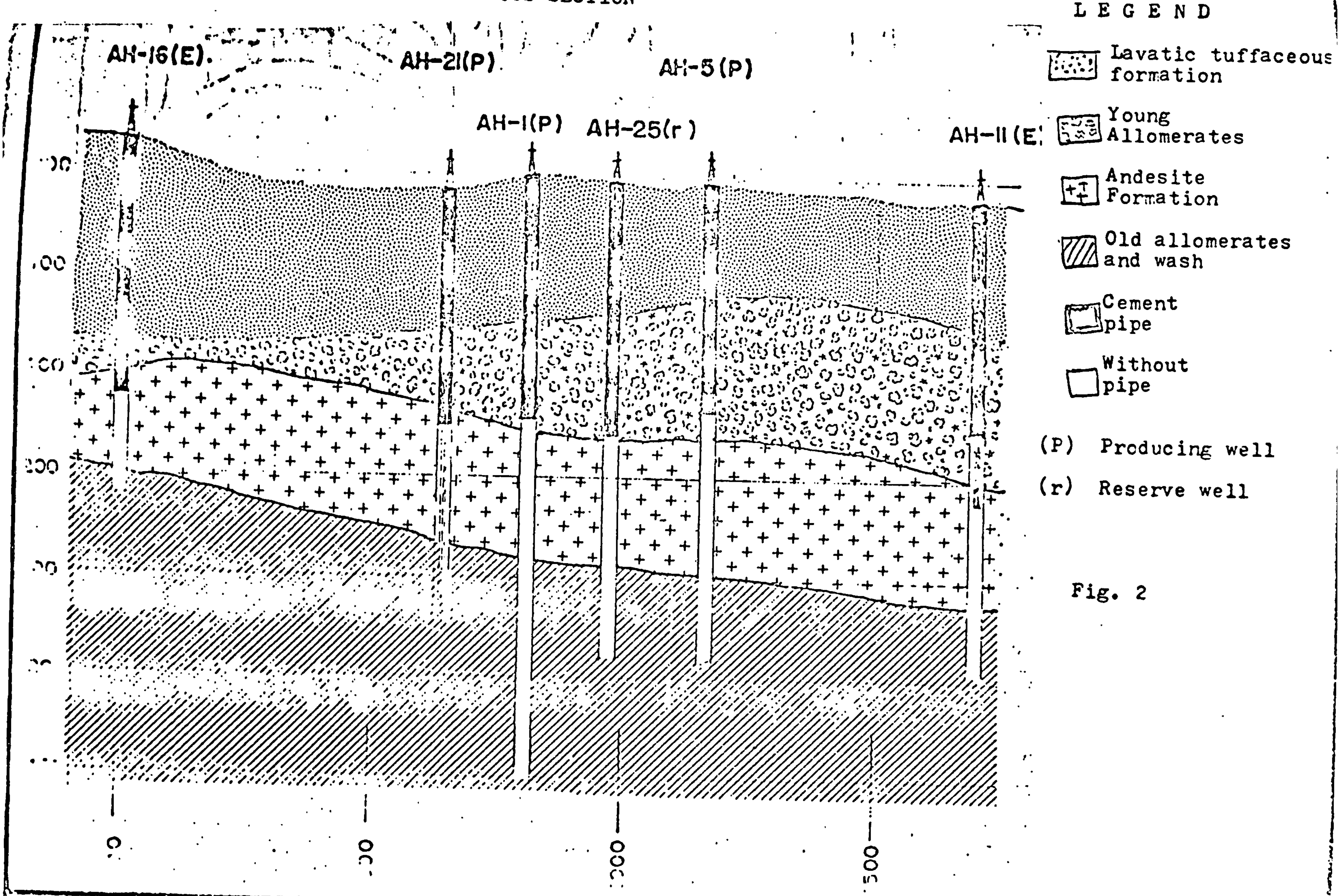
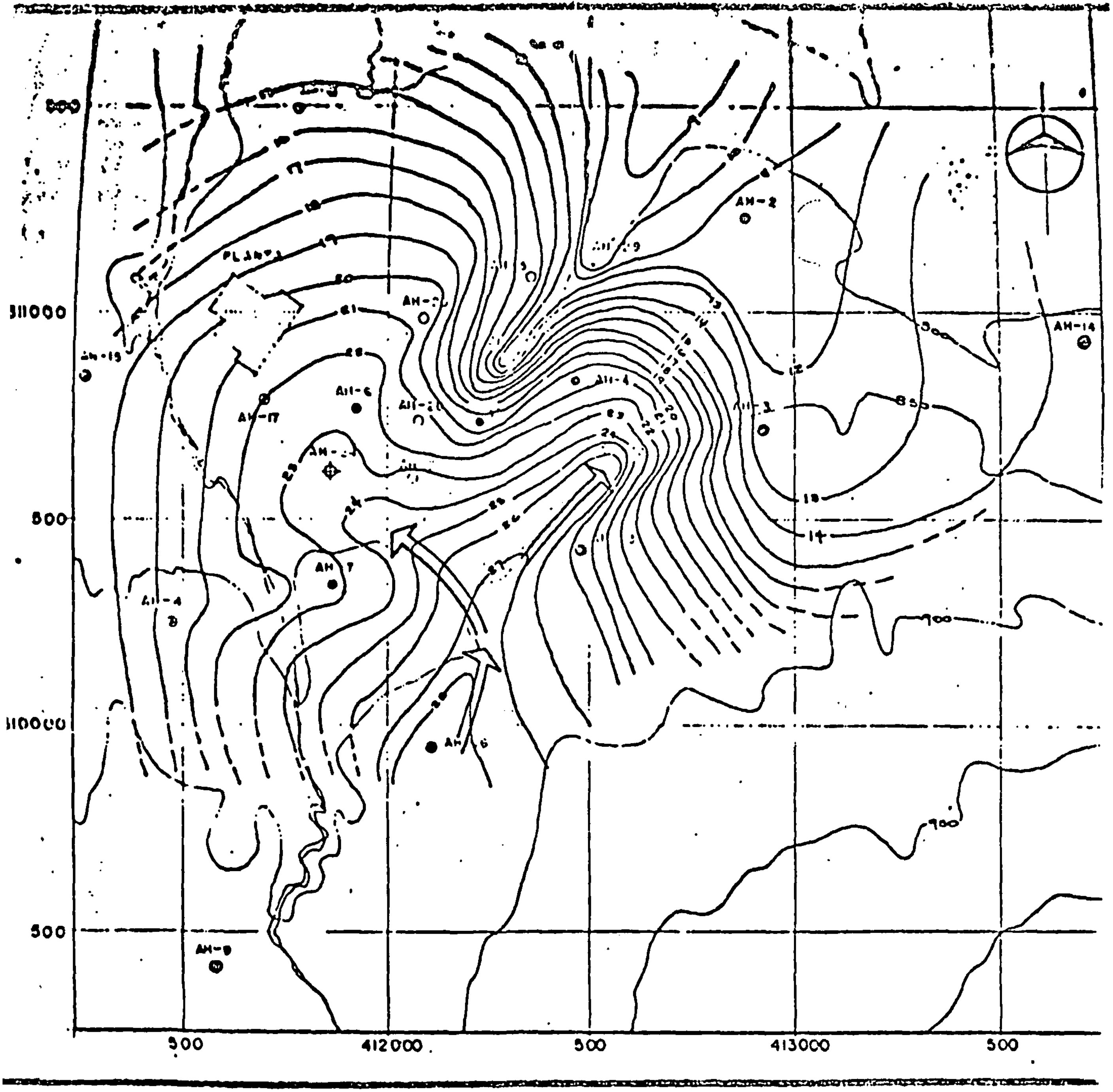


Fig. 2

AHUACHAPAN GEOTHERMAL FIELD



SYMBOLOGY

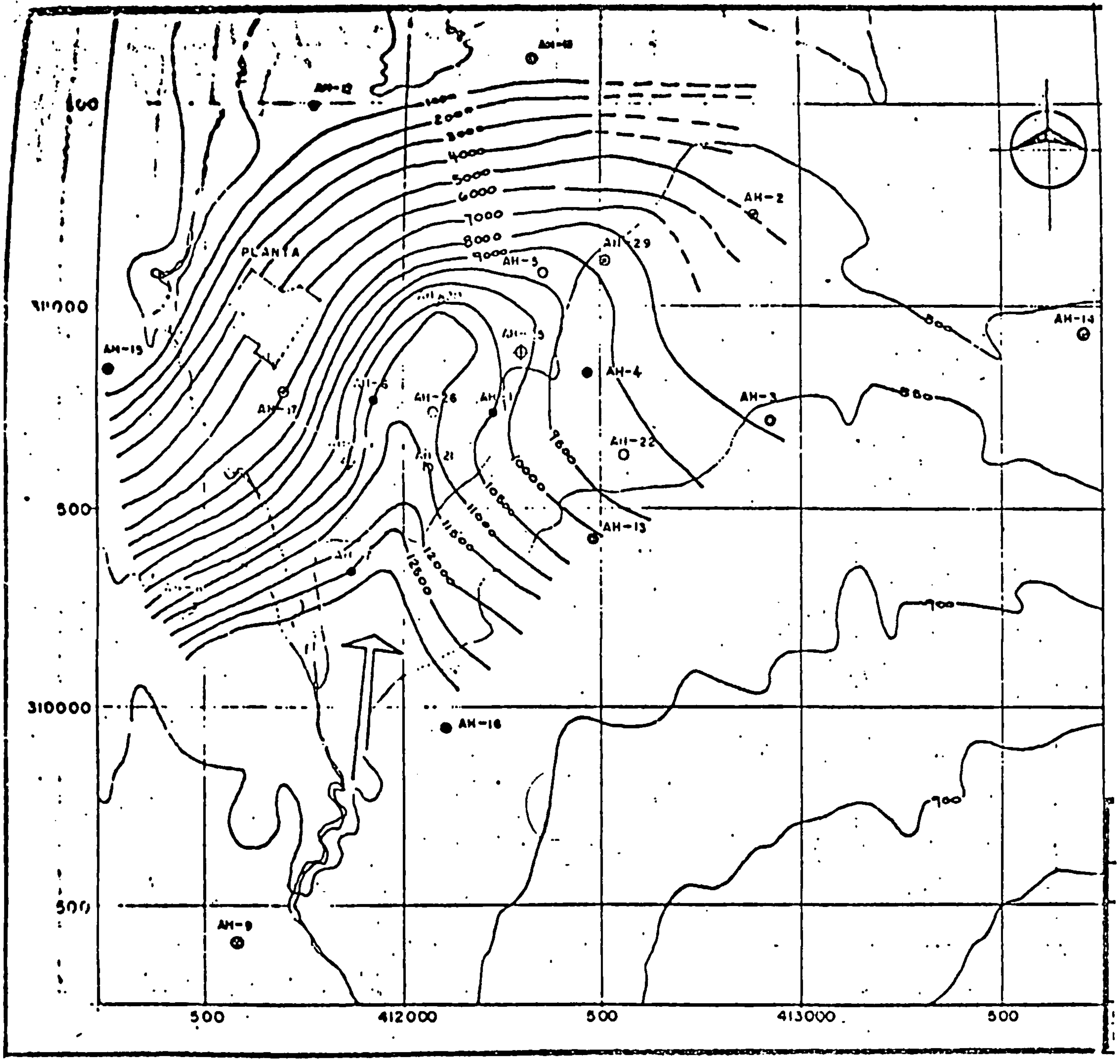
- ● Wells 1a Unit
- ○ Wells 2a Unit
- ⊙ Reinjection wells
- ○ Exploratory wells
- ⊕ Reserve wells

Pressure map at
elevation 450

Table 2

AHUACHAPAN WATER WELLS

POZO	Cl/B	Cl/As	Cl/SO$_4$	Cl/F	Cl/Br	Cl/I	Na/K	Na/Li	Na/Sr	Na/Ca	K/Rb
AH-1	22.05	2070	932	3755	534	4604	9.86	94.05	4911	23.75	276
H-4	19.22	1909	717	3753	588	4983	11.49	95.54	4187	21.75	289
H-5	20.19	1941	605	3850	554	4671	12.50	101.35	3354	19.77	293
H-6	21.38	1982	994	3332	588	4611	9.71	95.74	5080	23.78	277
-7	20.85	1884	1411	3647	558	4720	8.76	99.00	5294	23.63	328
-20	21.50	1916	978	3690	550	4617	9.81	97.30	5080	23.20	286
-21	20.81	2056	769	3684	551	4660	9.69	95.81	5269	1663	300
-22	22.19	2401	763	3811	538	4905	12.16	101.60	4083	20.23	297
-26	21.82	1943	621	3871	492	4291	10.52	96.00	4700	22.66	270
-11	19.46	n.d.	9.2	n.d.	n.d.	n.d.	48.49	n.d.	29464	81.28	n.d.
-12	3.98	n.d.	1.5	n.d.	n.d.	n.d.	23.42	n.d.	15180	230	n.d.
-14	18.71	n.d.	20.4	707	n.d.	n.d.	7.20	n.d.	n.d.	30.57	n.d.
-16	18.94	n.d.	53.0	3978	n.d.	n.d.	10.26	n.d.	3295	16.14	n.d.



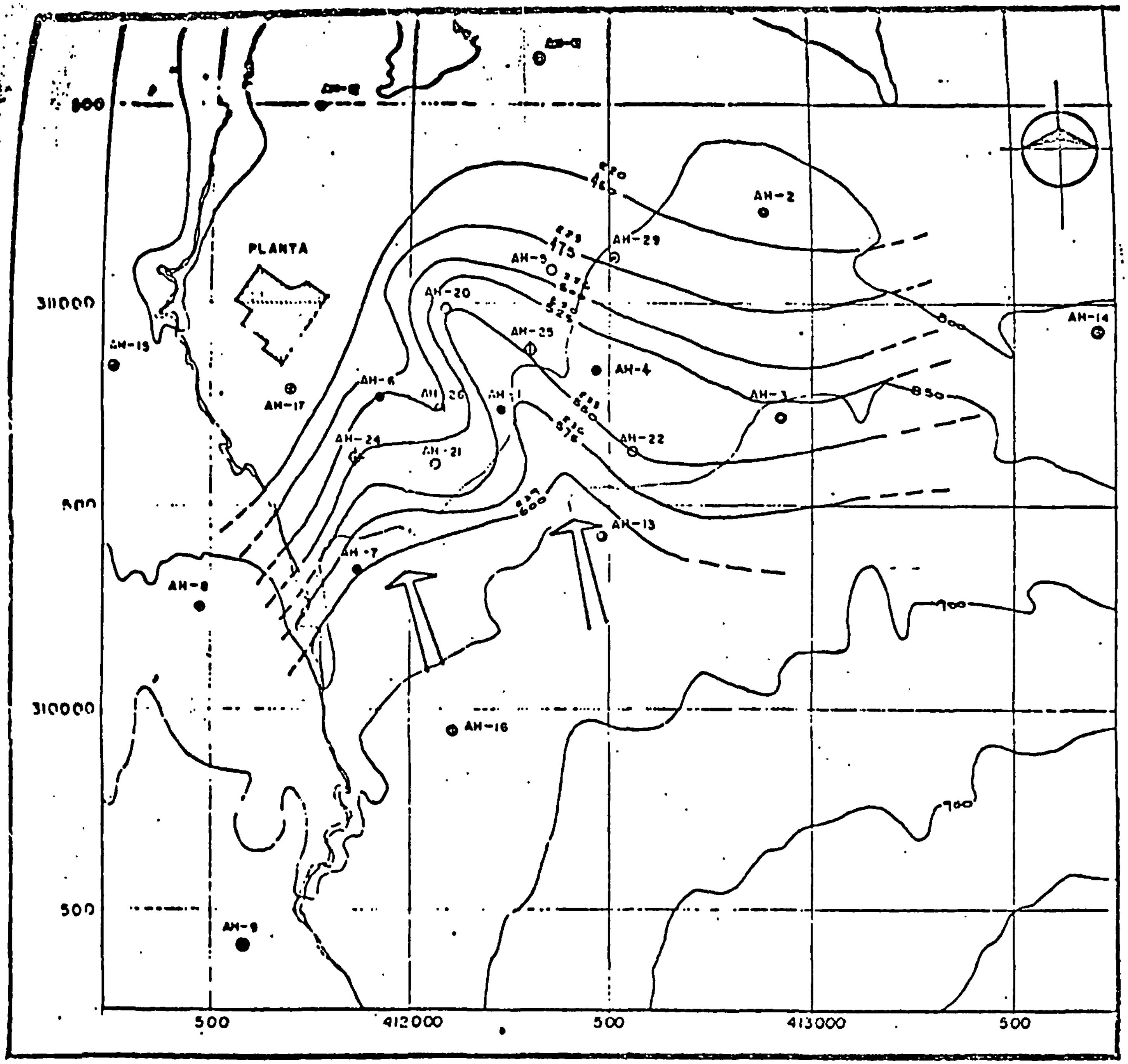
AHUACHAPAN GEOTHERMAL FIELD

Symbology

- ⊛ Wells 1a Unit
- ○ Wells 2a Unit
- ⦿ Reinjection wells
- ⊙ Exploratory Wells
- ⊕ Reserve Wells

Fig. 4

Map of chloride iso-concentrations in p.p.m.



AHUACHAPAN GEOTHERMAL FIELD

Symbology

- ⊛ Wells 1a Unit
- ○ Wells 2a Unit
- ⊙ Reinjection wells
- ⊕ Reserve Wells
- ⊛ Exploratory Wells

Map of silica isoconcentrations in p.p.m.

Fig. 5

PRESSURE RAT.

Fig. 6

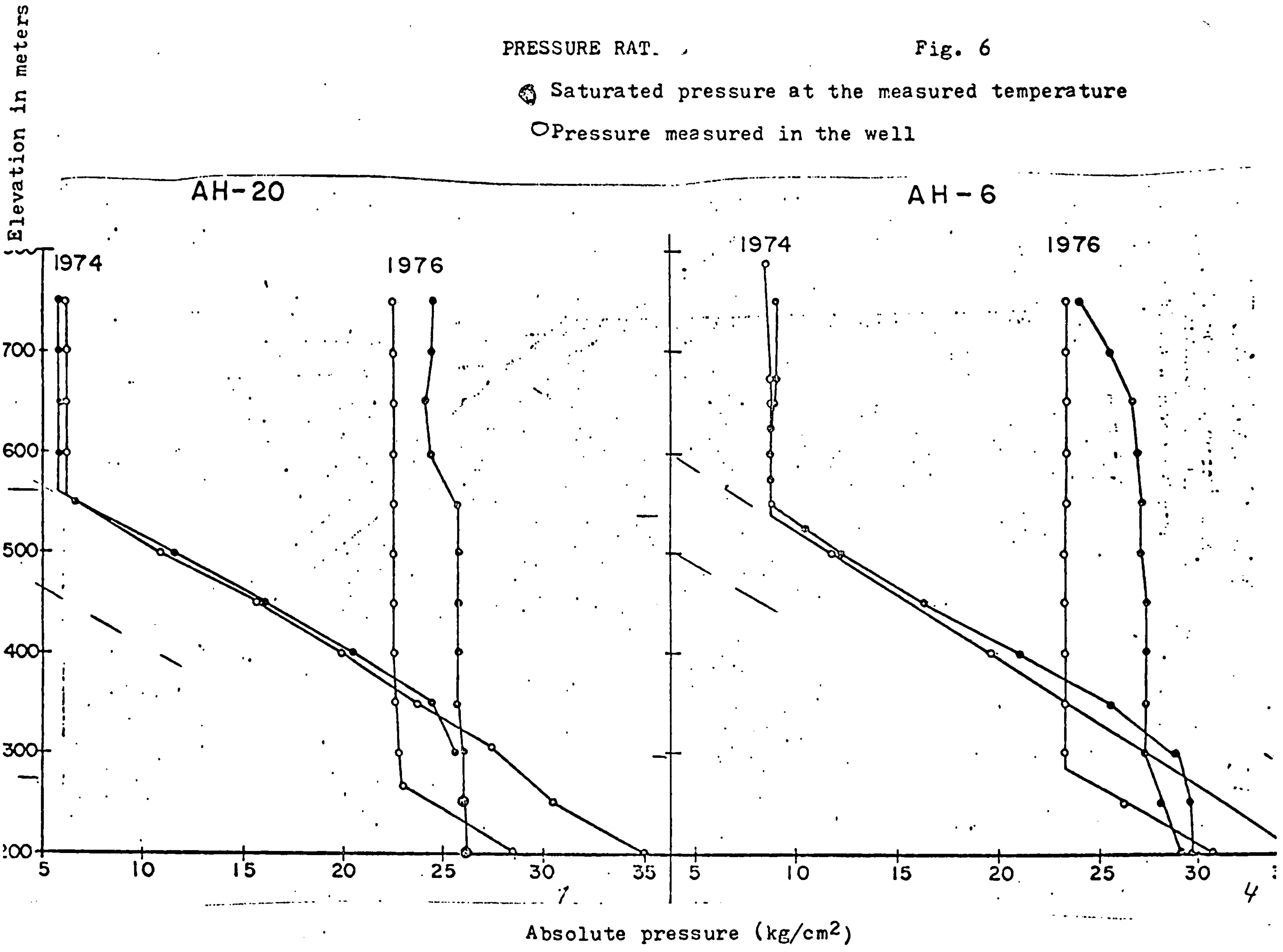
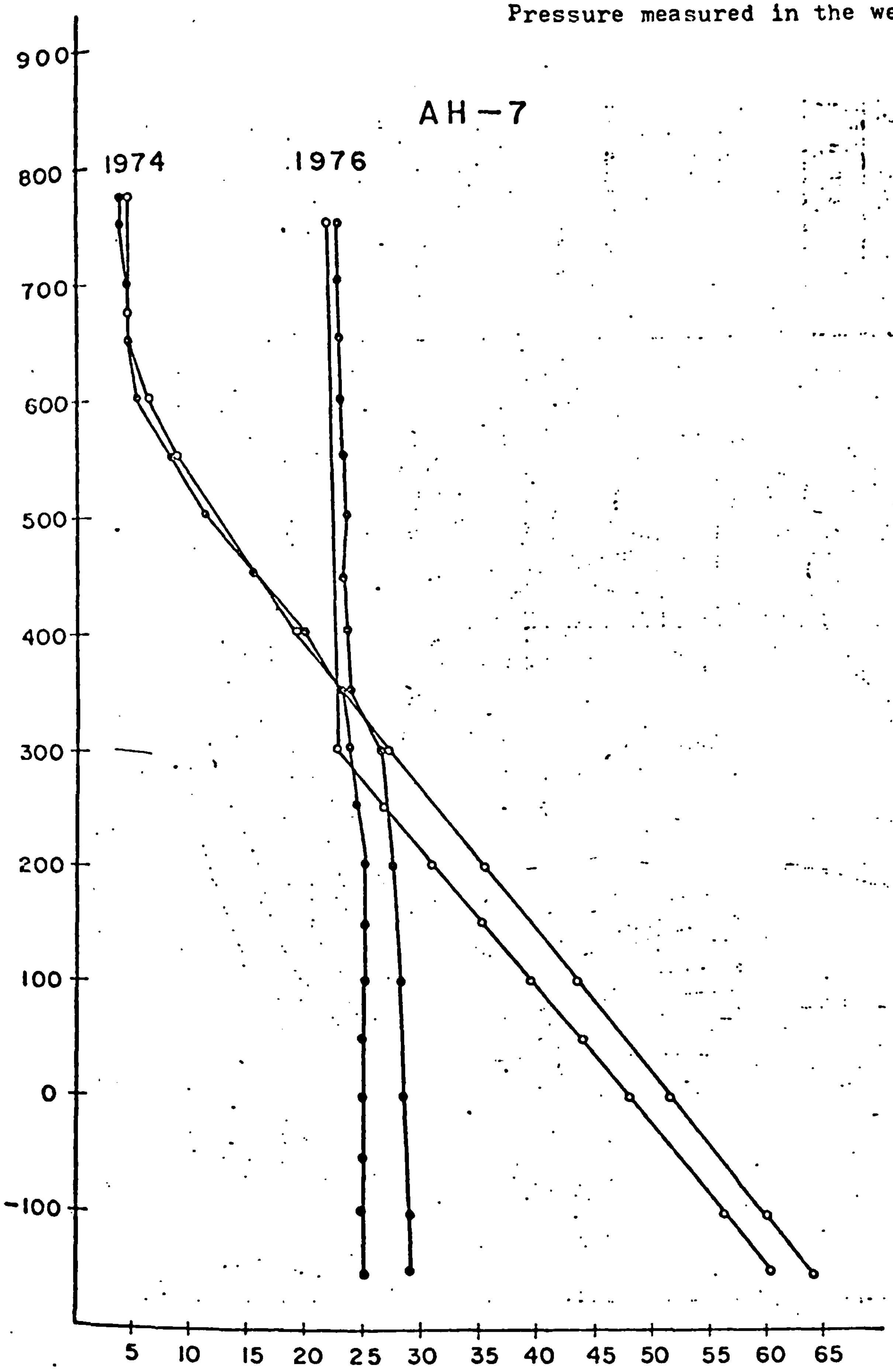


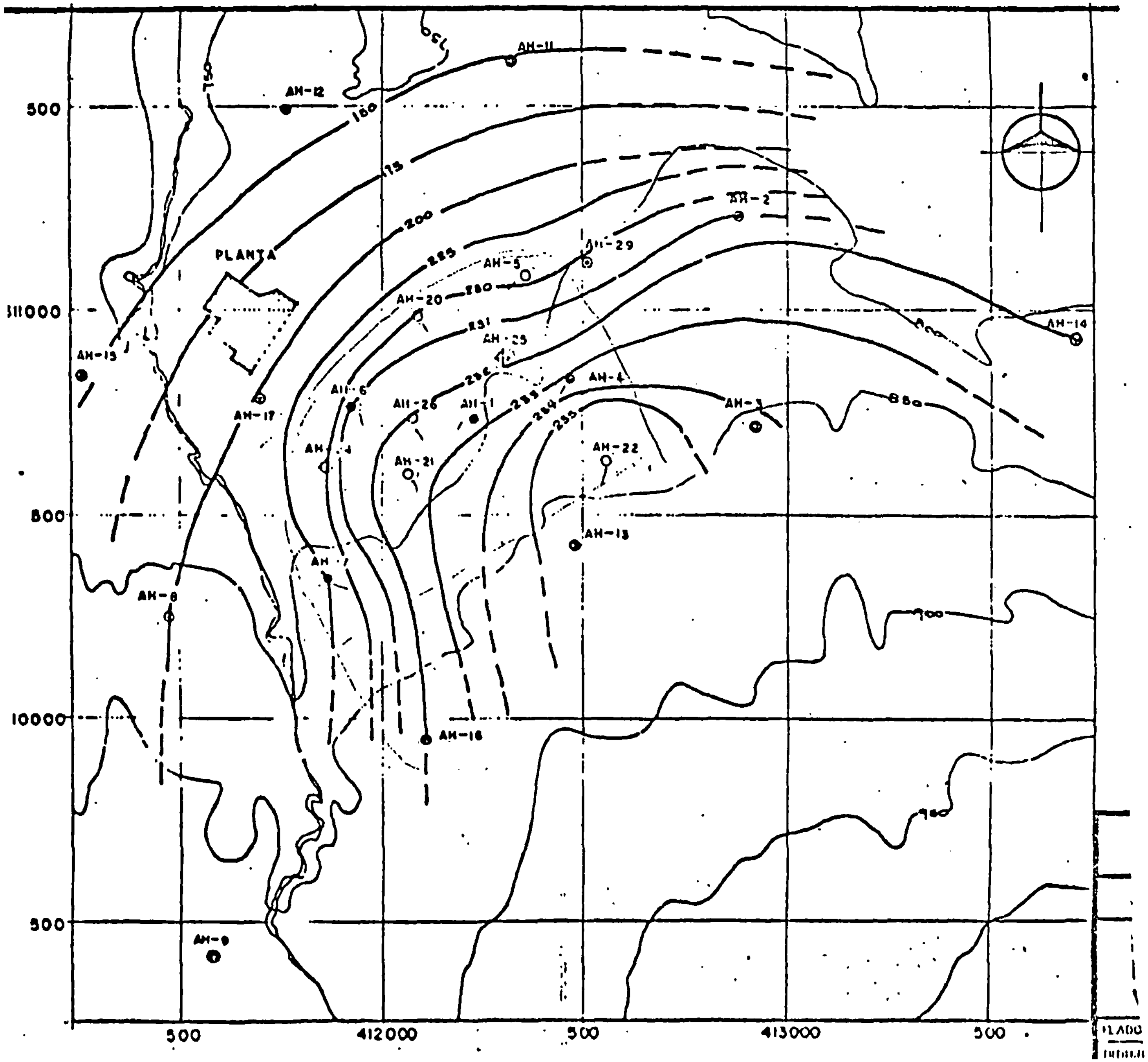
Fig. 7

PRESSURE RATIOS

Saturation pressure at the measured temperature

Pressure measured in the well



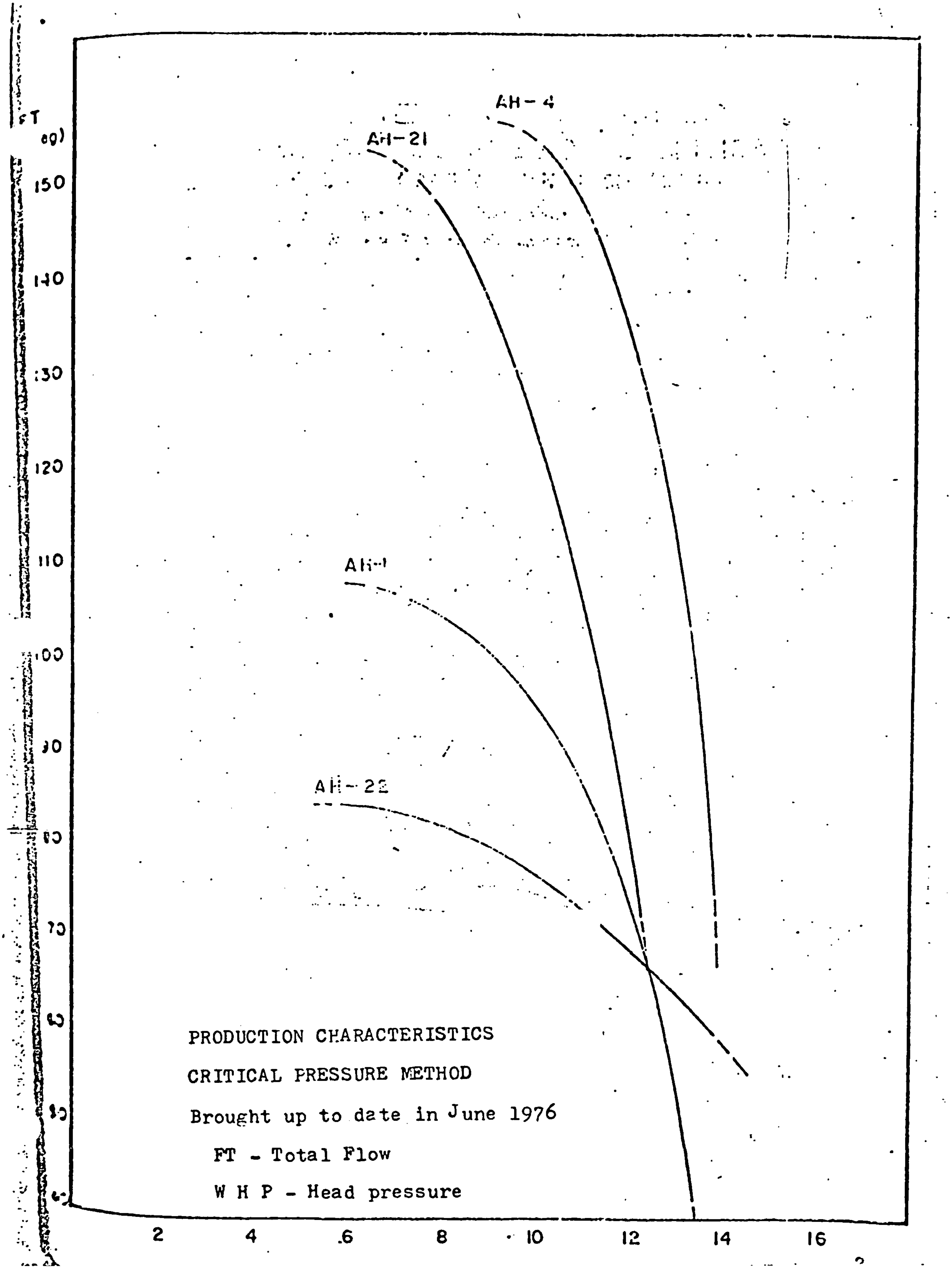


AHUACHAPAN GEOTHERMAL FIELD

Symbology

● Wells 1a Unit
○ Wells 2a Unit
⦿ Reinjection Wells
○ Exploratory Wells
⊕ Reserve Wells

Map of maxium temperatures measured in the reservoir



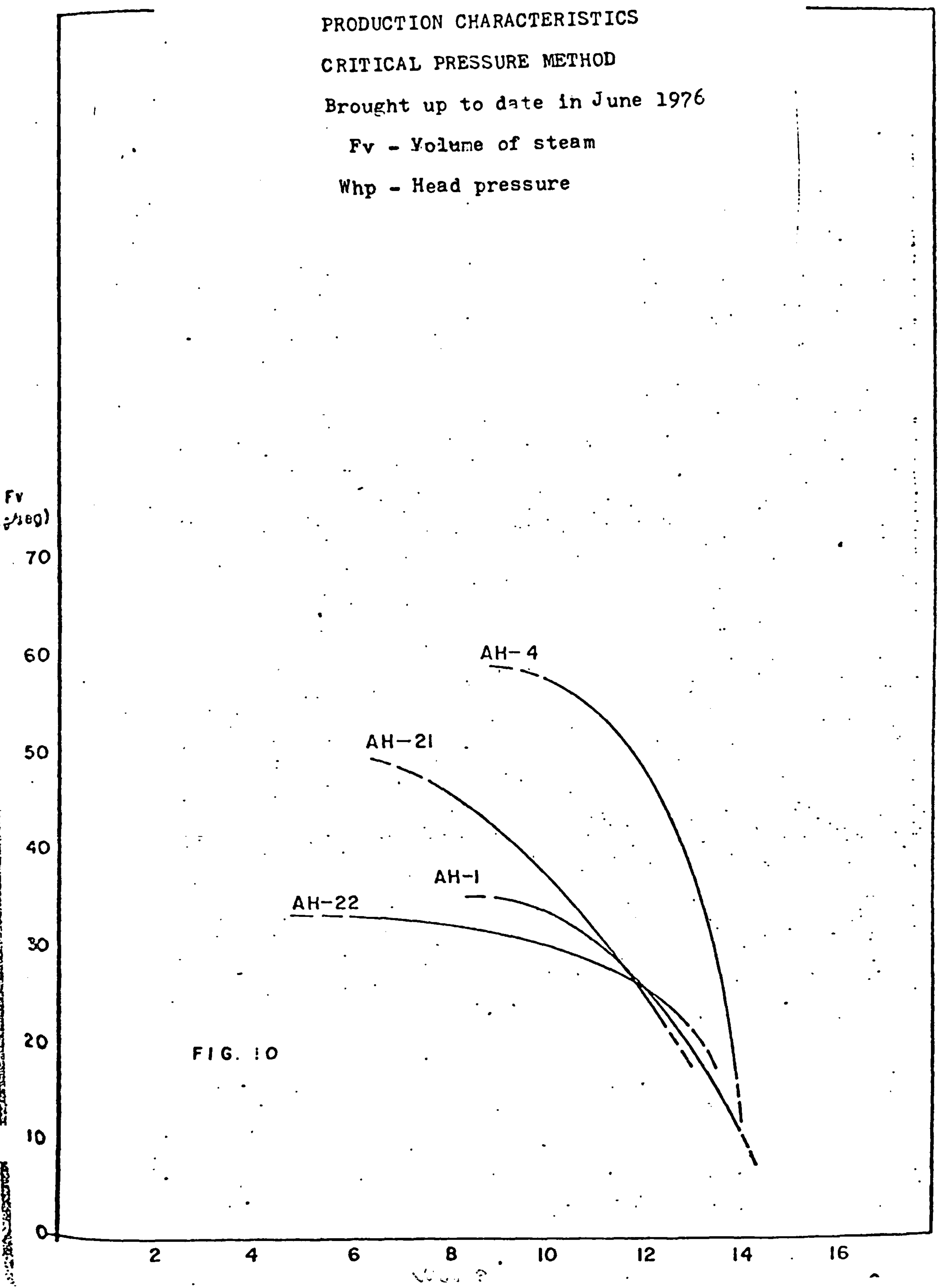
PRODUCTION CHARACTERISTICS

CRITICAL PRESSURE METHOD

Brought up to date in June 1976

FT - Total Flow

W H P - Head pressure



PRODUCTION CHARACTERISTICS

CRITICAL PRESSURE METHOD

Brought up to date in June 1976

Fv - Volume of steam

Whp - Head pressure

FIG. 10

PRODUCTION CHARACTERISTICS

CRITICAL PRESSURE METHOD

Brought up to date in June 1976

FT - total flow

WHP - head pressure

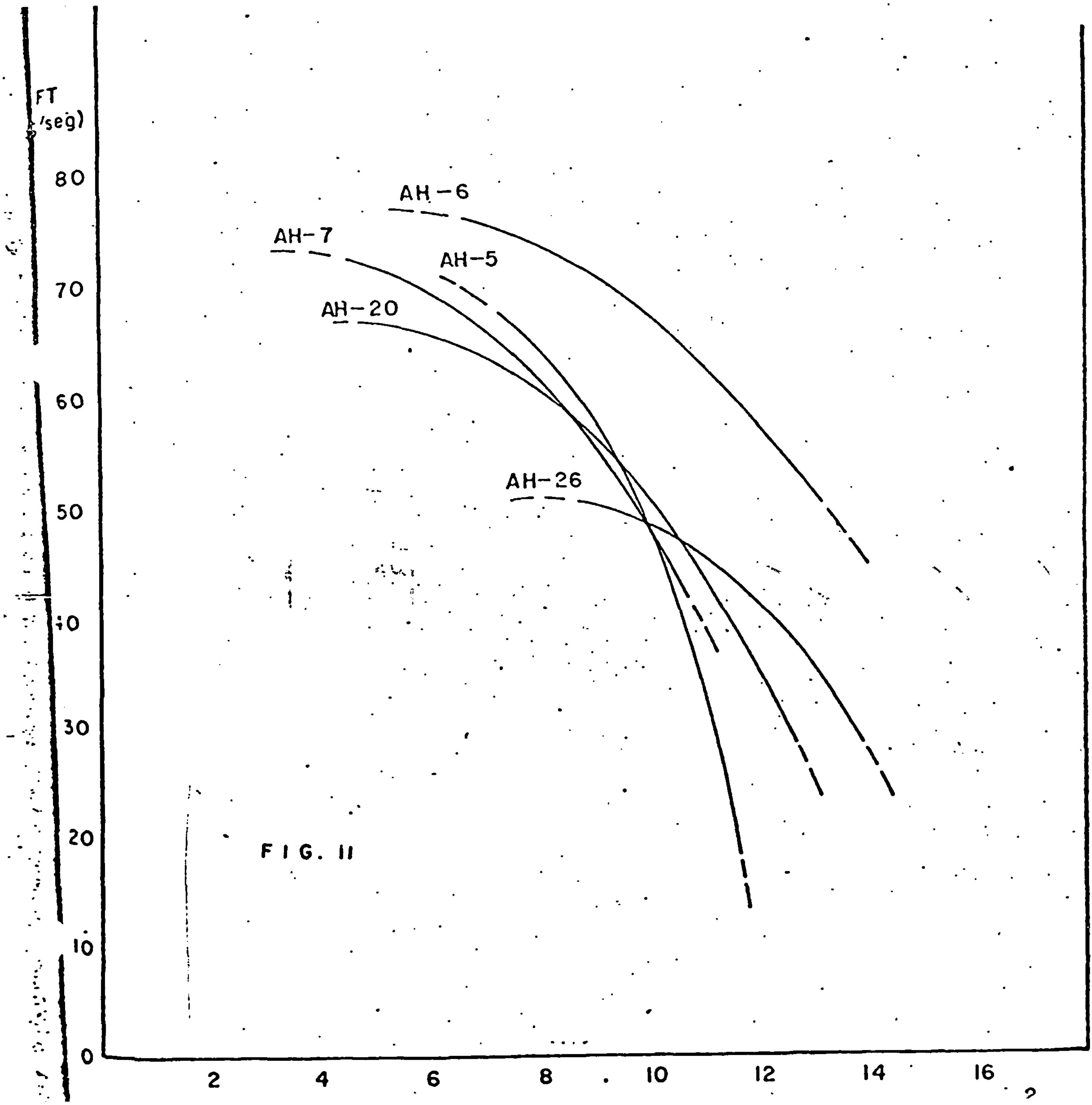


FIG. II

PRODUCTION CHARACTERISTICS

CRITICAL PRESSURE METHOD

Brought up to date in June 1976

Fv - Volume of steam
WHP - head pressure

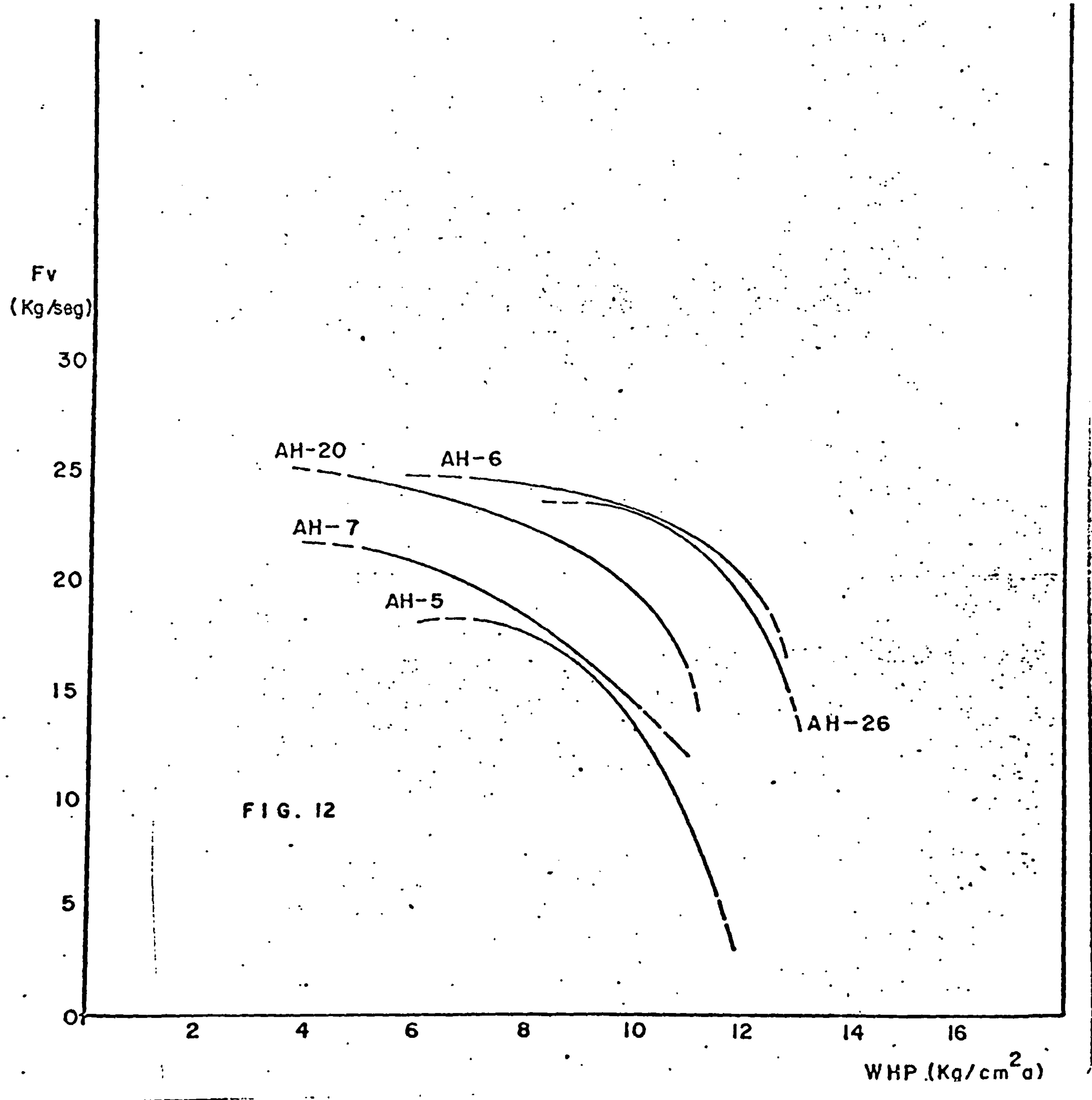


FIG. 12

CAMPO GEOTERMICO DE AHUACHAPAN

DESPUES DE UN AÑO DE EXPLOTACION

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RESUMEN

El presente trabajo pretende establecer las condiciones actuales de algunas de las características físico-químicas del campo geotérmico de Ahuachapán después de un año de explotación intensiva; presentándose también algunas hipótesis sobre los cambios que estan ocurriendo en las características de producción y en la composición química de los fluidos descargados.

1. INTRODUCCION

El campo geotérmico de Ahuachapán actualmente bajo explotación cubre un área aproximada de 3 km^2 y se encuentra situado al Oeste de El Salvador en el flanco Norte de la cadena volcánica del cuaternario que atravieza casi sin interrupciones todo el país siguiendo la dirección del graven central. Dicho graven se encuentra relleno de materiales eruptivos expulsados por los centros volcánicos cuaternarios.

El área bajo explotación parece ser solamente una parte de un sistema hidrotermal mas complejo que se extendería hacia Este en una distancia aproximada de 10 kms. Actualmente se realizan perforaciones exploratorias con el fin de investigar esta área; encontrándose temperaturas mayores de 200°C a 400 mts de profundidad.

Las manifestaciones superficiales del sistema hidrotermal de Ahuachapán se caracterizan por ser de carácter fumarólico en los flancos del sistema volcánico, acompañadas de extensas áreas de alteración hidrotermal y manantiales de carácter ácido, y en las zonas bajas del macizo volcánico por manantiales calientes de tipo $Cl-HCO_3$, que disminuyen en T y salinidad en dirección Norte, ver fígura 1.

Actualmente se han perforado 24 pozos profundos en el área de los cuales 11 son productores, 4 de reinyección y 9 exploratorios con algún tipo de producción alguno de ellos. Los pozos de producción descargan una mezcla agua-vapor en proporcio--

nes de 11% hasta 46%. El estrato productor se ha encontrado con espesores hasta de 300 mts, las máximas temperaturas medidas es de 239°C. El rango de producción es de 102 a 550 Ton/hr de mezcla.

En base a los buenos resultados de los pozos perforados - se han instalado dos unidades de media presión 5.5 con una capacidad de generación de 30MW cada una, las cuales son alimentadas con el vapor separado de 9 pozos con un promedio de 8.8MW por pozo. La generación de la primera unidad comenzo en Junio 1975 y - la segunda en Junio de 1976. Actualmente se efectuan los estudios para la implantación de la 3a. Unidad generadora programada para 1979 con una capacidad de 35MW.

En vista de la necesidad de estudiar las condiciones del reservorio bajo explotación intensiva , se ha establecido un control programado de mediciones y de muestreo de fluidos con el -- fin de detectar y evaluar cualquier cambio de condiciones físico-químicas del reservorio. Este control consiste basicamente en mediciones de presión de cabezal, caudales de agua, caudales de vapor; toma de muestras de fluidos, mediciones de producción y registros de temperatura y presión.

Las variaciones que se han detectado han sido:

- Aumento en la salinidad total
- Disminución del indice Na/K
- Disminución de los niveles hidrostáticos
- Variaciones en las características de producción de algunos pozos.

Todas estas variaciones tienen mayor incidencia en la zona de mayor explotación.

Actualmente se estan evaluando dichos cambios con el fin establecer posibles causas y efectos.

2. ASPECTOS GEOLOGICOS

La geología del campo geotérmico de Ahuachapán ha sido ampliamente estudiada. Para los fines del presente trabajo se ha - elaborado un corte vertical del campo en el cual es posible estudiar la sucesión estratigráfica, que básicamente consiste en:

- Formación tobácea-lávica	
- Aglomerado joven	Cuaternario
- Formación andesítica de Ahuachapán	
- Aglomerados antiguos	Terciario

2-1 Formación Tobácea-Lávica (Fígura 2)

Esta básicamente constituida por 2 miembros (formación tobacea con intercalaciones lávicas). No tiene importancia desde - un punto de vista de reconstrucción interna del reservorio. Presenta espesores hasta de 500 mts.

2-2 Aglomerado Joven

Tiene espesores del orden de 200 a 400 mts y es una formación volcánica bastante impermeable, que por sobreyacer la formación andesítica de Ahuachapán, sirve de sello efectivo al reservorio.

2-3 Formación Andesítica de Ahuachapán

Formación predominantemente constituida por lavas, con intercalaciones materiales tobáceos. Constituye la formación productora del campo. Se presenta bastante fracturada aunque no en forma uniforme, mostrando un aumento de su permeabilidad secundaria en los contactos con los aglomerados jóvenes y con el subestrato profundo. La situación del techo de la formación andesítica se presenta en el informe preparado por Ings. Jiménez y Campos en este simposium.

2-4 Aglomerado Antiguo

Constituye el basamento de la formación andesítica. Contiene eventualmente intercalaciones de breccias y de lavas. En -

algunos pozos este estrato muestra cierta permeabilidad secundaria.

3. SITUACION HIDROGEOLOGICA

En base a los programas de hidrología y geoquímica y con la comprobación de los resultados en los pozos profundos perforados se logro individualizar la existencia de 3 acuíferos principales:

3-1 Acuífero Somero

Esta localizado superficialmente en formaciones geológicas recientes constituidas por tobas, pomez y fluviales que yacen sobre las lava lavas del grupo volcánico Laguna Verde. Esta alimentado por la perc infiltración superficial de las aguas meteóricas. La composición química de las aguas de este acuífero muestran que son aguas predominantemente carbonatadas, mostrando concentraciones altas de sulfatos, cuando son calentadas por vapor subterraneo.

3-2 Acuífero Saturado

Este acuífero circula en las lavas y piroclásticos que constituyen la formación tobáceo-lávica, y tiene como lecho los aglomerados jóvenes altamente impermeables. El agua que circula de este acuífero proviene de la infiltración más ó menos profunda del agua de precipitación. Este acuífero alimenta los pozos domésticos y se presenta con cierta termalidad en algunas regiones, producida por conducción através del aglomerado joven mostrando aguas con altos contenidos de bicarbonatos de calcio y sodio, ó por mezcla con aguas del acuífero salino profundo produciendo aguas con alto contenido de cloruro de sodio y bicarbonatos de Ca y Na.

3-3 Acuífero Salino

Localizado en la formación andesítica de Ahuachapán tiene como sello superior la formación impermeable aglomerado joven y como basamento aglomerados macivos terciarios. Este acuífero circula através de las zonas de permeabilidad secundaria existentes en las andesitas.

Su extensión actual esta definida hacia el Sur del campo y hacia el Oeste, no conociéndose con exactitud sus límites Sur y Este, ya que aparentemente para extenderse en dirección Este hasta la región de Chipilapa. Las características químicas son su alta salinidad que consiste básicamente en cloruros de sodio, potasio y calcio, acompañados de una amplia gama de componentes menores Li, Sr, Cs, Rb, I, Br, As, B.

Los datos piezométricos y las características geológicas sugieren que la zona de recarga de este acuífero se encuentra en los grupos volcánicos localizados al Sur del campo, donde los cráteres facilitan la infiltración profunda del agua, que se ha demostrado ser de origen predominantemente meteórica.

La descarga natural de este acuífero parece ser la serie de manantiales localizada al Norte del campo (El Salitre, La Ceiba, San Lorenzo) que muestran relaciones atómicas similares a las de este acuífero, aunque sus concentraciones absolutas son menores que el agua del acuífero saturado. La extracción masiva de fluido de este acuífero en la zona central del área del campo geotérmico ha producido una inversión de flujo, con dirección a la zona de mayor explotación, produciéndose una depresión de los niveles piezométricos, esto esta acompañado de una invasión de agua que tiende a sustituir la extraida; las características de esta agua parecen ser su mayor termalidad y mayor contenido salino.

4. QUIMICA DE LOS FLUIDOS

4-1 Generalidades

El agua descargada por los pozos del campo geotérmico de Ahuachapán esta caracterizada por ser de tipo predominantemente cloruro de sodio presentándose también como componentes dominantes potasio, sílice, calcio, boro. Ver tabla 1.

Descargada a presión atmosférica tiene un pH ligeramente alcalino entre 7.10 y 7.80 y se encuentra en su punto de ebullición. La extensión del acuífero salino que alimenta los pozos -- productores del área se encuentra actualmente indefinido, conociéndose hasta la fecha solamente dos de sus límites: hacia el - Oeste como lo indica los resultados del pozo Ah-15 que no muestra salinidad y los resultados de los pozos Ah-11 y Ah-12 al Norte del campo que muestran una salinidad bastante reducida. Esta rápida disminución de la salinidad en esas direcciones nos indican claramente las limitaciones del acuífero salino en esa dirección hecho que ha sido comprobado con la baja permeabilidad y -- temperaturas en la zona de dichos pozos.

En las otras direcciones donde no se ha podido delimitar la extensión del acuífero de alta temperatura tenemos un efecto de concentración en dirección S-SO como se nota en el mapa de -- isoconcentración de cloruros. (Figura 4).

Todo parece indicar que el agua salina del acuífero bajo explotación tiene un origen común aunque no se posible excluir - la posibilidad de mezclas con agua de menor salinidad de alta -- temperatura. Hasta la fecha no se ha podido detectar un gradiente de salinidad en sentido vertical, ya que existen pozos cercanos perforados a la misma profundidad con concentraciones diferentes, pero es evidente la existencia de un gradiente horizontal de concentración en dirección S-SW. La existencia de este -- gradiente nos indica que la emigración de fluidos en el estrato productor es horizontal y que los pozos con concentraciones más altas (pozos Ah-7, Ah-16) estarían más cercanos a la alimentación del reservorio.

Aparentemente la caida de los niveles piezómetricos del - acuífero productor causados por la explotación estan ocasionando una migración más rápida del agua de mayor salinidad y temperatura hacia el centro del campo. Este hecho esta comprobado con el incremento de concentraciones que se ha hecho en los pozos Ah-1, Ah-4, Ah-6, lo mismo que con una disminución del indice Na/K en algunos pozos. (Fígura 4).

Las relaciones atómicas Cl/B, Cl/As, Cl/F, Cl/Br, Cl/I indican también que el agua salina tiene un origen común.

4-2 Relación Na/K

Esta relación cuya importancia por su dependencia con la temperatura es bien conocida, tiene en el fluido descargado por los pozos de Ahuachapán un rango entre 12.5 y 8.76 que corresponde a un rango las temperaturas entre 222 y 274°C (White 1970) -- que difiere en su límite superior a la máxima temperatura medida en el reservorio que es 239°C en el pozo Ah-22. Podemos afirmar que la relación Na/K no ha alcanzado su equilibrio en la región del campo donde existe grandes diferencias entre la T medida y - la T calculada por la relación Na/K; estas diferencias pueden observarse en la siguiente tabla en la cual se reportan los valo-- res de temperatura máxima medida y temperatura calculada por el indice Na/K.

Pozo	T máxima °C	T Na/K °C	Diferencia
Ah-1	232	255	23
Ah-4	234	233	-1
Ah-5	230	222	-8
Ah-6	231	257	26
Ah-7	230	274	44
Ah-20	225	256	31
Ah-21	233	258	25
Ah-22	239	226	-13
Ah-26	232	241	9

De la tabla anterior y del mapa de temperaturas Na/K comparado con el de temperaturas máximas se puede observar que los valores se alejan de las temperaturas medidas en dirección S-SO culminando en el pozo Ah-7 que muestra la mayor diferencia. Esto indica que el sodio-potasio no ha alcanzado su equilibrio con -- las temperaturas de las rocas de reservorio en esa dirección y - que el equilibrio lo alcanza cuando circula en dirección N-NE. - Este hecho es importante para inferir la posible zona de alimentación del reservorio. Existe también la posibilidad de que los bajos indices reportados en esa dirección sean indicación de que el agua que alimenta el reservorio haya estado en contacto con rocas de mayor temperatura en una zona mas profunda no necesariamente cercana al reservorio en explotación y que no alcanza a establecerse el equilibrio en la zona de alimentación inmediata al reservorio. Hasta el momento no se ha detectado temperaturas mayores de 239°C en la zona de perforación.

Esta relación también confirma la posible extención del - reservorio en dirección S-SE y sus límites N y NO partiendo del campo en explotación.

El mapa de temperaturas de Na/K parece indicar conjuntamente con el temperaturas máximas, con el de isoconcentración de cloruros y el de concentración de SiO_2 que la zona de alimentación se encuentra al Sur del campo bajo explotación y que la circulación de fluidos tiene una dirección lateral con tendencia al N-NE.

4-3 Concentraciones de SiO_2

Las concentraciones de SiO_2 corresponden con bastante --- exactitud a las esperadas para agua en equilibrio cuarzo a las - temperaturas medidas del reservorio. El mapa de isoconcentraciones de sílice muestra una tendencia clara a un aumento hacia el Sur del campo, coincidiendo esto con las máximas temperaturas medidas y con los indices Na/K. Todas las evidencias nos indican que el flujo tiene una dirección N-NE convergiendo antes en el - centro del área de mayor explotación. (Figura 5).

Si calculamos las entalpias de agua del reservorio utilizando las concentraciones de SiO_2 en el agua descargada, se observará que los valores son bastante menores que los calculados por medio de mediciones. Este hecho pone en evidencia la existencia que cierta cantidad de vapor generado en el reservorio esta siendo expulsado con la mezcla.

4-4 Relaciones Cl/B, Cl/As, Cl/Br, Cl/I (Tabla 2).

Esta serie de relaciones se muestran bastante constantes en las aguas descargadas por los pozos productores, confirmando un solo origen del agua que alimenta al acuífero salino. Es de notar que la relación Cl/B se mantiene dentro del rango medio aún en los pozos Ah-14 y Ah-16, considerados marginales del campo en explotación. Este hecho es importante porque amplia la extención del acuífero salino hacia el S-SE a la vez que sugiere una posible comunicación con el acuífero salino existente en el área de Chipilapa.

Las relaciones Cl/Br, Cl/I son bastante bajas comparadas a las encontradas en campos similares y el origen de las altas concentraciones de Br (40 ppm) y I (8 ppm) no ha sido tovadia explicado.

La variación en las concentraciones absolutas de B, As, Br y I parece estar relacionada con un proceso de dilución del agua de alimentación del reservorio, en dirección N-NE aunque a la fecha no sea posible detectar en otra forma este proceso.

5. ESTADO FISICO DEL CAMPO DE AHUACHAPAN

A partir de 1975 se inicia la explotación artificial en proporciones considerables en el campo geotérmico de Ahuachapán. Hasta la fecha la cantidad total de masa extraída es del orden de $26x10^3$[illegible]. Esta extracción artificial de masa ha provocado cambios en las condiciones físicas del acuífero que origina la zona geotérmica de Ahuachapán.

El cambio de las condiciones físicas originales se ha detectado por medio de un programa de mediciones rutinarias que -- comprenden: registros de presión y temperatura, mediciones de -- producción y control del agua descargada.

La condición inicial del acuífero, antes de comenzar con los programas de extracción en gran escala con fines de generación, es de esperar que era la determinada por la condición de - saturación. La evidencia que sostiene la condición de saturación es decir la existencia generalizada de una sola fase; es posible obtenerla de las relaciones de presión medida en el pozo con las presiones de saturación para las temperaturas medidas. Las figuras 6 y 7 nos muestran estas relaciones para los pozos Ah-6, --- Ah-7 y Ah-20 en 1974. Se han escogido dichos pozos por ser ellos representantes de dos situaciones del campo: Ah-6 y Ah-20 estan localizados en la zona de mayor explotación y el Ah-7 por ser un pozo bastante retirado de dicha zona y que ha demostrado no ser sensible a muchas de las variaciones observadas.

En dichas figuras vemos como la condición de saturación estaba generalizada para los 3 pozos escogidos, ocurriendo solamente un cambio de esa condición cuando la presión hidrostática, superada en la presión de saturación. También se han graficado - las mismas relaciones para la condición actual de dichos pozos, en la que se observa claramente como la condición de saturación se ha roto en los pozos Ah-6 y Ah-20 conservándose bastante similar en el pozo Ah-7.

La similitud de las relaciones antes del proceso de extracción nos indican una condición de saturación en el acuífero original en 1974, mientras que las variaciones observadas para 1976 indican que en la zona de mayor influencia de la extracción han ocurrido cambios notables en la condición del acuífero y que dichos cambios no han afectado a los pozos situados fuera del área de mayor extracción.

Estas relaciones de presión con la presión de saturación sugieren la aparición de una fase vapor en el reservorio, que se ría explicable en base a una disminución del nivel hidrostático.

Con la extracción de masa, sin hacer aún consideraciones sobre la existencia de una mecanismo de recarga se ha producido un descenso en el nivel de agua del reservorio que implica necesariamente una caída en la presión. Esta caida de presión deberá ser acompañada de una caida en la temperatura hasta el punto en que el agua alcance un equilibrio en la temperatura de la formación rocosa. La condición de saturación entonces impondrá un descenso en la presión hasta que se alcance la presión de vapor saturado correspondiente a estas temperaturas de equilibrio. Debajo del nivel de agua, las presiones a cualquier profundidad disminuirán en la cantidad correspondiente a la caida de presión en el nivel del agua, la temperatura caerá con la profundidad hasta el punto en que la presión es mayor que la presión de saturación y se dispondrá de calor desde esta profundidad hasta el nivel -- del agua. Este calor disponible produciría teoricamente el aparecimiento de una fase vapor que llenará la formación y mantendrá la presión sobre el nivel del agua más ó menos igual a la pre--- sión de dicho nivel. En este punto deberán producirse cambios en la entalpia de la descarga de pozos individuales, ya que el vapor producido por el "flasheo" en el interior del pozo se añadirá el vapor existente en el reservorio; hecho que ya se ha detectado - para algunos pozos. Básicamente, es desde este punto de vista -- que se justifica las hipótesis sobre el estado actual del reservorio de Ahuachapán. Para las descargas individuales de los pozos Ah-4 y Ah-6, que son pozos ubicados en el centro del área - de explotación se han observado las condiciones de producción -- que se registran en la tabla-2, donde se comparan con las características de la descarga del pozo Ah-7 situado un poco más lejos de la zona afectada por la explotación; características que tipifican la descarga de un pozo en el cual el porcentaje de vapor - en la descarga total es debido únicamente al proceso de "flasheo" a partir de agua saturada a 222°C.

Una alternativa razonable a la hipótesis del aparecimiento de una fase vapor en el interior del reservorio sería de considerar un aumento en el interior del pozo, es decir, un descenso del nivel de "flasheo". Por otra aparte, se necesitaría un aumento bastante considerable para explicar las proporciones líquido-vapor señaladas, aumento que nos parece no es justificable en base a las variaciones termodinámicas consideradas.

rather considerable

indicated

Faltaría hacer algunas consideraciones sobre la hipótesis de un sistema de recarga pero hasta ahora la única evidencia en esta dirección es cualitativa y se obtuvo durante el receso de la primera unidad en los meses de Diciembre/75 - Enero/76. Período en que se observó una recuperación en los niveles de agua en los pozos productores así como una recuperación en la presión de los mismos que excedía los errores de medición. En otra parte de este reporte se verá que también la composición química de las aguas del campo conducen a establecer la existencia de una recarga. Así pués, queda establecido que el comportamiento del campo geotérmico de Ahuachapán es el correspondiente a un campo en donde las descargas de los pozos individuales son del tipo agua-vapor, que originalmente estaba constituido por una fase líquida y ha sido llevado por la explotación a un estado de dos fases: --- agua-vapor.

5-1 Temperaturas

? 23 on map

En base a los datos obtenidos por los 24 pozos actualmente perforados, se ha podido construir un mapa de temperaturas máximas medidas del reservorio. (Fig.8). En dicho mapa se observa que el área de mayor temperatura (220-239°C) se encuentra localizada en una extención de 1 km^2 que comprende todos los pozos actualmente en producción. Los límites de la zona hipertermal se encuentra bien definida en dirección Norte por los pozos Ah-11 y Ah-12 y hacia el Oeste por el pozo Ah-15. En dirección Sur y --- S-SE el área parece extenderse hasta la región de Chipilapa, según se ha demostrado por los resultados del pozo profundo CH-1 y los pozos exploratorios en proceso de perforación. Este hecho ex tendería el área de hipertermalidad aproximadamente a 8-10 km^2 que nos da una idea de la potencialidad del sistema.

Un hecho que se ha evidenciado es la ampliación del área de mayor temperatura debido a la explotación intensiva probablemente debido a una mayor movilidad del fluido de alta temperatura hacia la zona de extracción.

También es de notar que los pozos ubicados en la parte alta del reservorio muestran las temperaturas más altas, esto confirmaría que la alimentación primaria del reservorio ocurre en dirección Sur.

La distribución vertical de temperaturas medidas despues de la estabilización térmica, de las formaciones, esta caracterizada por un aumento gradual de gradiente hasta alcanzar el techo del reservorio despues del cual hay una tendencia notable a mantener valores que oscilan entre los 230-239°C. Ocurriendo generalmente una inversión al alcanzar los aglomerados masivos.

CAPACIDAD DE PRODUCCION

La capacidad de producción actual del campo considerando solamente los 9 pozos productores conectados a la Central Geotérmica es del orden de 1630 T/hr de mezcla la cual separada a una presión media de 5.9 kgr/cm^2 resulta en 493 t/hr de vapor y 2137 T/hr de agua, dando una relación vapor/agua media de 0.23. De los pozos anteriormente considerados de ellos (Ah-4 y Ah-21) se encuentran restringidos debido a la capacidad menor de los separadores ciclónicos.

A continuación se reportan las características de producción de los pozos productores. (Tabla 3).

Las curvas características de producción, medidas por el método de presiones críticas se pueden observar en las gráficas 9 al 12 En ellas podemos observar las características generales

TABLA - 2

COMPARACION DE LAS DESCARGAS DE LOS POZOS Ah-4, Ah-6 y Ah-7

	Pozo Ah-4	Pozo Ah-6	Pozo Ah-7
-Presión de separación (Kg/cm^2)	6.2	5.9	5.8
-Flujo total (T/hr)	472	224	228.6
-Flujo de agua (T/hr)	385.92	164.6	198
-Flujo de vapor (T/hr)	85.75	59.4	30.6
-Entalpía de la mezcla (Kgal/Kg)	251.1	291.6	224.87
-Porcentaje de vapor calculado a la presión de separación	18.18	26.55	13.8
-Porcentaje de separación esperado para agua saturada*	15.91	15.7	13.9
-Diferencia (f) - (g)	2.27	10.85	0.1

* Para el cálculo de (g) se toma como base la entalpía del agua a la temperatura registrada en el pozo.

CARACTERISTICAS DE PRODUCCION

Pozos	P.S. Kgr/cm^2	Flujo Total T/hr	Flujo Agua T/hr	Flujo Vapor T/hr	Porcent. Separac.	Entalpía	MW Estim.
Ah-1	5.8	344	298	46	13.37	224	7
Ah-4**	6.2	472	386	86	18.2	251	13
Ah-6	5.9	224	165	59	26.6	291	9
Ah-7	5.8	229	198	31	13.8	225	5.5
Ah-5	5.6	239	213	26	10.8	211	4
Ah-20	5.5	226	183	43	19.0	251	6.5
Ah-21* **	5.9	502	423	82	16.3	220	12.5
Ah-22	5.9	293	221	72	24.5	281	10
Ah-26	5.8	102	54	48	46.8	392	9

T < 200°
↓

Failure?:
2 24
3 25
8 29
9
11 ✓
12 ✓
13
14
15 ✓
16
17 ✓

9 good
14 bad
23 Total
~ 40% success

* Cálculo estimado

** Pozo restringido

de producción de cada pozo.

A causa de la explotación intensiva del campo se ha notado cierta tendencia general a un aumento de la relación vapor/agua, que en algunos pozos ha sido más marcada, como es el caso del pozo Ah-6 que por su ubicación y profundidad parece ser el más sensible a sufrir variaciones en su producción.

De la tabla de las características de producción podemos observar dos hechos significativos.

1. El rango de producción de los pozos es bastante amplio, hecho que esta relacionado intimamente con la distribución de la permeabilidad secundaria en el campo que se ha demostrado ser totalmente imprevisible. Si podemos observar que los pozos de mayor capacidad son los ubicados en dirección S-SE en la parte topograficamente elevada del campo.
2. Un rango también amplio de entalpia de la mezcla que va desde valores de 211 Kcal/Kgr para el pozo Ah-5 a valores de 392 Kcal/Kgr para el pozo Ah-26. Este hecho parece ser indicativo de que con la explotación intensiva se ha formado una fase de vapor en la parte central del campo. Este hecho se discutío en un capítulo anterior.

12 13 14 15

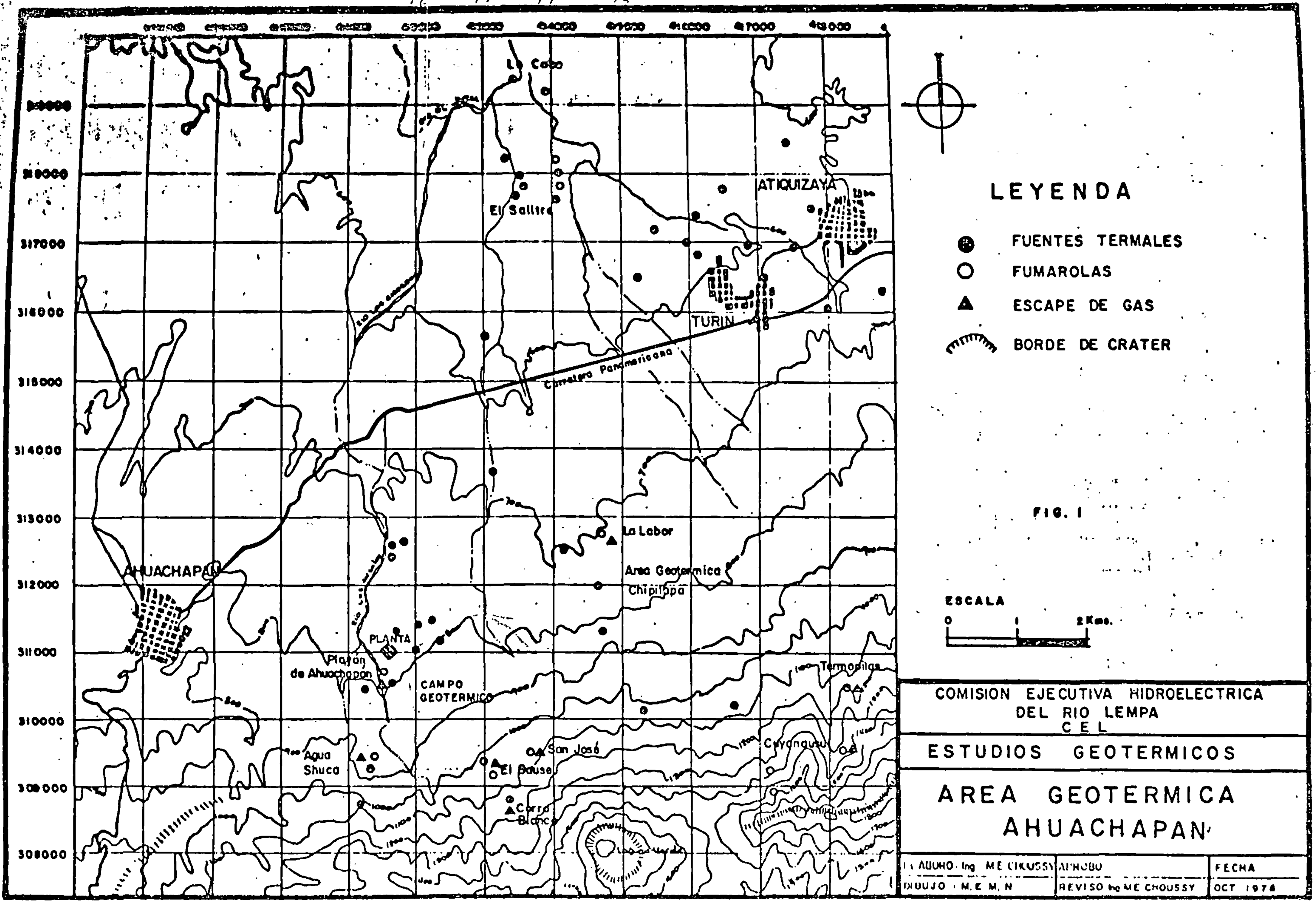


FIG. 1

COMISION EJECUTIVA HIDROELECTRICA
DEL RIO LEMPA
C E L

ESTUDIOS GEOTERMICOS

AREA GEOTERMICA
AHUACHAPAN

ELABORO · Ing M.E. CHOUSSY	APROBO	FECHA
DIBUJO · M.E.M.N	REVISO Ing M.E. CHOUSSY	OCT 1974

AREA GEOTERMICA DE AHUACHAPAN
SECCION TRANSVERSAL

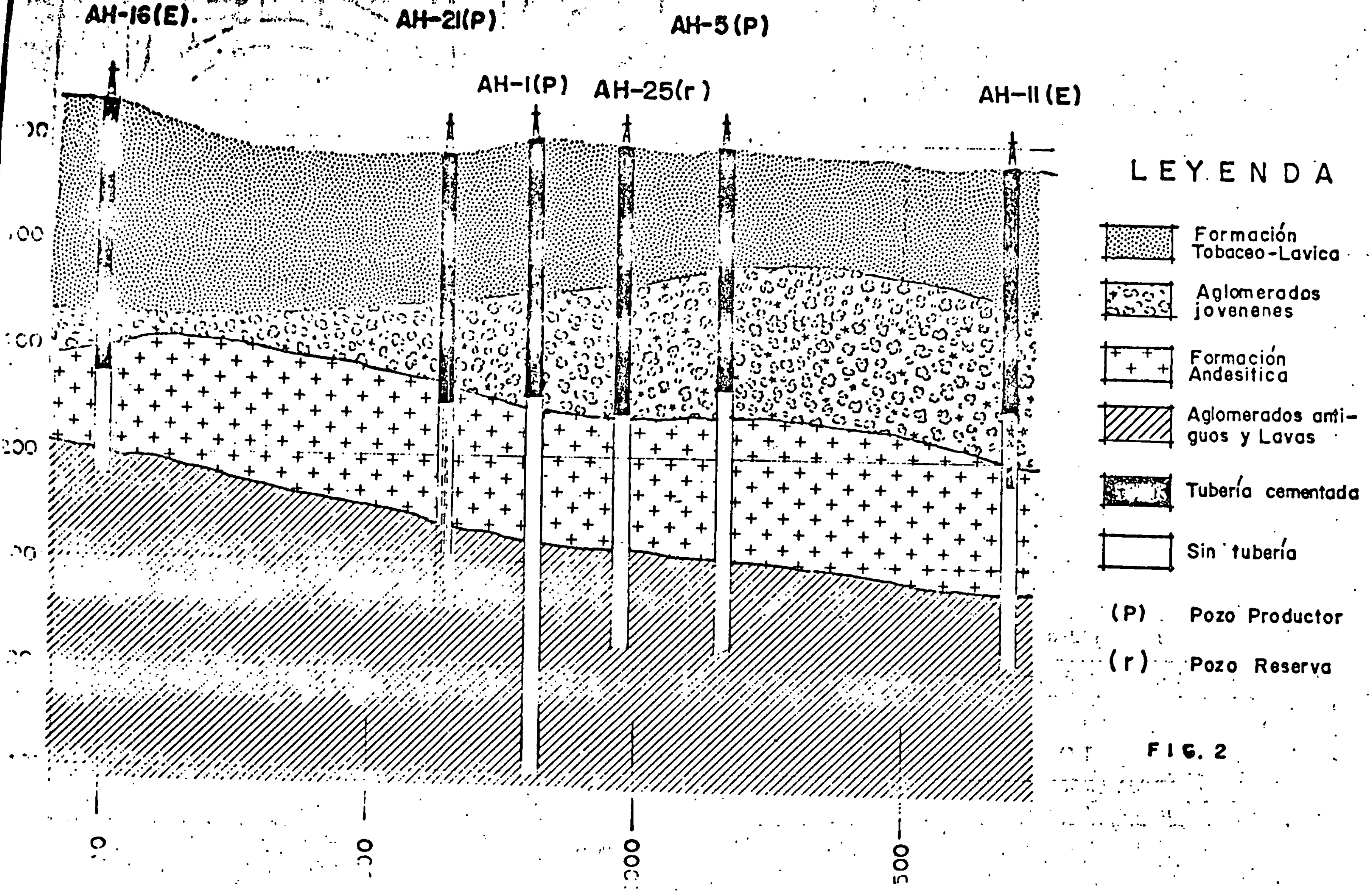
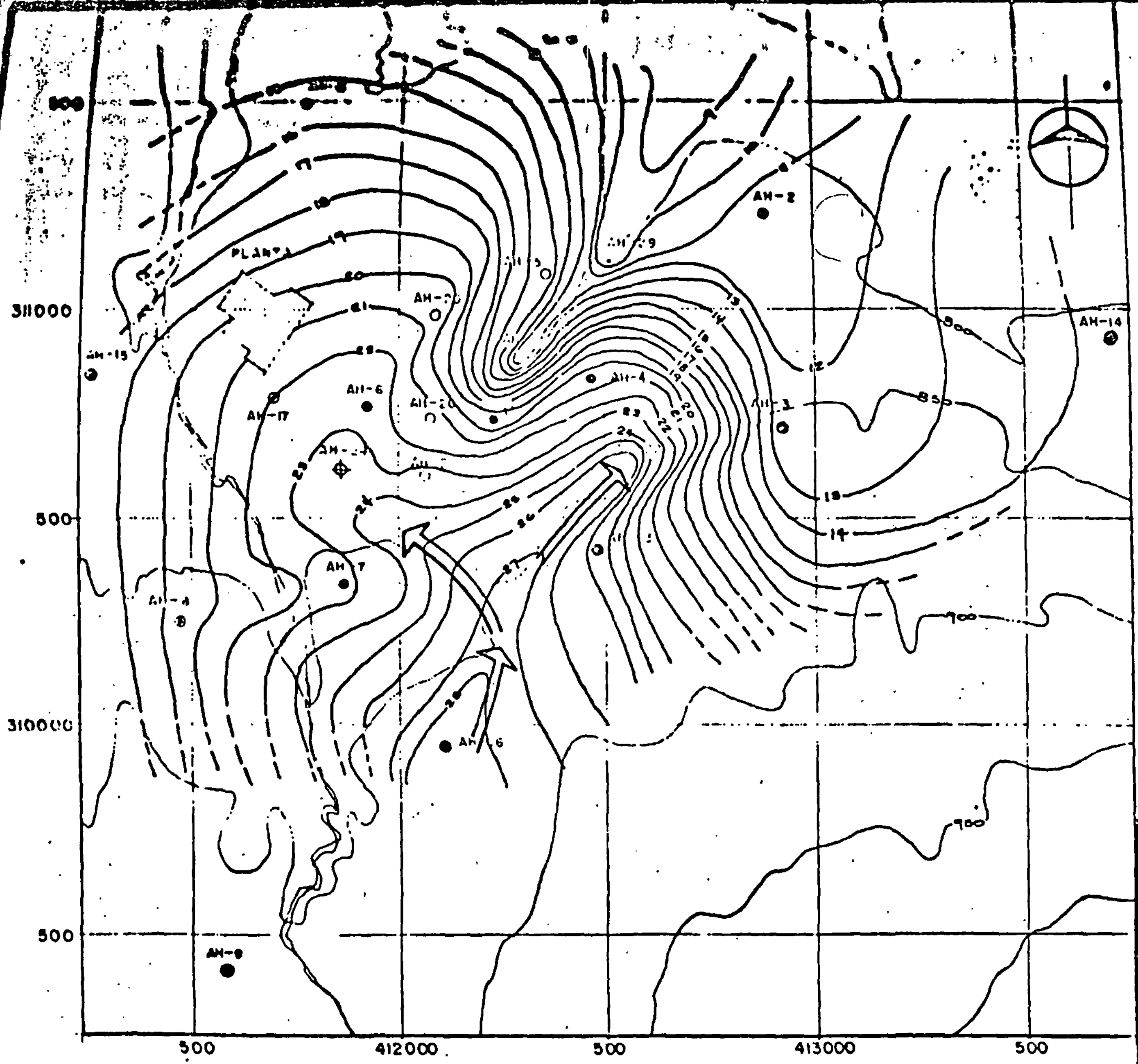


FIG. 2

CAMPO GEOTERMICO AHUACHAPAN



SIMBOLOGIA

- ● POZOS 1a. UNIDAD
- ○ POZOS 2a. UNIDAD
- ◉ POZOS REINYECCION
- ⊗ POZOS EXPLORATORIOS
- ⊕ POZOS RESERVA

Escala
0 500mts.

COMISION EJECUTIVA HIDROELECTRICA
DEL RIO LEMPA
C E L

ESTUDIOS GEOTERMICOS

MAPA DE PRESIONES A COTA 450

ELABORO: Ing. M.E. CHOUSSY	APROBO:	FECHA:
DIBUJO: M.E.M.N.	REVISO: Ing. M.E. CHOUSSY	OCT 1976

[illegible] DE LAS AGUAS

TABLA I

POZOS AHUACHAPAN, expresados en p.p.m.

* Muestras tomadas en el fondo del pozo

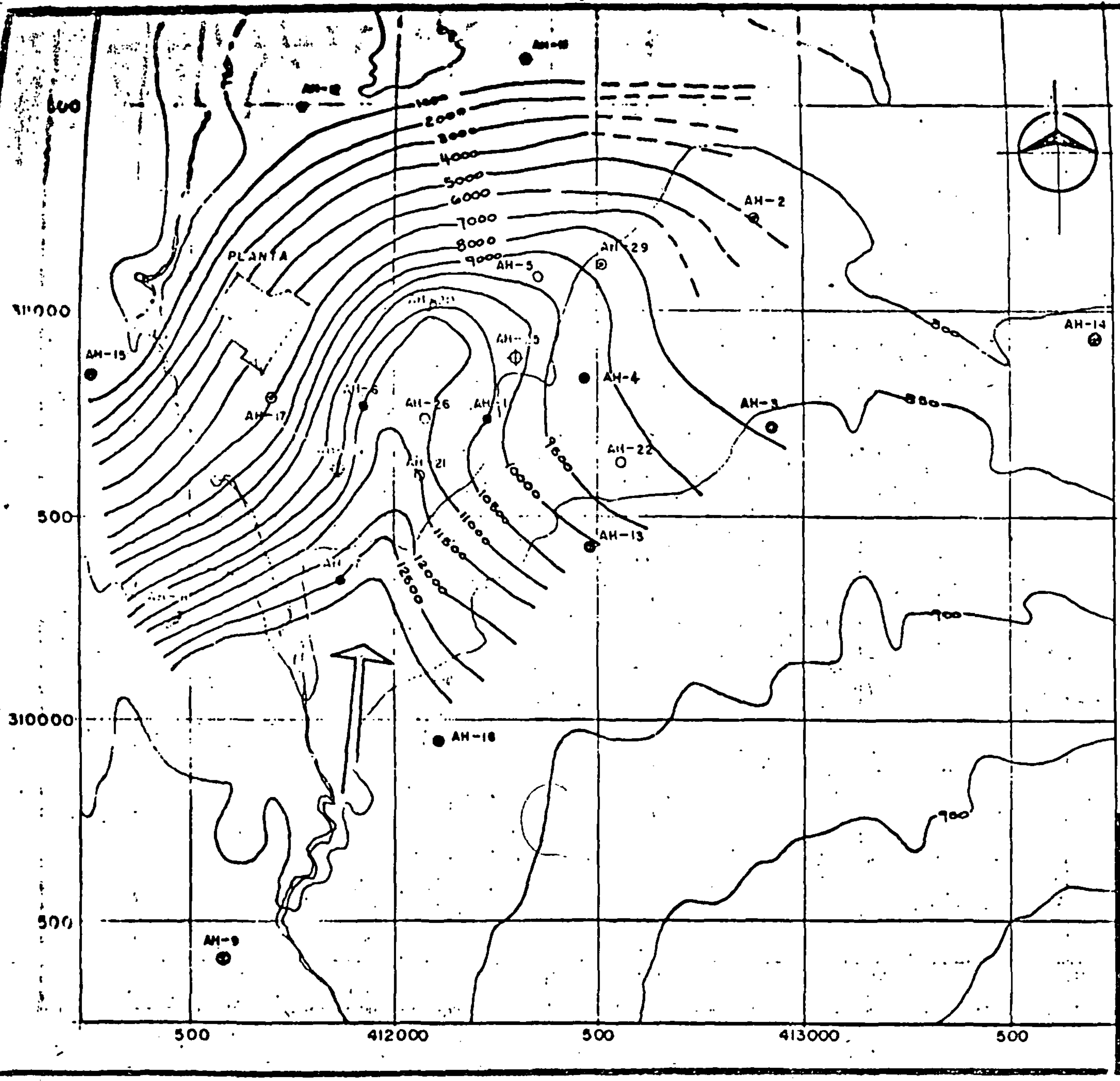
POZO	Na	K	Ca	Mg	Li	Sr	As	Sb	Cs	Rb	Cl	SO_4	HCO_3	B	SiO_2	F	Br	I
AH-1	5000	1000	425	0.090	18.5	4.50	10.8	2.25	5.84	7.90	10600	30.8	34.4	147	577	1.51	46.04	8.24
AH-4	5000	740	400	0.125	15.7	4.55	10.0	1.88	4.60	5.57	9050	34.2	32.5	144	535	1.29	35.70	6.50
AH-5	5000	680	440	0.240	14.8	5.68	9.90	1.75	4.05	5.05	9110	40.8	28.1	138	470	1.24	38.10	6.98
AH-6	6000	1050	439	0.088	18.8	4.50	11.6	2.12	6.30	8.25	10900	29.7	46.5	156	500	1.75	43.0	8.46
AH-7	6600	1280	486	0.084	20.0	4.75	14.0	2.50	6.55	8.50	12500	23.3	26.6	178	610	1.78	50.40	9.20
AH-20	6000	1040	450	0.074	18.5	4.50	12.0	n. d.	6.00	7.90	10900	30.2	31.6	155	556	1.58	45.91	8.45
AH-21	6100	1140	480	0.011	19.1	4.70	11.8	n. d.	6.30	8.30	11500	40.5	40.3	169	535	1.67	48.38	10.14
AH-22	5080	710	437	0.155	15.0	4.74	10.2	n. d.	4.50	5.20	9217	32.7	31.5	127	552	1.27	39.75	6.85
AH-26	5600	900	430	0.300	17.5	4.54	11.0	n. d.	5.75	7.25	10130	44.2	36.3	142	500	1.40	47.74	8.45
AH-11 *	69.6	24.4	14.9	0.345	n. d.	0.09	n. d.	n. d.	n. d.	n. d.	770	228	317	12.1	n. d.	n. d.	n. d.	n. d.
AH-12 *	99.2	7.20	0.75	0.232	n. d.	0.025	n. d.	n. d.	n. d.	n. d.	27.04	48.50	146	2.08	n. d.	n. d.	n. d.	n. d.
AH-14 *	1950	460	111	0.06	n. d.	n. d.	n. d.	n. d.	n. d.	n. d.	3068	408.0	120	50.0	327	2.32	n. d.	n. d.
AH-16 *	3200	530	345	0.50	n. d.	3.70	n. d.	n. d.	n. d.	n. d.	5652	289.0	31.35	91.0	182	0.76	n. d	n. d.

TABLA 2

AGUAS POZOS AHUACHAPAN

POZO	Cl/B	Cl/As	Cl/SO_4	Cl/F	Cl/Br	Cl/I	Na/K	Na/Li	Na/Sr	Na/Ca	K/Rb
AH-1	22.05	2070	932	3755	534	4604	9.86	94.05	4911	23.75	276
H-4	19.22	1909	717	3753	588	4983	11.49	95.54	4187	21.75	289
H-5	20.19	1941	605	3850	554	4671	12.50	101.35	3354	19.77	293
H-6	21.38	1982	994	3332	588	4611	9.71	95.74	5080	23.78	277
H-7	20.85	1884	1411	3647	558	4720	8.76	99.00	5294	23.63	328
H-20	21.50	1916	978	3690	550	4617	9.81	97.30	5080	23.20	286
H-21	20.81	2056	769	3684	551	4660	9.69	95.81	5269	16.63	300
H-22	22.19	2401	763	3811	538	4905	12.16	101.60	4083	20.23	297
H-26	21.82	1943	621	3871	492	4291	10.52	96.00	4700	22.66	270
H-11	19.46	n.d.	9.2	n.d.	n.d.	n.d.	48.49	n.d.	29464	81.28	n.d.
H-12	3.98	n.d.	1.5	n.d.	n.d.	n.d.	23.42	n.d.	15180	230	n.d.
H-14	18.71	n.d.	20.4	707	n.d.	n.d.	7.20	n.d.	n.d.	30.57	n.d.
H-16	18.94	n.d.	53.0	3978	n.d.	n.d.	10.26	n.d.	3295	16.14	n.d.

CAMPO GEOTERMICO AHUACHAPAN



SIMBOLOGIA

- ● POZOS 1a. UNIDAD
- ○ POZOS 2a. UNIDAD
- ◉ POZOS REINYECCION
- ▨ POZOS EXPLORATORIOS
- ⊕ POZOS RESERVA

Escala 0 500mts

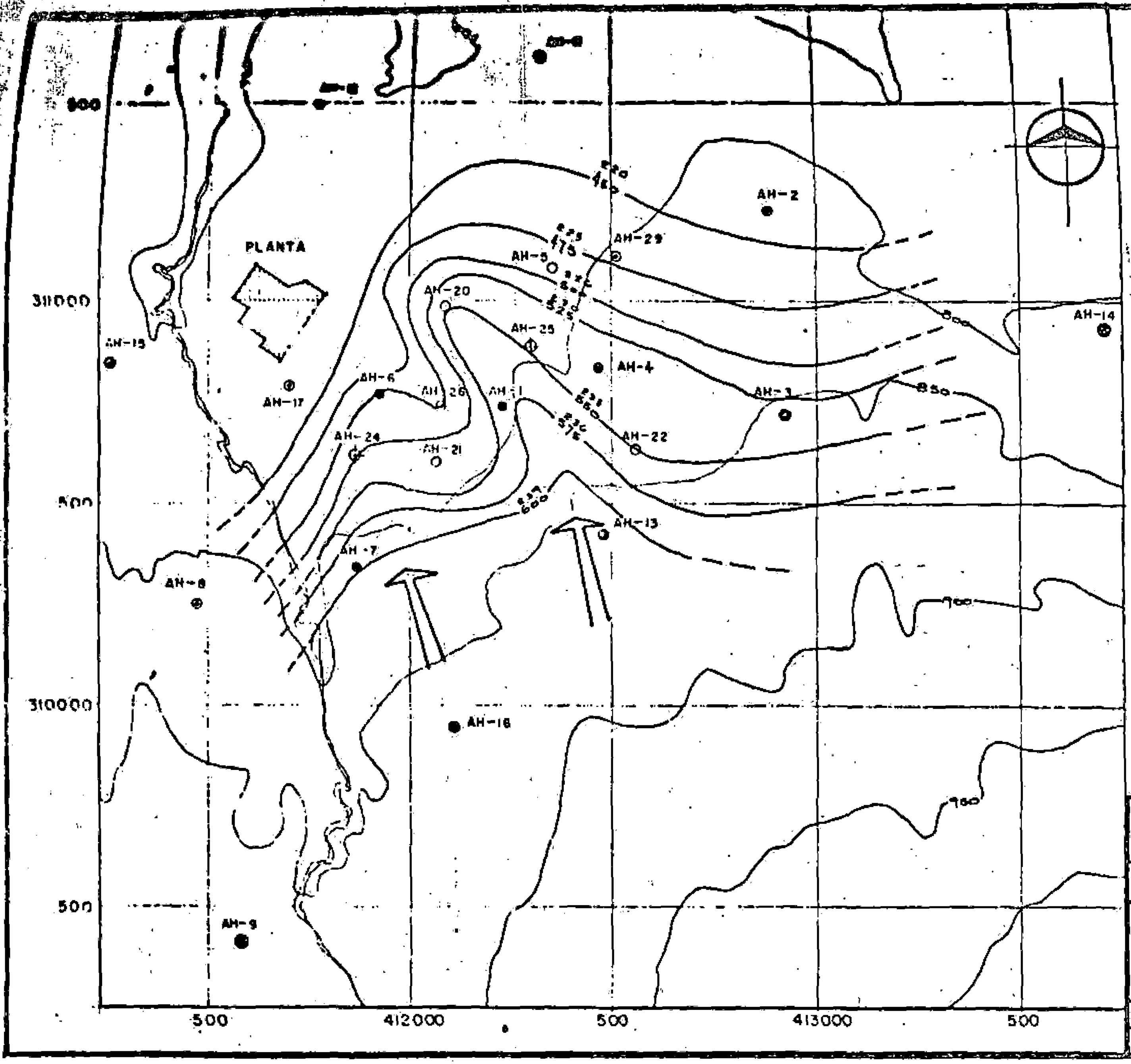
FIG. 4

COMISION EJECUTIVA HIDROELECTRICA
DEL RIO LEMPA
CEL

ESTUDIOS GEOTERMICOS

MAPA DE ISOCONCENTRACIONES DE CLORUROS EN p.p.m.

ELABORO: Ing. M.E. CHOUSSY	APROVO:	FECHA:
DIBUJO: M E M. N.	REVISO: Ing. M.E. CHOUSSY	OCT 1976



CAMPO GEOTERMICO
AHUACHAPAN

SIMBOLOGIA

● POZOS 1a. UNIDAD
○ POZOS 2a. UNIDAD
◎ POZOS REINYECCION
▨ POZOS EXPLORATORIOS
⊕ POZOS RESERVA

Escala
0 500mts.

FIG. 5

COMISION EJECUTIVA HIDROELECTRICA
DEL RIO LEMPA
C E L

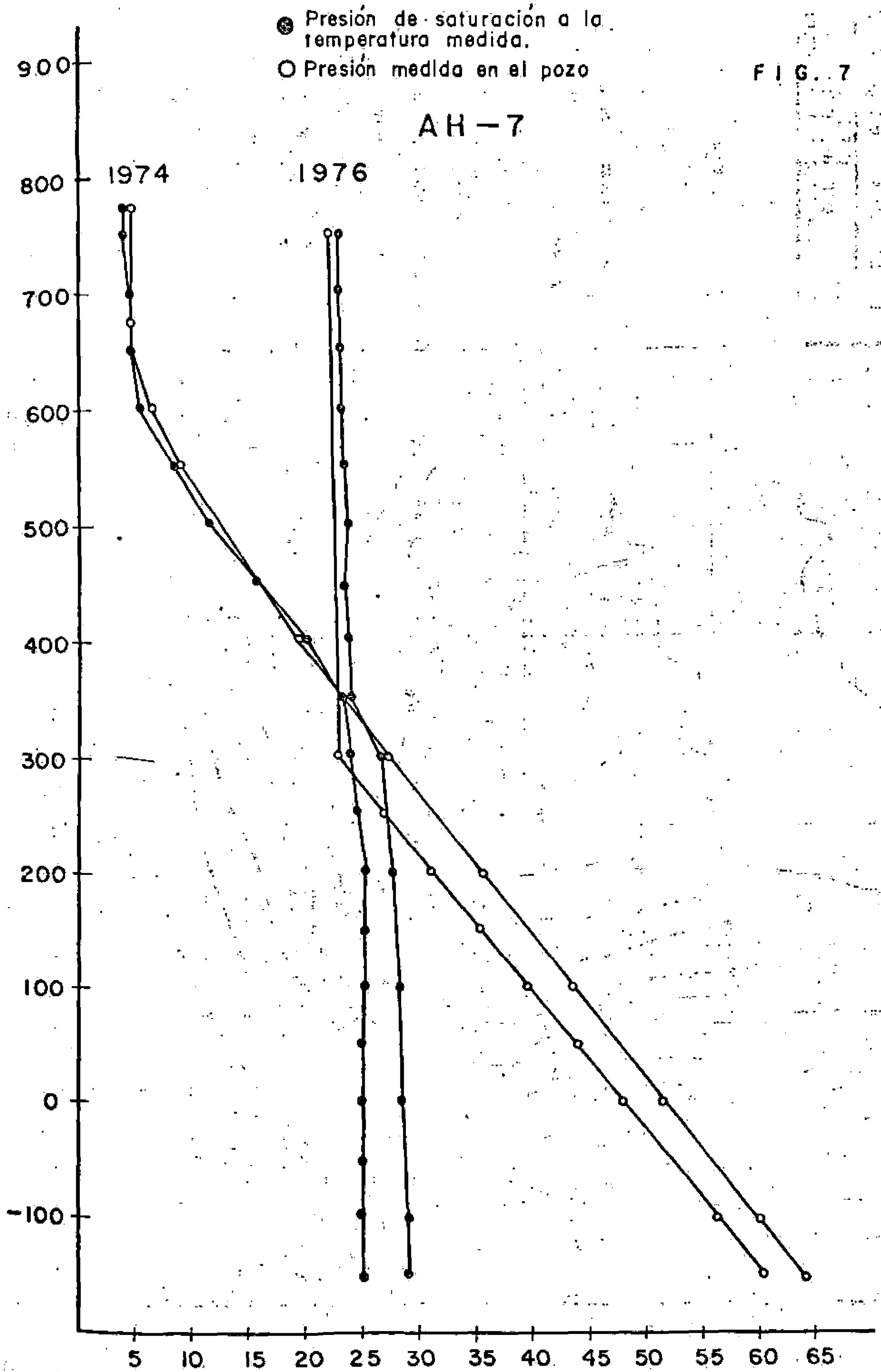
ESTUDIOS GEOTERMICOS

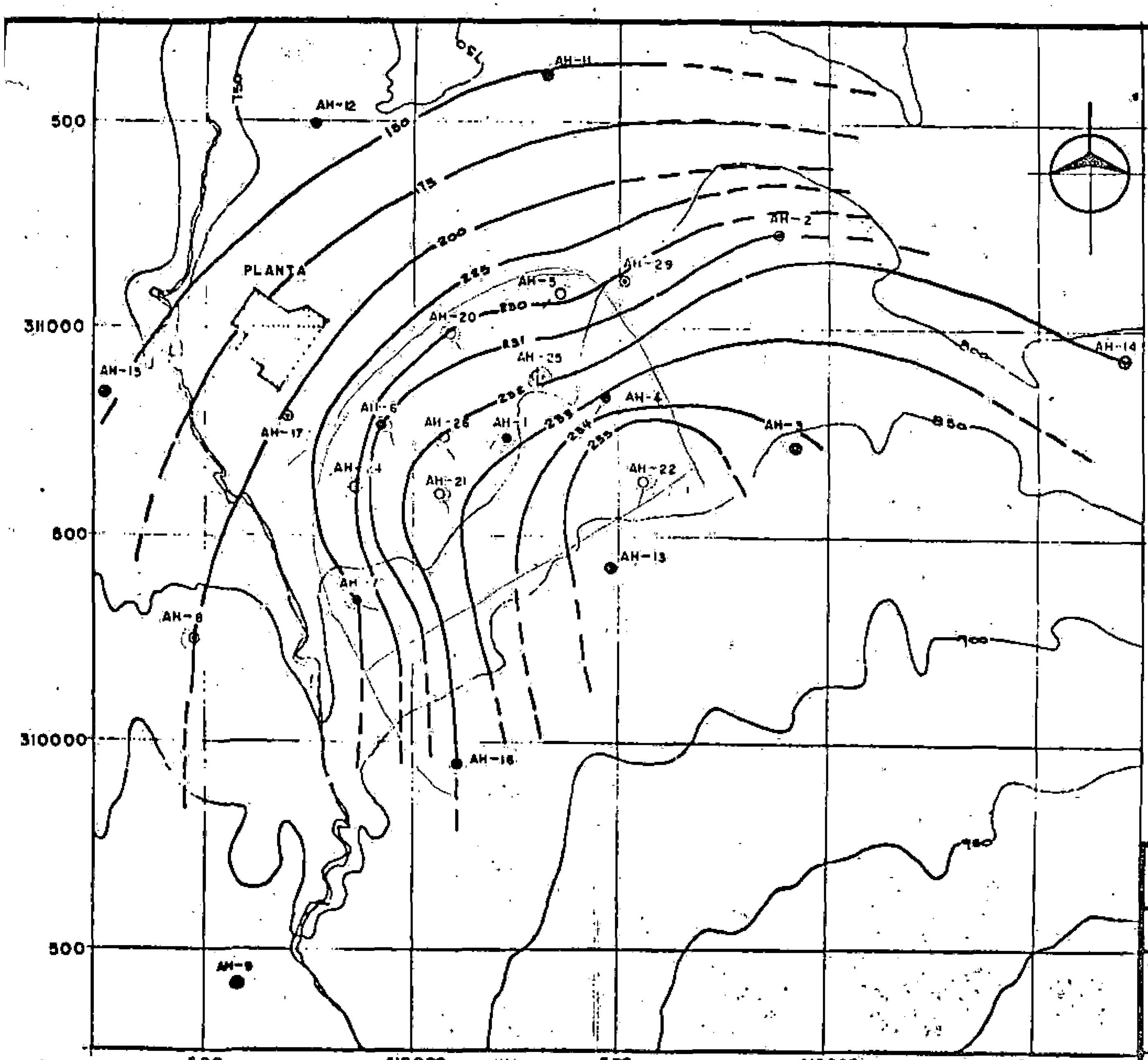
MAPA DE ISOCONCENTRACIONES
DE SILICE EN p.p.m.

ELABORO: Ing. M.E. CHOUSSY	APROBO:	FECHA:
DIBUJO: M.E. M. N.	REVISO Ing. M.E. CHOUSSY	O C T. 1 9 7 6

RELACIONES DE PRESION

FIG. 7





CAMPO GEOTERMICO AHUACHAPAN

SIMBOLOGIA

- ● POZOS la. UNIDAD
- ○ POZOS 2a. UNIDAD
- ◉ POZOS REINYECCION
- ○ POZOS EXPLORATORIOS
- ⊕ POZOS RESERVA
- ○ *producción*

Escala

0 500mts.

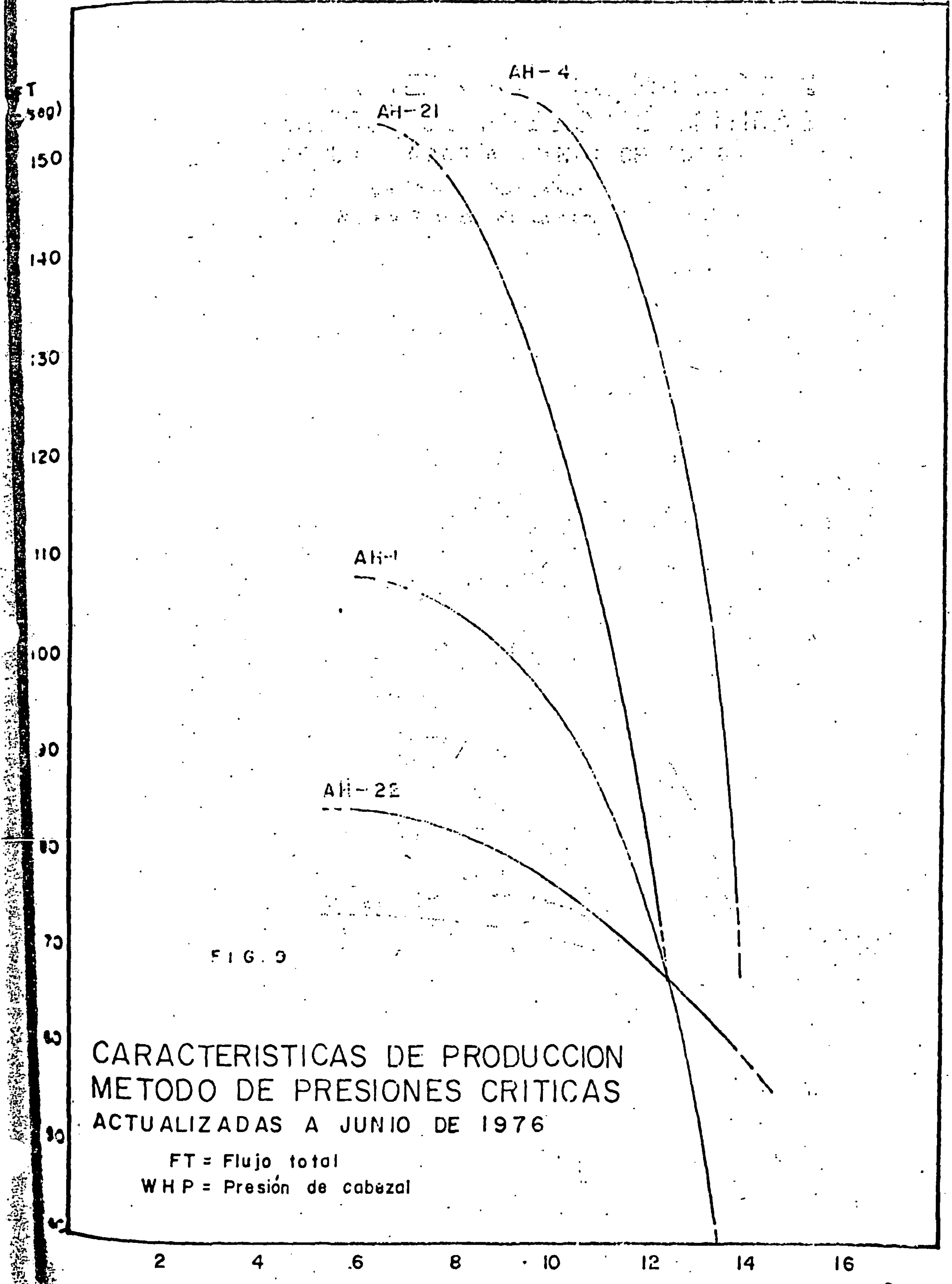
FIG.- 8

COMISION EJECUTIVA HIDROELECTRICA
DEL RIO LEMPA
C E L

ESTUDIOS GEOTERMICOS

MAPA DE TEMPERATURAS MAXIMAS MEDIDAS EN EL RESERVORIO.

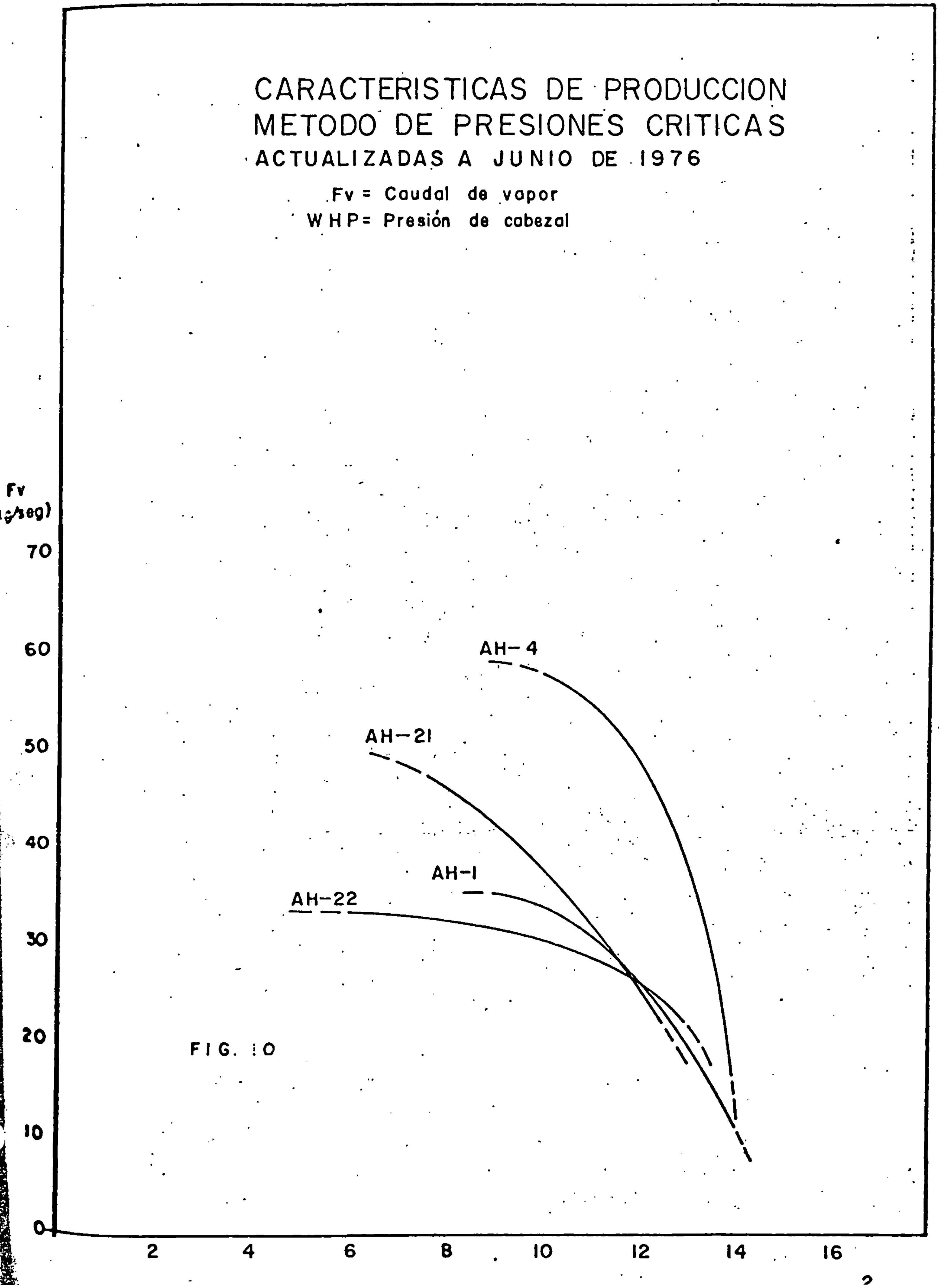
ELABORO Ing M.E. CHOUSSY	APROVO:	FECHA:
DIBUJO: M.F.M.N	REVISO Ing M.E.CHOUSSY	OCT. 1978



F I G. 9

CARACTERISTICAS DE PRODUCCION
METODO DE PRESIONES CRITICAS
ACTUALIZADAS A JUNIO DE 1976

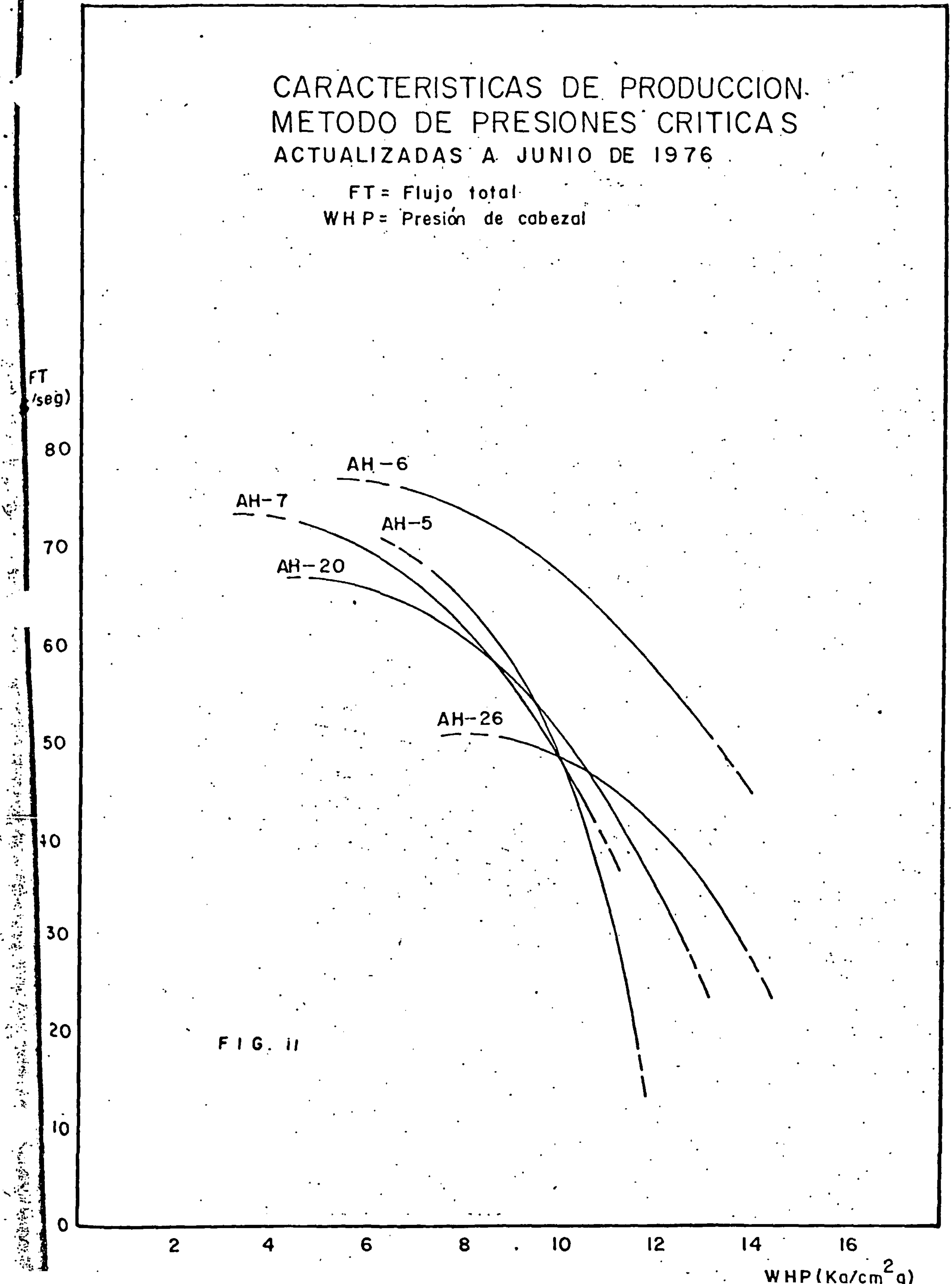
FT = Flujo total
WHP = Presión de cabezal



CARACTERISTICAS DE PRODUCCION
METODO DE PRESIONES CRITICAS
ACTUALIZADAS A JUNIO DE 1976

Fv = Caudal de vapor
WHP= Presión de cabezal

FIG. 10



CARACTERISTICAS DE PRODUCCION
METODO DE PRESIONES CRITICAS
ACTUALIZADAS A JUNIO DE 1976

FT= Flujo total
WHP= Presión de cabezal

FIG. 11

CARACTERISTICAS DE PRODUCCION
METODO DE PRESIONES CRITICAS
ACTUALIZADAS A JUNIO DE 1976

Fv = Caudal de vapor
WHP = Presión de cabezal

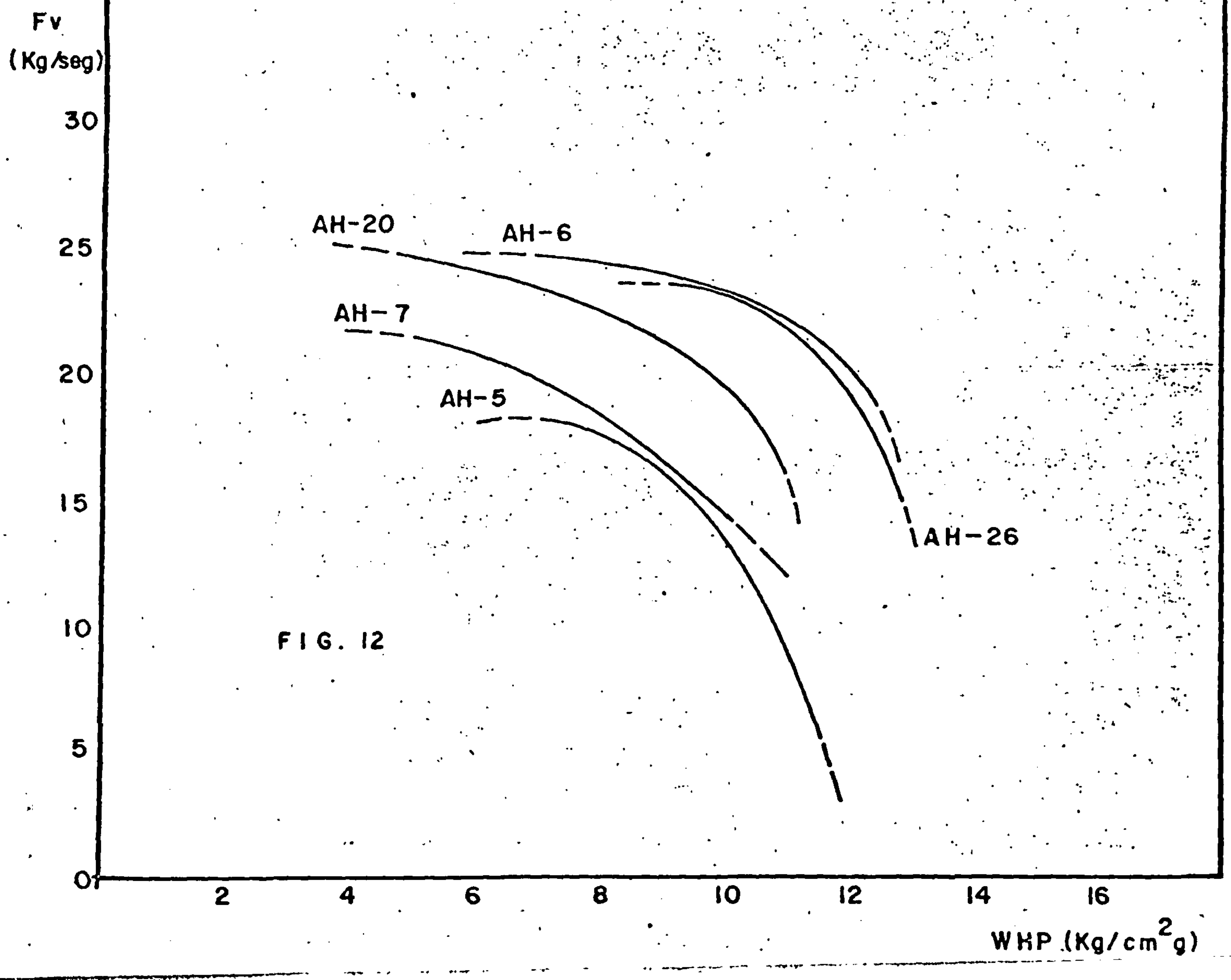


FIG. 12

GEOPHYSICAL SURVEYS IN THE AHUACHAPAN GEOTHERMAL AREA

by Jose Gonzalez G.

ABSTRACT

This report contains the results of the geophysical surveys done in the Ahuachapan area, which included the following studies: magnetic, gravimetric, geothermal, and of electric resistivity. These results, together with the geological and geochemical data, served as the basis for selecting the sites for the three exploratory wells that to date have been drilled in the area.

The measurements, magnetic as well as gravimetric, were made along a basic grid that was laid out in the northern part of the area and along the roads in the southern part of the same region, covering an area of approximately 200 km2. The results gave a general outline of the anomalies characteristic of this region.

The magnetic values show the variations in vertical intensity of the field, measured by a flux-gate magnetometer, and the results are shown on the corresponding maps by isogammas. The gravimetric data are shown on the maps of Bouguer anomalies and were calculated by using four different density values, due to the fact that this information was lacking at the time the respective computations were done.

A temperature survey at 1.5 m depth was done in the Ausoles area by measuring 8 of the 11 existing fields in the southern sector. With the data obtained, maps with isotherms showing the temperature distribution at the indicated depth were prepared.

In order to get data regarding the geothermal gradient, 24 wells were drilled distributed in such a way so as to cover the areas of interest and on the basis of the available geological surveys. The wells are 100 m deep and have a diameter of NX (3½"). Standard 1" Ø pipe was installed in order to facilitate the measurement of temperature.

Measurements of electric resistivity made up the major part of the basic data which determined the sites for the exploratory wells. Continuous profiles had been run along the basic grid and along some of the neighboring roads, as well as vertical soundings in certain selected places. Nevertheless, it is necessary to point out that the work is incomplete, as can be seen from the respective map, and as a result it will be necessary to continue with these measurements in order to be able to rely on the greatest amount of data possible. According to the results from the first exploratory wells, at least in regards to temperature, the aforementioned values have been determined based on the data provided by this method.

For the vertical soundings as well as for the continuous profiles, the Schlumberger configuration was used initially. But in July of 1967 by recommendation of Dr. G. Bodvarsson, and in order to try to eliminate the inductive effect caused by the specified configuration, we changed to the dipole-dipole system (polar arrangement). With the latter method it has been possible to measure vertical soundings with a maximum area of 4 km which is equivalent to 8 and 12 km respectively in the Schlumberger and Wenner configurations.

Based on the characteristics found in the area, it has been estimated that it would be necessary to run continuous profiles with measurements every 250 m and 1 km spacing between electrodes, 1.5 km in certain places. Also, it would be necessary to cover in great detail the areas of interest, drawing a 5 - - m curve for the site of the future exploratory wells.

2. Magnetometry

Based on experience gained in other countries, with regards to the application of the magnetic method in geothermal exploration, we prepared to study the feasibility of its use by taking advantage of the visit that Sr. G. Palmason, an Icelandic geophysicist, made to our project in March of 1966 as a United Nations consultant.

Mr. Palmason ran profiles encompassing the Ausoles of Ahuachapan, Agua Shuca, La Labor, and part of the Salitre field, doing measurements every 50 m. The instrument used was a Canadian flux-gate magnetometer, J. Sharpe brand, Model MF-1 for measuring the vertical intensity of the field, which he brought from Iceland in order to test the feasibility of using this method.

According to the data obtained, variations in vertical magnetic intensity of approximately 1000 gammas were found in addition to a gradual decrease in that intensity beginning near Salitre and going towards the Ausoles zone in the south; a decrease that was between 500 and 600 gammas.

Aside from the aforementioned details, many negative anomalies were observed in the area south of Ausoles that could be related to the thermal activity characteristic of that area.

In view of the results obtained and per the recommendation of Mr. Palmason, a Canadian magnetometer, McPhar M700 of the same type as the one previously mentioned, and with an accuracy of ± 5 gammas was acquired. Measurements were done every 50 m in the area along the lines contained in the basic grid as well as in the other measured lines in order to provide the topographic control that would serve as support for the gravimetric surveying planned in the area.

In order to control the diurnal variation, a base station was established at a site selected for its insulation from disturbing influences. It had shown, at least during the period when the measurements were done, a tranquil period in which the maximum variation in the temperatures at the base never exceeded 40 gammas and as a result it was not necessary to make any adjustment in the measured readings.

The data from the readings at approximately 5,000 stations, are shown in the map of isograms of the vertical magnetic variation, No. P-23-A-45. According to this map, the zones of magnetic "lows" are located in the vicinity of Ausoles and the "highs" at Salitre. At the same time one can notice the "highs" between the Ahuachpana Ausoles and Chipilapa and that they would correspond to the batches of lava that are found in that area. Nevertheless, the "low" in the "San Lazaro" dome calls attention to the fact that this is contrary to what would be expected in this dome. For this reason it is believed necessary to know the residual magnetism in order to do the final interpretations of the data.

3. Gravimetry

The first gravimetric work was done in 1962, consisting of the measurement of 4 parallel profiles 5 km long and 1 km apart, laid out in a normal way in the direction of a presumed fault in the Salitre volcano. A Worden gravimeter was used and the measurements were done with a 50 m spacing. The work was carried out by the General Office of Cartography in cooperation with the Interamerican Geodetic Service. The profiles showed certain interesting features in the vicinity of the Salitre volcano but unfortunately the area of interest wasn't reached and as a result the work remained inconclusive.

Because of these results and by enlarging the aforementioned network, a survey of the area shown on the respective maps was planned and carried out, with stations every 200 m. For horizontal as well as vertical control, a survey of the area was done, relying on the control stations of the General Office of Cartography, utilizing a Wild RDS self-reducing transit in order to get the precision necessary for this type of survey. For the gravimetric measurements a Worden No. 397 gravimeter with a constant of 0.3710 (3) milligals by division was employed. Point "A" (B.M. S-9) was selected as the reference station and the "La Capilla" triangulation station was linked with the aforementioned Point "A". For the purpose of control of the "drift" an intermediate station was established at Atiquizaya.

The number of stations measured reached 1100 total in the circuits corresponding to the different lines of the network. The results are shown in maps Nos. P-23-A-50/53, with the Bouguer anomalies coming from the use of the following density values: 1.8, 2.0, 2.25, and 2.50 gr/cm3; since at the time that the calculations were made there wasn't greater information about the densities of the rocks in the area under study. The calculations of the anomalies were done by means of an IBM 1620 computer belonging to the General Office of Cartography.

The grid of anomalies shows us certain features that could be interpreted as indicators of the distribution of some subsoil structures in the southern part of the field which could help us in trying to become familiar with the permeability conditions in that zone. Nevertheless, in accordance with the recommendations made by Dr. Bodvarsson it would be useful to draw another map of anomalies based on a density of 2.7 gr/cm3 and enlarge the survey to cover 5 to 10 km outside of the thermal area with a distance of 1 km between stations; concerning the value of 2.7 gr/cm3 I wish to add that according to personal communication with Ing. M. Jimenez, this would correlate with the values found by him in the rock samples in the area.

When this information has been obtained one can complete the grid of anomalies in the field and try to become familiar with the prominent structural features for the purpose of studying the permeability characteristics of the reservoir.

4. Geothermal gradient and Surface Measurements of Temperature

By taking into consideration the importance of knowing the temperature conditions in the subsoil, a program for drilling wells, in order to measure the geothermal gradient, was planned and carried out which simultaneously correlated this data with the surveys of electric resistivity. At the same time a temperature survey in the Ausoles area was done, covering 8 of the 11 existing fields in the southern part of the area.

The number of wells drilled was 24, distributed for the most part in the southern region, with a depth of 100 m and a diameter of NX (3½"). For the temperature measurements "thermistor" drills with two conveyors were used. The thermistors used were of 10000 ohms of resistance at 25°C and the readings were done with either a Wheatstone bridge or with a Yellow Springs Instrument brand direct reading telethermometer, using an adjustment corresponding to the resistance employed. In order to facilitate the insertion of the drill, standard 1" ∅ pipe was placed in the wells, a method which allowed reaching the desired objective

The accuracy of the measured values was $\leq$ 0.5°C according to the tests done in the Project's laboratory and the results are shown on map P-23-A-40-A-.

In relation to the caloric conductivity, some tests were done in the Bundesanstalt für Bodenforschung laboratory in Hannover, Federal Republic of Germany. The samples measured came from the Tobar 1 and the following results were obtained:

Depth of the sample	Caloric conductivity
35 m	2.8×10^{-3} (cal./cm./sec./°C)
40 m	3.5×10^{-3}
58 m	4.3×10^{-3}

The tendency towards smaller conductivities at lesser depths could indicate a meteorization in the basalt found in the well.

Because of the lack of necessary information relative to all of the wells, the gradient was calculated using only the temperature values measured at the surface and in the ground, selecting an average value of 23°C for the value at the surface.

For the purpose of becoming familiar with the surface temperature in the Ausoles area, temperature was measured in holes 1.5 m deep and 1" Ø. In order to cover these areas a grid was laid out with lines running North-South, East-West, 100 m apart and with holes every 15 m. In certain places of interest the distance between lines was reduced to 50 m. For the measurements, drills with thermistors were used, anchored with wood rods to facilitate insertion and properly insulated, using the same type of telethermometer that was mentioned previously.

The data obtained from these measurements appears on Map P-23-A-81; as one can see, the "Playon" and the "La Labor" fields indicate a greater area with temperatures above 70°C in comparison with the rest of the other measured fields.

According to the data shown in the two aforementioned maps, the areas in km2 of the zones in the southern part of the field are summarized in the following form:

Basic data	Area in km2 Min	Max
Surface manifestations	21	30
Geothermal gradient Area included by the curve of 40°C/100 m	21.5	

5. Electric resistivity

In accord with the experience of other countries, principally New Zealand, in the application of the resistivity method in geothermal exploration, it was decided to use this method more intensively in the exploratory works of the Project.

The first measurements were done in March of 1966 under the direction of Mr. G. Palmason, using Canadian equipment, J. Sharpe brand, Model SP5-R which had been previously acquired by the United Nations. The tests were done at the "El Salitre" field in the proximities of the thermal sources and in the environs of "El Limon" in the "La Labor" Hacienda. According to these tests, one can clearly see from the beginning that the instrument was not sufficiently adequate for measuring the relatively low values of resistivities found in these thermal areas even in the surface stratum inasmuch as, with the type of configuration employed - Wenner - hardly had an expansion of a - 26 m been obtained when it became impossible to take more readings due to the inadequacy of the instrument. As an experiment an arrangement of batteries in a series was improvised for the purpose of increasing the voltage to 540, getting an expansion of a - 144 m. Neverthless, even then it wasn't possible to extend the soundings to the necessary levels and as a result it was decided to acquire an instrument that would be powerful enough to measure the values of low resistivities that were expected to be found in the thermal areas under study and in order to reach the deep zones of interest.

In January, 1967, the first measurements were begun using the Canadian McPhar R203 which is equipped with a 2.5 KVA generator, 850 volt, 5 amperes and 0.3 cycles per second transmitter and a receiver with a maximum sensitivity of 100 microvolts on a complete scale; the precision of the instrument is 2%.

As a result of the first tests carried out in "El Salitre" and "Playon de Ahuachapan" under the direction of Dr. O. Kappelmeyer, it was decided to run continuous profiles with measurements every kilometer or more, based on the conditions of the terrain. The configuration used was the Schlumberger one with the following characteristics: distance between current electrodes - 1 km and 50 km between the potential electrodes. Besides the continuous profiles, vertical soundings were measured at selected sites, with the same configuration and a maximum expansion of 4 km.

On examining the curves resulting from the vertical soundings, it can be seen that in all of them there is a pronounced increase (greater than 45°) in the resistivity curve, beginning with a few hundreds of meters (200 m approximately), which exceeds the possible theoretical values. This increase shows up in all of the soundings in an identical form such that it makes one suspect an anomalous cause that systematically changes the measured values and that these values do not maintain a relation with the ones that would be expected based on the geological conditions in the area. In July of 1967, taking advantage of the visit of Prof. G. Bodvarsson, this problem was studied by doing measurements not only within the thermal areas but also in the following areas, outside of these zones: El Playon (Quezaltepeque), Guazapa and Playa de San Diego (La Libertad). Having come to the conclusion that the problem was due to the inductive effect originating from the use of alternating current in the type of configuration that was employed, it was decided to change this type and from then on adopting the dipole-dipole configuration with polar arrangement in order to try to reduce this effect to a minimum.

In concurrance with Prof. Bodvarsson the following allowances were made for the effects originating from the use of alternating current in the measurements: in these circumstances the alternating fields cause induction between the current and potential circuits as well as the so-called "skin effect". In the resistivity measurements the two fields are combined or it could be that the inductive effects increase the apparent resistivity, just as was verified by the results of the experimental measurements done in the aforementioned areas. The ratio between the induced electromotive force and the conducting field depends as much on the type of configuration as on the depth in which the "skin effect" is noticed. As a result, it is believed that in order to be able to reduce to a minimum this disturbing influence, it is best to use the dipole-dipole configuration since the Schlumberger as well as the Wenner offer lesser possibilities for use with alternating current, even with a very low frequency as in this case.

Based on the conditions found in the thermal zones it was decided to run new profiles with the following characteristics: 1 km between the centers of pairs of electrodes and 500 m between current and potential electrodes.

On returning from my study trip I put into practice the New Zealand techniques. Runs of new profiles have been started always with the dipolar configuration but with measurements every 250 m and, in addition, at experimental roads the distance between centers of pairs of electrodes has been increased to 1.5 km in order to get better penetration. Nevertheless, as can be clearly seen on the map, the measurements are incomplete, They should cover the La Labor field and all of the southern part of the area, as well as the eastern sector, in order to define the limits of the same.

Besides the profiles run along some roads, a special survey was done in "San Raimundo" in order to locate a site for the "Salitre-I" well. Three parallel lines, 250 m apart and 3.5 km long were laid out and the measurements were made every 250 m just as it appears on the indicated map. In addition, 2 vertical soundings in the Santa Ana-Ahuachapan highway were measured (km 85-95) with a maximum expansion of 4 km which theoretically would be equivalent to 8 and 12 km respectively in the Schlumberger and Wenner configurations.

Due to the fact that, as was previously indicated, the resistivity method is the one that served as the basis for choosing a site for the exploratory wells, I will leave the respective commentaries for the final part of this report in order to deal more fully with the different features found upon correlating the resistivity measurements with the data obtained from the three exploratory wells drilled to date.

6. Discussion of the Results

Regarding the magnetic and gravimetric surveys, as was discussed in the corresponding chapters, one can say that they provided interesting data although it was less decisive and conclusive when compared with the data from the resistivity surveys. The latter have basicallymade up almost the totality of the information utilized for the selection of the well sites.

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Bouguer anomaly

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Fig.- 1

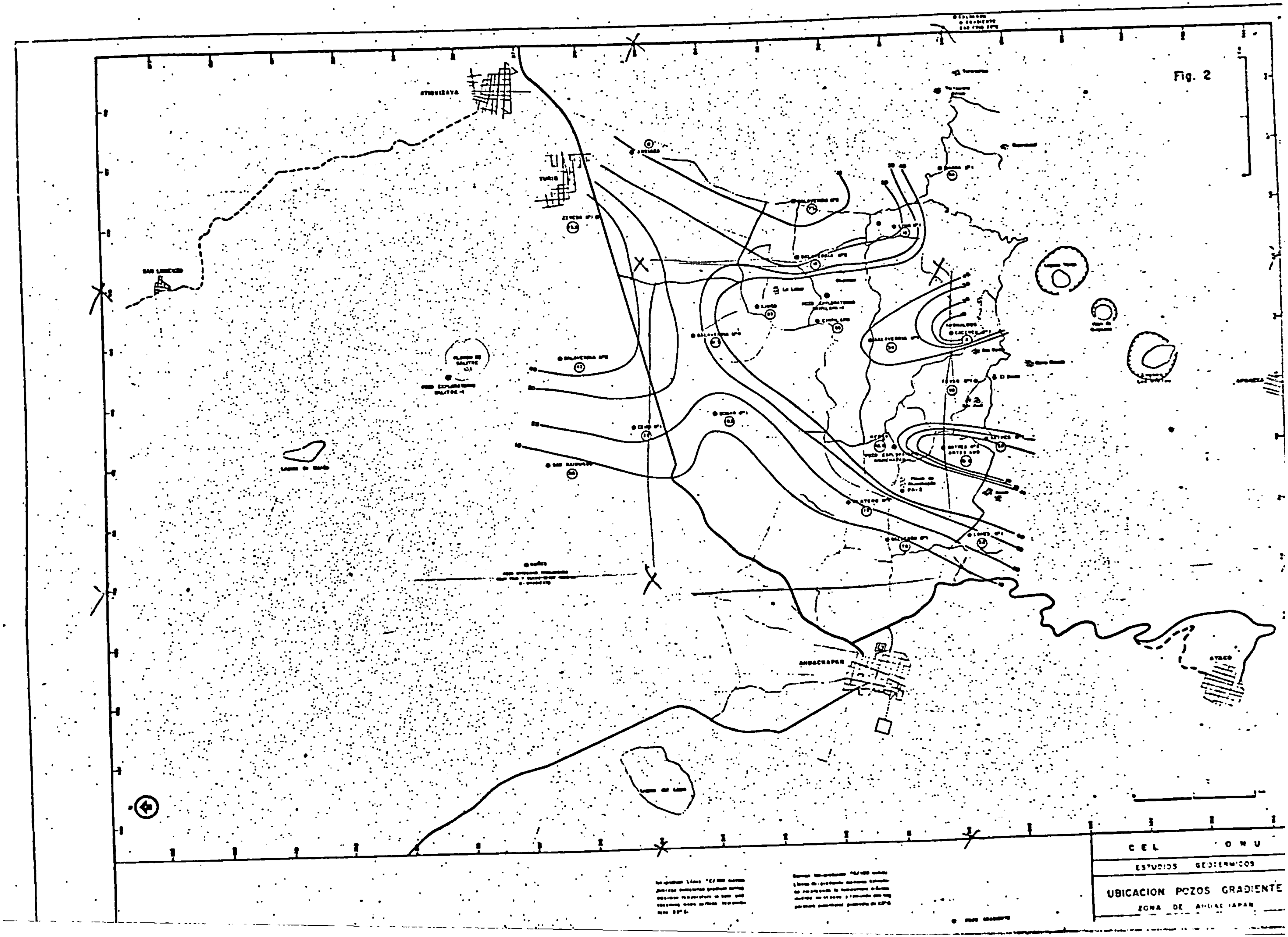


Fig. 2

CEL ONU

ESTUDIOS GEOTERMICOS

UBICACION POZOS GRADIENTE

ZONA DE AHUACHAPAN

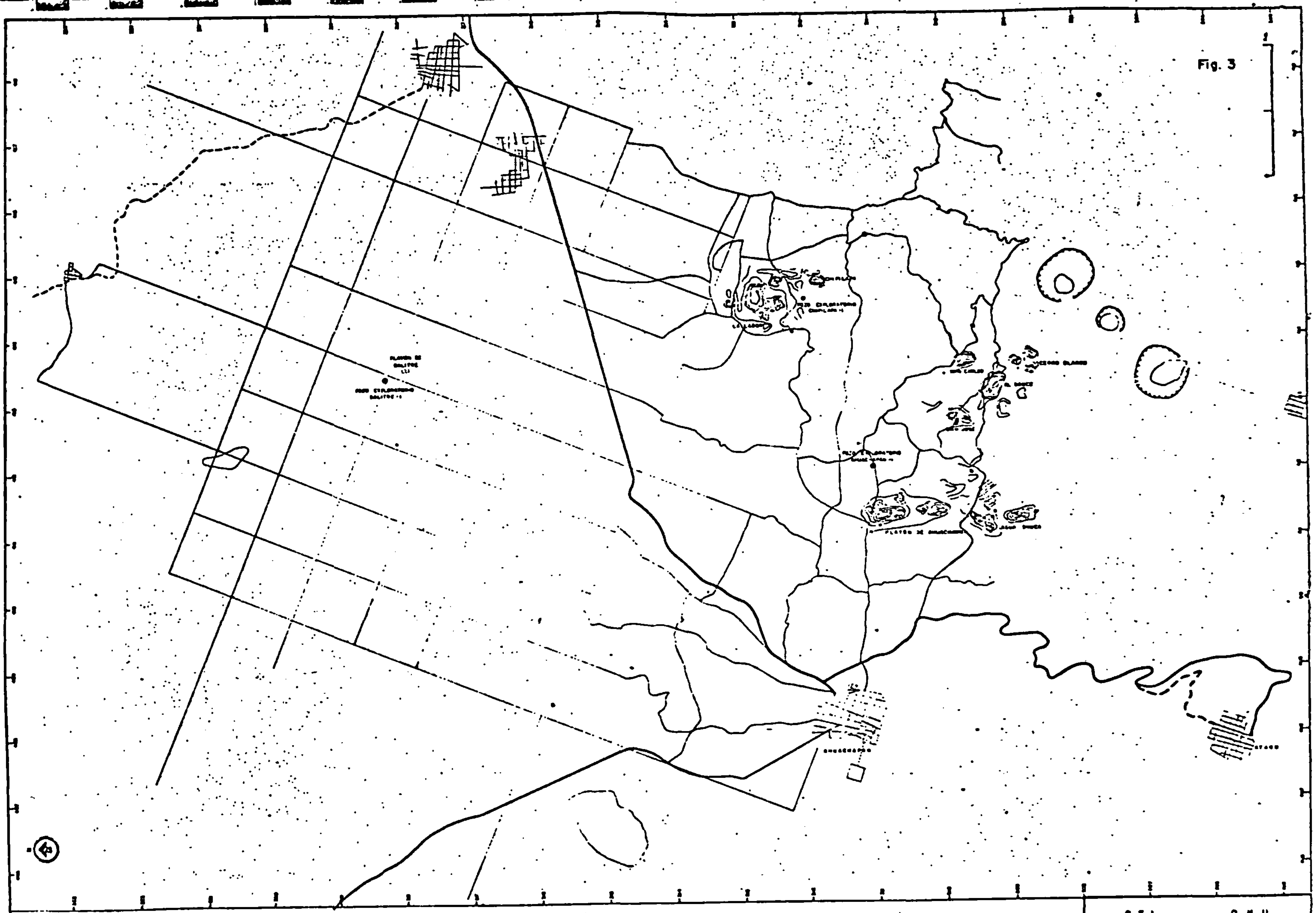


Fig. 3

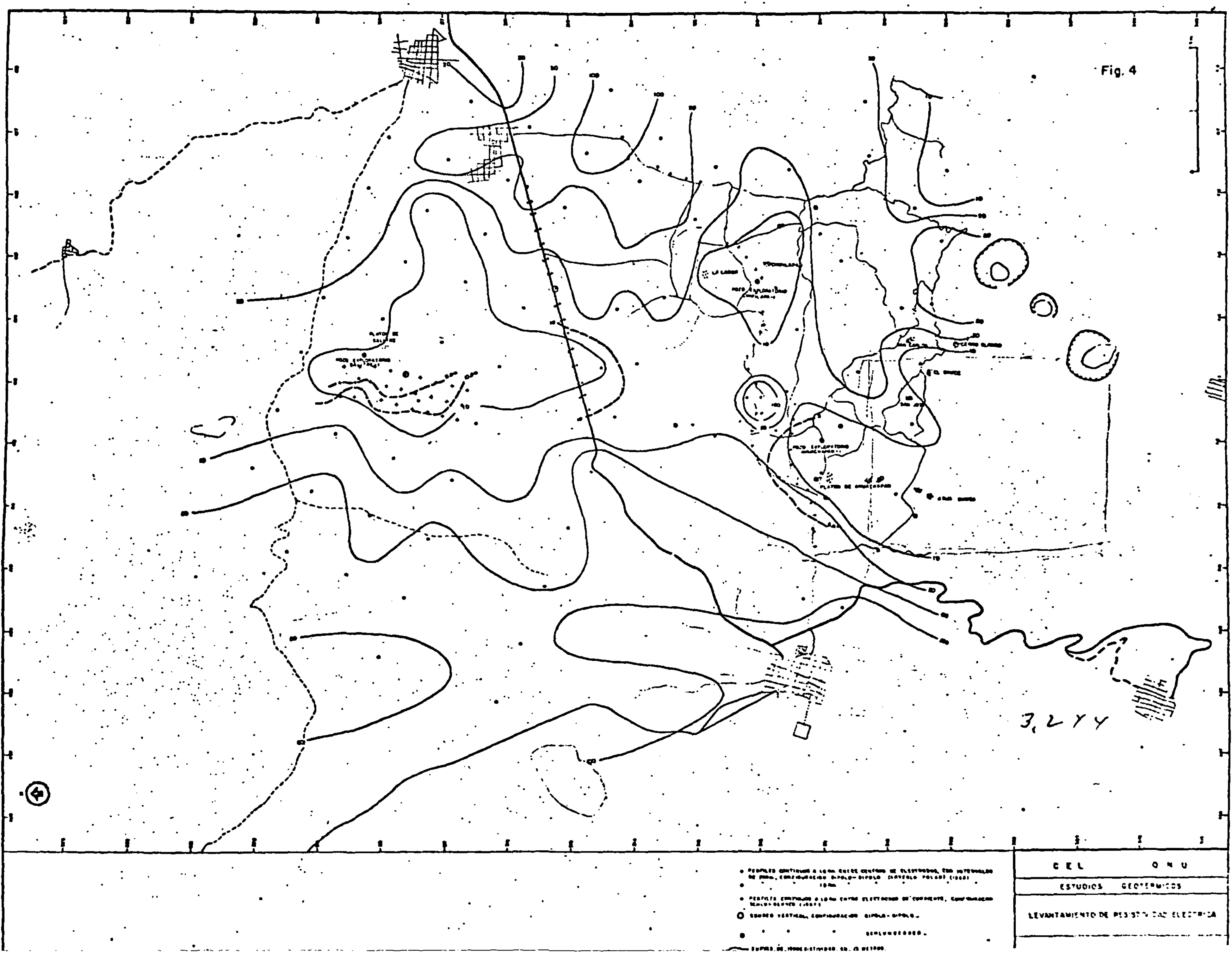
C E L O N U

ESTUDIOS GEOTERMICOS

ISOTERMAS A 15m DE PROFUNDIDAD
AREA DE AHUACHAPAN

SAN SALVADOR | [illegible] | P-23-8-91

Fig. 4

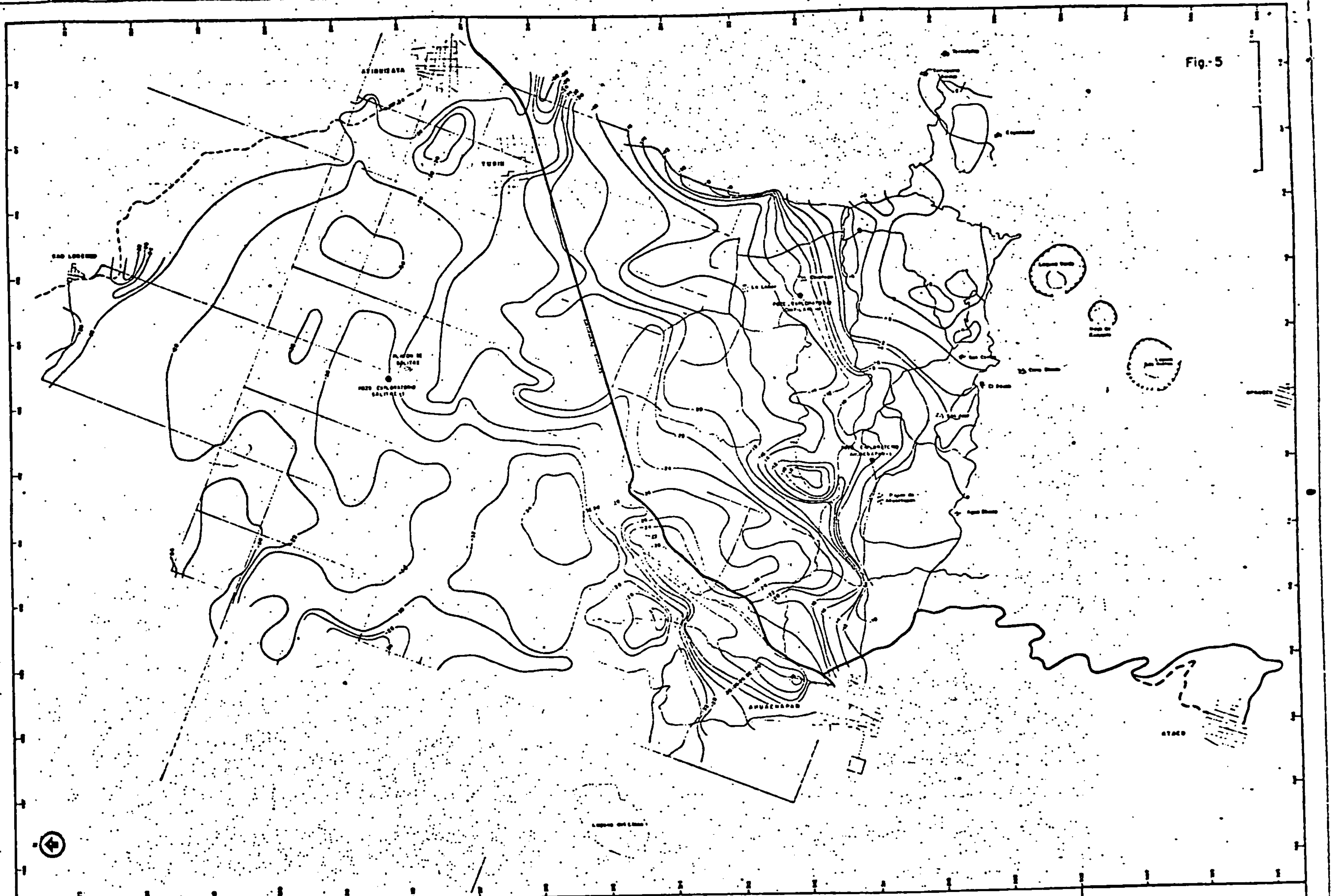


CEL ONU

ESTUDIOS GEOTERMICOS

LEVANTAMIENTO DE RESISTIVIDAD ELECTRICA

Fig.- 5



C E L   O N U.

ESTUDIOS GEOTERMICOS

AREA DE AHUACHAPAN

LEVANTAMIENTO GRAVIMETRICO

ANOMALIA BOUGUER

[illegible]

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SAN SALVADOR	[illegible]	P-73 A 31

CEL - ONU
ESTUDIO DE LOS
RECURSOS GEOTERMICOS
EL SALVADOR

FECHA: 25 NOV. 1968.

Variacion de la resistividad del terreno con la temperatura y la porosidad. El contenido de cloruros es asumido constante, y m (factor de cementacion) es tomado igual a 2.2.-

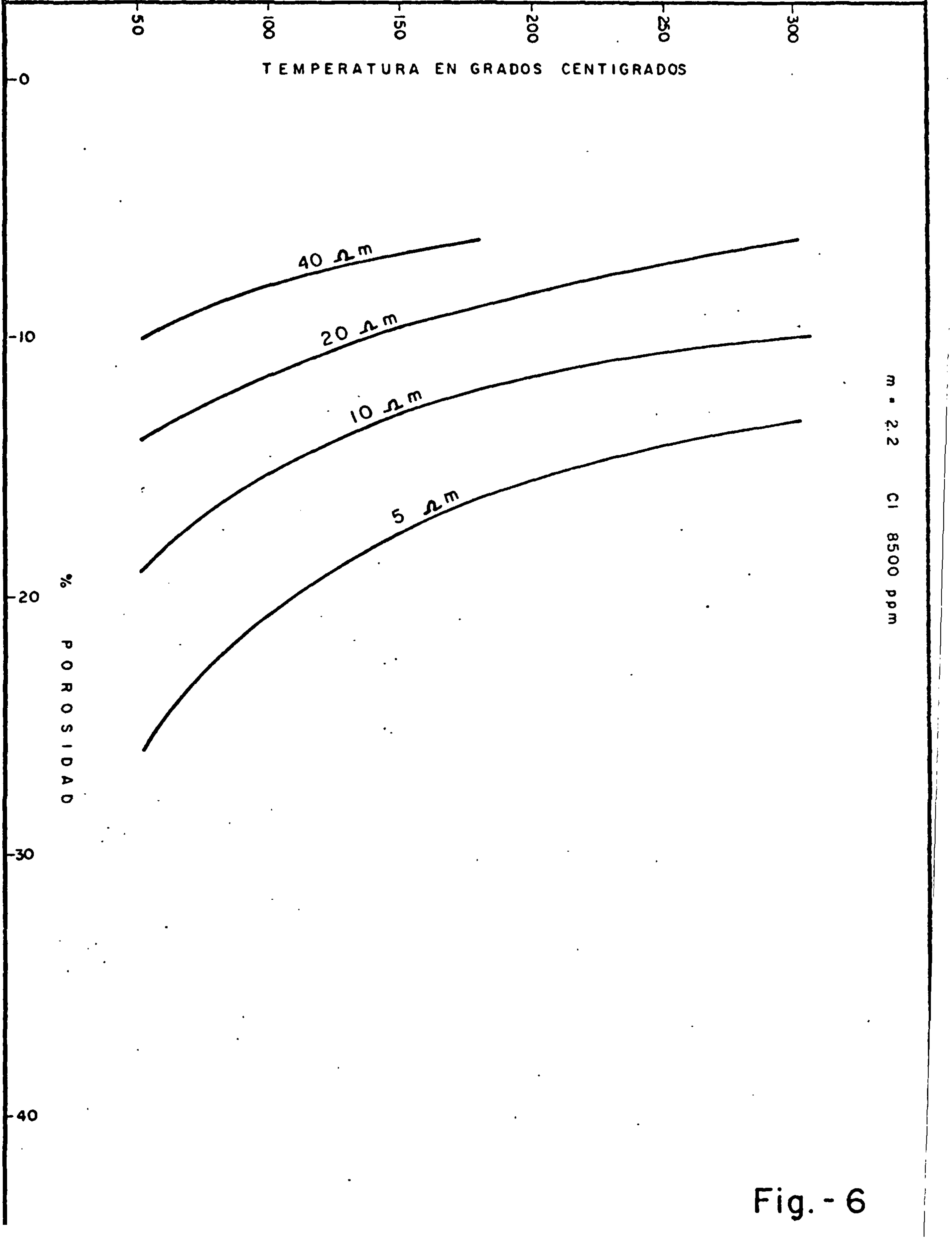

Fig. - 6

CEL -- ONU
ESTUDIO DE LOS
RECURSOS GEOTERMICOS
EL SALVADOR

FECHA: Nov. 27-1968

Variación de la resistividad del terreno con la temperatura y la porosidad. El contenido de cloruros es asumido constante, y m (factor de cementacion) es tomado igual a 1.6.

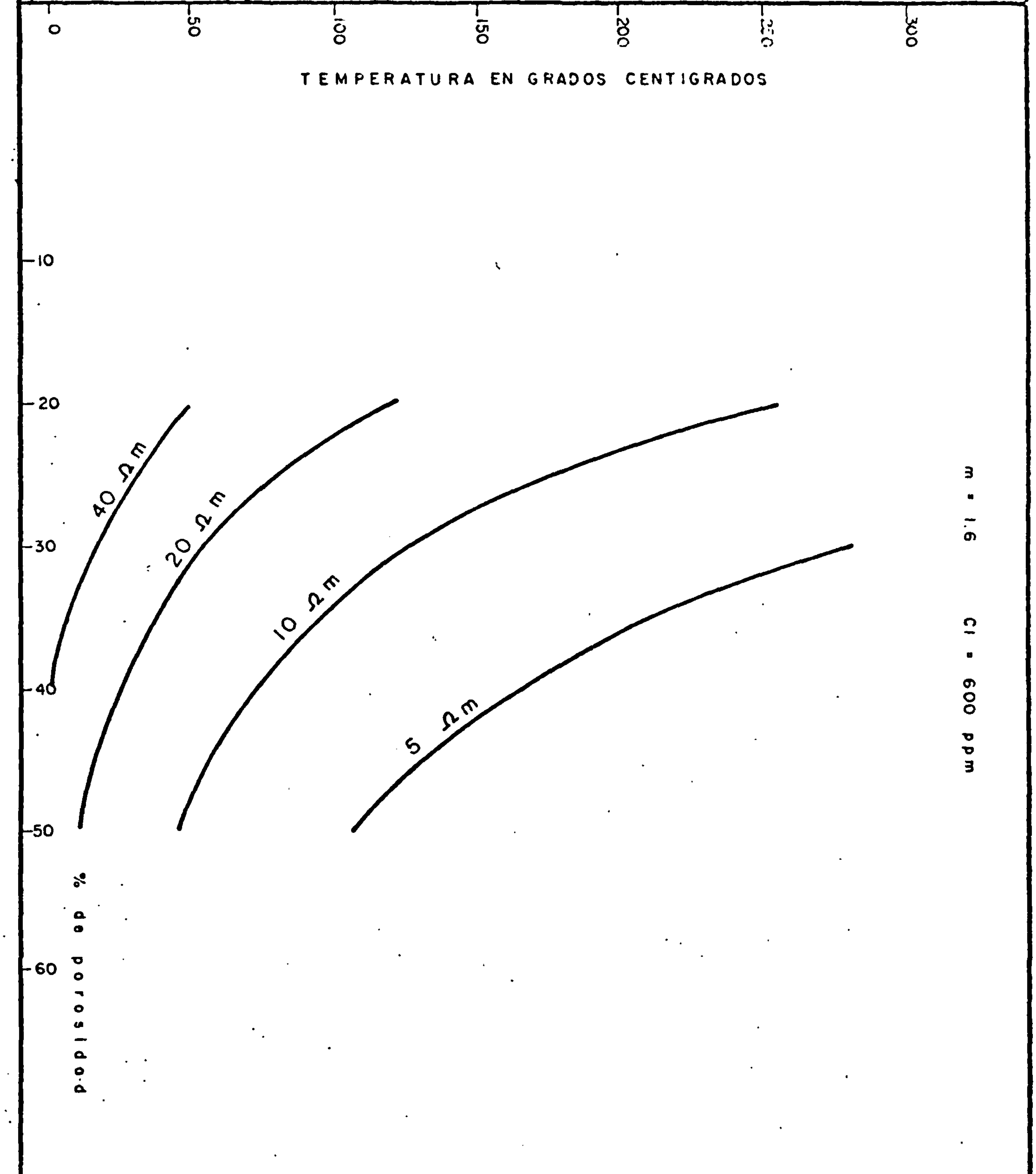

Fig.- 7

GEOPHYSICAL SURVEYS IN THE AHUACHAPAN GEOTHERMAL AREA

by Jose Gonzalez G.

ABSTRACT

This report contains the results of the geophysical surveys done in the Ahuachapan area, which included the following studies: magnetic, gravimetric, geothermal, and of electric resistivity. These results, together with the geological and geochemical data, served as the basis for selecting the sites for the three exploratory wells that to date have been drilled in the area.

The measurements, magnetic as well as gravimetric, were made along a basic grid that was laid out in the northern part of the area and along the roads in the southern part of the same region, covering an area of approximately 200 km2. The results gave a general outline of the anomalies characteristic of this region.

The magnetic values show the variations in vertical intensity of the field, measured by a flux-gate magnetometer, and the results are shown on the corresponding maps by isogammas. The gravimetric data are shown on the maps of Bouguer anomalies and were calculated by using four different density values, due to the fact that this information was lacking at the time the respective computations were done.

A temperature survey at 1.5 m depth was done in the Ausoles area by measuring 8 of the 11 existing fields in the southern sector. With the data obtained, maps with isotherms showing the temperature distribution at the indicated depth were prepared.

In order to get data regarding the geothermal gradient, 24 wells were drilled distributed in such a way so as to cover the areas of interest and on the basis of the available geological surveys. The wells are 100 m deep and have a diameter of NX (3½"). Standard 1" Ø pipe was installed in order to facilitate the measurement of temperature.

Measurements of electric resistivity made up the major part of the basic data which determined the sites for the exploratory wells. Continuous profiles had been run along the basic grid and along some of the neighboring roads, as well as vertical soundings in certain selected places. Nevertheless, it is necessary to point out that the work is incomplete, as can be seen from the respective map, and as a result it will be necessary to continue with these measurements in order to be able to rely on the greatest amount of data possible. According to the results from the first exploratory wells, at least in regards to temperature, the aforementioned values have been determined based on the data provided by this method.

For the vertical soundings as well as for the continuous profiles, the Schlumberger configuration was used initially. But in July of 1967 by recommendation of Dr. G. Bodvarsson, and in order to try to eliminate the inductive effect caused by the specified configuration, we changed to the dipole-dipole system (polar arrangement). With the latter method it has been possible to measure vertical soundings with a maximum area of 4 km which is equivalent to 8 and 12 km respectively in the Schlumberger and Wenner configurations.

Based on the characteristics found in the area, it has been estimated that it would be necessary to run continuous profiles with measurements every 250 m and 1 km spacing between electrodes, 1.5 km in certain places; Also, it would be necessary to cover in great detail the areas of interest, drawing a 5 - - m curve for the site of the future exploratory wells.

2. Magnetometry

Based on experience gained in other countries, with regards to the application of the magnetic method in geothermal exploration, we prepared to study the feasibility of its use by taking advantage of the visit that Sr. G. Palmason, an Icelandic geophysicist, made to our project in March of 1966 as a United Nations consultant.

Mr. Palmason ran profiles encompassing the Ausoles of Ahuachapan, Agua Shuca, La Labor, and part of the Salitre field, doing measurements every 50 m. The instrument used was a Canadian Flux-gate magnetometer, J. Sharpe brand, Model MF-1 for measuring the vertical intensity of the field, which he brought from Iceland in order to test the feasibility of using this method.

According to the data obtained, variations in vertical magnetic intensity of approximately 1000 gammas were found in addition to a gradual decrease in that intensity beginning near Salitre and going towards the Ausoles zone in the south; a decrease that was between 500 and 600 gammas.

Aside from the aforementioned details, many negative anomalies were observed in the area south of Ausoles that could be related to the thermal activity characteristic of that area.

In view of the results obtained and per the recommendation of Mr. Palmason, a Canadian magnetometer, McPhar M700 of the same type as the one previously mentioned, and with an accuracy of ∠- 5 gammas was acquired. Measurements were done every 50 m in the area along the lines contained in the basic grid as well as in the other measured lines in order to provide the topographic control that would serve as support for the gravimetric surveying planned in the area.

In order to control the diurnal variation, a base station was established at a site selected for its insulation from disturbing influences. It had shown, at least during the period when the measurements were done, a tranquil period in which the maximum variation in the temperatures at the base never exceeded 40 gammas and as a result it was not necessary to make any adjustment in the measured readings.

The data from the readings at approximately 5,000 stations, are shown in the map of isogams of the vertical magnetic variation, No. P-23-A-45. According to this map, the zones of magnetic "lows" are located in the vicinity of Ausoles and the "highs" at Salitre. At the same time one can notice the "highs" between the Ahuachpana Ausoles and Chipilapa and that they would correspond to the batches of lava that are found in that area. Nevertheless, the "low" in the "San Lazaro" dome calls attention to the fact that this is contrary to what would be expected in this dome. For this reason it is believed necessary to know the residual magnetism in order to do the final interpretations of the data.

3. Gravimetry

The first gravimetric work was done in 1962, consisting of the measurement of 4 parallel profiles 5 km long and 1 km apart, laid out in a normal way in the direction of a presumed fault in the Salitre volcano. A Worden gravimeter was used and the measurements were done with a 50 m spacing. The work was carried out by the General Office of Cartography in cooperation with the Interamerican Geodetic Service. The profiles showed certain interesting features in the vicinity of the Salitre volcano but unfortunately the area of interest wasn't reached and as a result the work remained inconclusive.

Because of these results and by enlarging the aforementioned network, a survey of the area shown on the respective maps was planned and carried out, with stations every 200 m. For horizontal as well as vertical control, a survey of the area was done, relying on the control stations of the General Office of Cartography, utilizing a Wild RDS self-reducing transit in order to get the precision necessary for this type of survey. For the gravimetric measurements a Worden No. 397 gravimeter with a constant of 0.3710 (3) milligals by division was employed. Point "A" (B.M. S-9) was selected as the reference station and the "La Capilla" triangulation station was linked with the aforementioned Point "A". For the purpose of control of the "drift" an intermediate station was established at Atiquizaya.

The number of stations measured reached 1100 total in the circuits corresponding to the different lines of the network. The results are shown in maps Nos. P-23-A-50/53, with the Bouguer anomalies coming from the use of the following density values: 1.8, 2.0, 2.25, and 2.50 gr/cm3; since at the time that the calculations were made there wasn't greater information about the densities of the rocks in the area under study. The calculations of the anomalies were done by means of an IBM 1620 computer belonging to the General Office of Cartography.

The grid of anomalies shows us certain features that could be interpreted as indicators of the distribution of some subsoil structures in the southern part of the field which could help us in trying to become familiar with the permeability conditions in that zone. Nevertheless, in accordance with the recommendations made by Dr. Bodvarsson it would be useful to draw another map of anomalies based on a density of 2.7 gr/cm3 and enlarge the survey to cover 5 to 10 km outside of the thermal area with a distance of 1 km between stations; concerning the value of 2.7 gr/cm3 I wish to add that according to personal communication with Ing. M. Jimenez, this would correlate with the values found by him in the rock samples in the area.

When this information has been obtained one can complete the grid of anomalies in the field and try to become familiar with the prominent structural features for the purpose of studying the permeability characteristics of the reservoir.

4. Geothermal gradient and Surface Measurements of Temperature

By taking into consideration the importance of knowing the temperature conditions in the subsoil, a program for drilling wells, in order to measure the geothermal gradient, was planned and carried out which simultaneously correlated this data with the surveys of electric resistivity. At the same time a temperature survey in the Ausoles area was done, covering 8 of the 11 existing fields in the southern part of the area.

The number of wells drilled was 24, distributed for the most part in the southern region, with a depth of 100 m and a diameter of NX ($3\frac{1}{2}$"). For the temperature measurements "thermistor" drills with two conveyors were used. The thermistors used were of 10000 ohms of resistance at 25°C and the readings were done with either a Wheatstone bridge or with a Yellow Springs Instrument brand direct reading telethermometer, using an adjustment corresponding to the resistance employed. In order to facilitate the insertion of the drill, standard 1" Ø pipe was placed in the wells, a method which allowed reaching the desired objective

The accuracy of the measured values was $\leq$ 0.5°C according to the tests done in the Project's laboratory and the results are shown on map P-23-A-40-A-.

In relation to the caloric conductivity, some tests were done in the Bundesanstalt für Bodenforschung laboratory in Hannover, Federal Republic of Germany. The samples measured came from the Tobar 1 and the following results were obtained:

Depth of the sample	Caloric conductivity
35 m	2.8×10^{-3} (cal./cm./sec./°C)
40 m	3.5×10^{-3}
58 m	4.3×10^{-3}

The tendency towards smaller conductivities at lesser depths could indicate a meteorization in the basalt found in the well.

Because of the lack of necessary information relative to all of the wells, the gradient was calculated using only the temperature values measured at the surface and in the ground, selecting an average value of 23°C for the value at the surface.

For the purpose of becoming familiar with the surface temperature in the Ausoles area, temperature was measured in holes 1.5 m deep and 1" Ø. In order to cover these areas a grid was laid out with lines running North-South, East-West, 100 m apart and with holes every 15 m. In certain places of interest the distance between lines was reduced to 50 m. For the measurements, drills with thermistors were used, anchored with wood rods to facilitate insertion and properly insulated, using the same type of telethermometer that was mentioned previously.

The data obtained from these measurements appears on Map P-23-A-81; as one can see, the "Playon" and the "La Labor" fields indicate a greater area with temperatures above 70°C in comparison with the rest of the other measured fields.

According to the data shown in the two aforementioned maps, the areas in km2 of the zones in the southern part of the field are summarized in the following form:

Basic data	Area in km2	
	Min	Max
Surface manifestations	21	30
Geothermal gradient		
Area included by the curve of 40°C/100 m	21.5	

5. Electric resistivity

In accord with the experience of other countries, principally New Zealand, in the application of the resistivity method in geothermal exploration, it was decided to use this method more intensively in the exploratory works of the Project.

The first measurements were done in March of 1966 under the direction of Mr. G. Palmason, using Canadian equipment, J. Sharpe brand, Model SP5-R which had been previously acquired by the United Nations. The tests were done at the "El Salitre" field in the proximities of the thermal sources and in the environs of "El Limon" in the "La Labor" Hacienda. According to these tests, one can clearly see from the beginning that the instrument was not sufficiently adequate for measuring the relatively low values of resistivities found in these thermal areas even in the surface stratum inasmuch as, with the type of configuration employed - Wenner - hardly had an expansion of a - 26 m been obtained when it became impossible to take more readings due to the inadequacy of the instrument. As an experiment an arrangement of batteries in a series was improvised for the purpose of increasing the voltage to 540, getting an expansion of a - 144 m. Neverthless, even then it wasn't possible to extend the soundings to the necessary levels and as a result it was decided to acquire an instrument that would be powerful enough to measure the values of low resistivities that were expected to be found in the thermal areas under study and in order to reach the deep zones of interest.

In January, 1967, the first measurements were begun using the Canadian McPhar R203 which is equipped with a 2.5 KVA generator, 850 volt, 5 amperes and 0.3 cycles per second transmitter and a receiver with a maximum sensitivity of 100 microvolts on a complete scale; the precision of the instrument is 2%.

As a result of the first tests carried out in "El Salitre" and "Playon de Ahuachapan" under the direction of Dr. O. Kappelmeyer, it was decided to run continuous profiles with measurements every kilometer or more, based on the conditions of the terrain. The configuration used was the Schlumberger one with the following characteristics: distance between current electrodes - 1 km and 50 km between the potential electrodes. Besides the continuous profiles, vertical soundings were measured at selected sites, with the same configuration and a maximum expansion of 4 km.

On examining the curves resulting from the vertical soundings, it can be seen that in all of them there is a pronounced increase (greater than 45°) in the resistivity curve, beginning with a few hundreds of meters (200 m approximately), which exceeds the possible theoretical values. This increase shows up in all of the soundings in an identical form such that it makes one suspect an anomalous cause that systematically changes the measured values and that these values do not maintain a relation with the ones that would be expected based on the geological conditions in the area. In July of 1967, taking advantage of the visit of Prof. G. Bodvarsson, this problem was studied by doing measurements not only within the thermal areas but also in the following areas, outside of these zones: El Playon (Quezaltepeque), Guazapa and Playa de San Diego (La Libertad). Having come to the conclusion that the problem was due to the inductive effect originating from the use of alternating current in the type of configuration that was employed, it was decided to change this type and from then on adopting the dipole-dipole configuration with polar arrangement in order to try to reduce this effect to a minimum.

In concurrance with Prof. Bodvarsson the following allowances were made for the effects originating from the use of alternating current in the measurements: in these circumstances the alternating fields cause induction between the current and potential circuits as well as the so-called "skin effect". In the resistivity measurements the two fields are combined or it could be that the inductive effects increase the apparent resistivity, just as was verified by the results of the experimental measurements done in the aforementioned areas. The ratio between the induced electromotive force and the conducting field depends as much on the type of configuration as on the depth in which the "skin effect" is noticed. As a result, it is believed that in order to be able to reduce to a minimum this disturbing influence, it is best to use the dipole-dipole configuration since the Schlumberger as well as the Wenner offer lesser possibilities for use with alternating current, even with a very low frequency as in this case.

Based on the conditions found in the thermal zones it was decided to run new profiles with the following characteristics: 1 km between the centers of pairs of electrodes and 500 m between current and potential electrodes.

On returning from my study trip I put into practice the New Zealand techniques. Runs of new profiles have been started always with the dipolar configuration but with measurements every 250 m and, in addition, at experimental roads the distance between centers of pairs of electrodes has been increased to 1.5 km in order to get better penetration. Nevertheless, as can be clearly seen on the map, the measurements are incomplete. They should cover the La Labor field and all of the southern part of the area, as well as the eastern sector, in order to define the limits of the same.

Besides the profiles run along some roads, a special survey was done in "San Raimundo" in order to locate a site for the "Salitre-I" well. Three parallel lines, 250 m apart and 3.5 km long were laid out and the measurements were made every 250 m just as it appears on the indicated map. In addition, 2 vertical soundings in the Santa Ana-Ahuachapan highway were measured (km 85-95) with a maximum expansion of 4 km which theoretically would be equivalent to 8 and 12 km respectively in the Schlumberger and Wenner configurations.

Due to the fact that, as was previously indicated, the resistivity method is the one that served as the basis for choosing a site for the exploratory wells, I will leave the respective commentaries for the final part of this report in order to deal more fully with the different features found upon correlating the resistivity measurements with the data obtained from the three exploratory wells drilled to date.

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Fig.- I

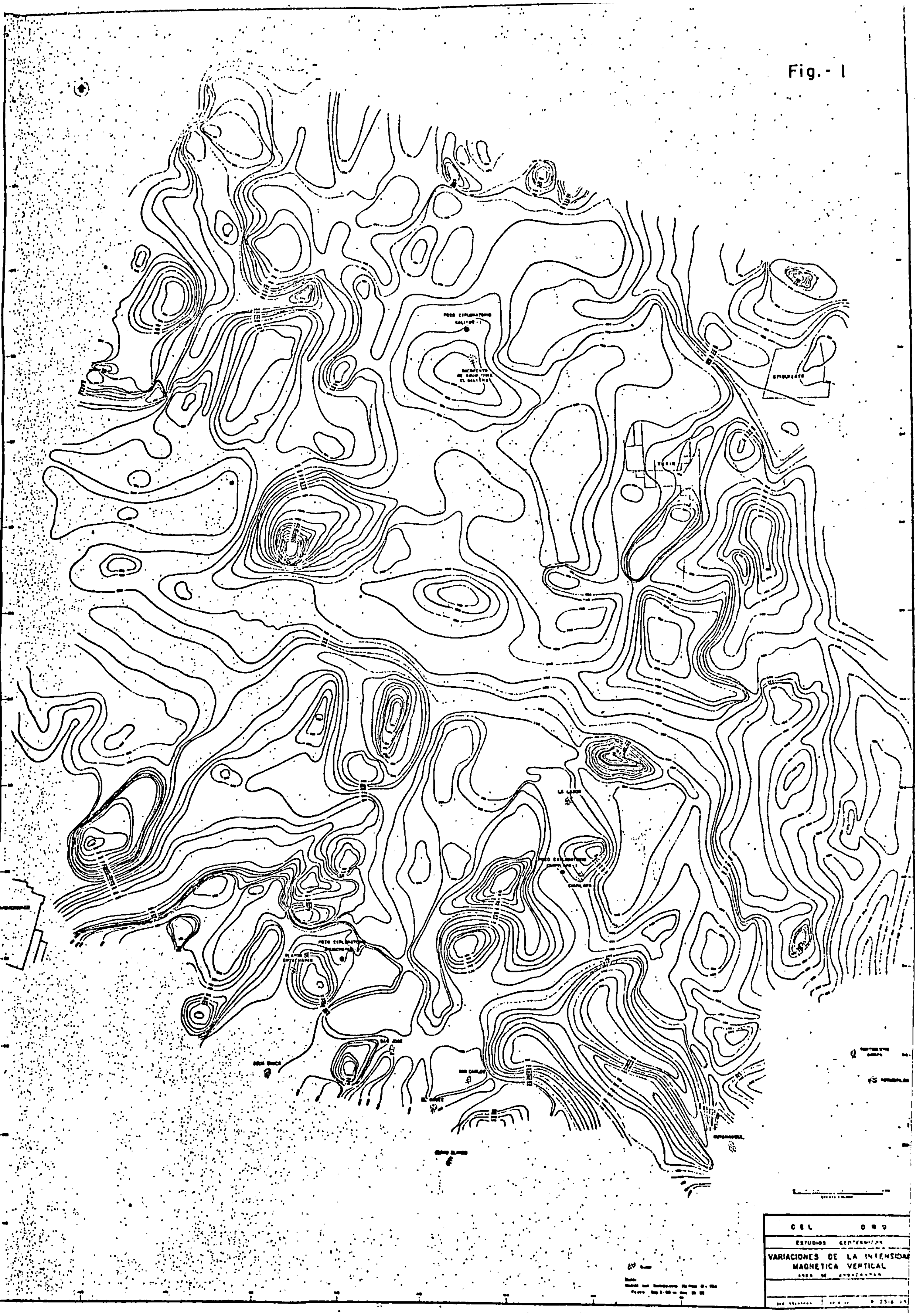
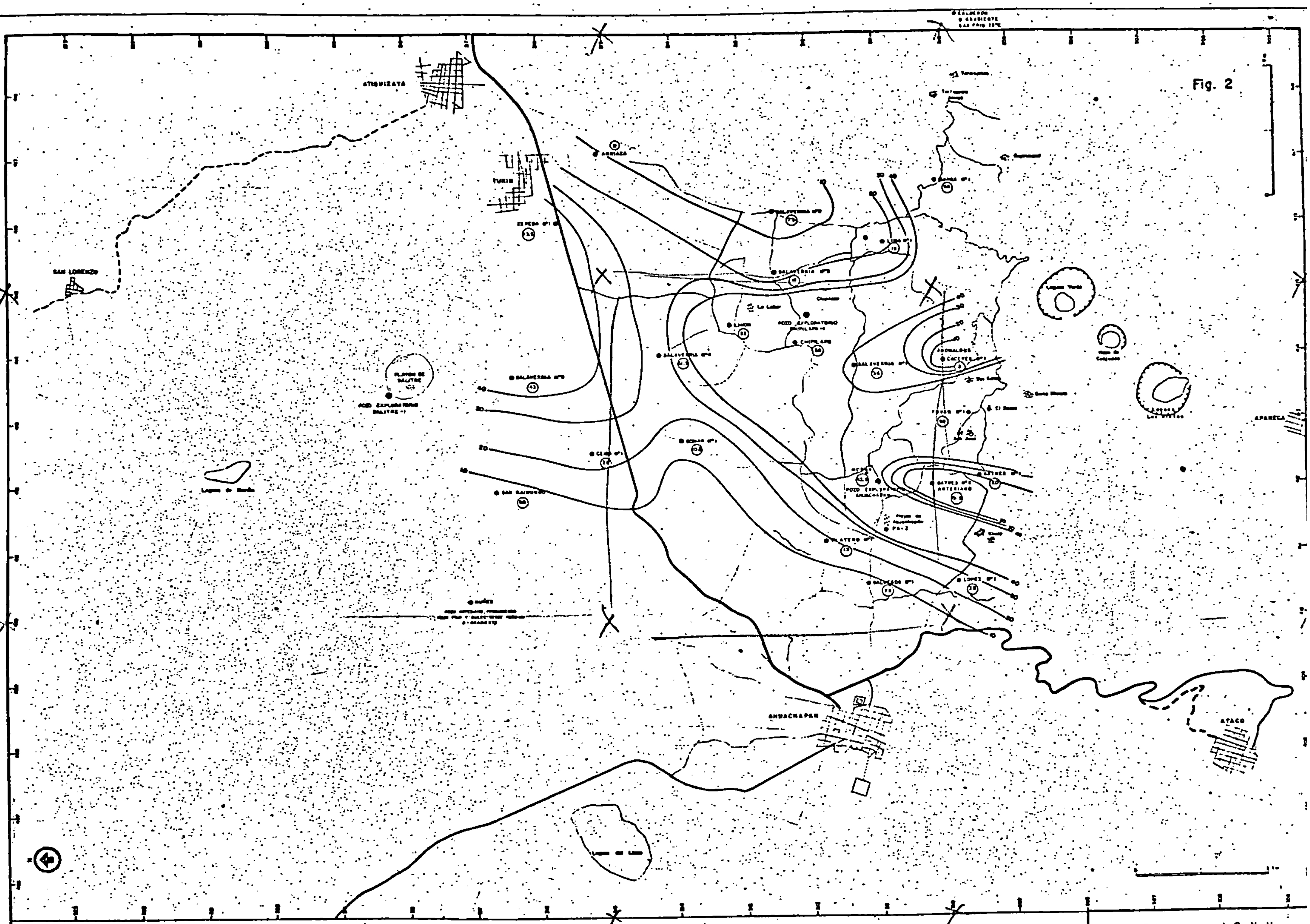

POZO EXPLORATORIO
SALITRE - 1
NACIMIENTO
DE AGUA TIBIA
EL SALITRE
TERMAS
LA LABOR
POZO EXPLORATORIO
CHIPILAPA - 1
CHIPILAPA
POZO EXPLORATORIO
SAN JOSE
SAN CARLOS
CEL
ESTUDIOS GEOTERMICOS
VARIACIONES DE LA INTENSIDAD
MAGNETICA VERTICAL
AREA DE AHUACHAPAN

Fig. 2



POZO GRADIENTE

CEL ONU

ESTUDIOS GEOTERMICOS

UBICACION POZOS GRADIENTE

ZONA DE AHUACHAPAN

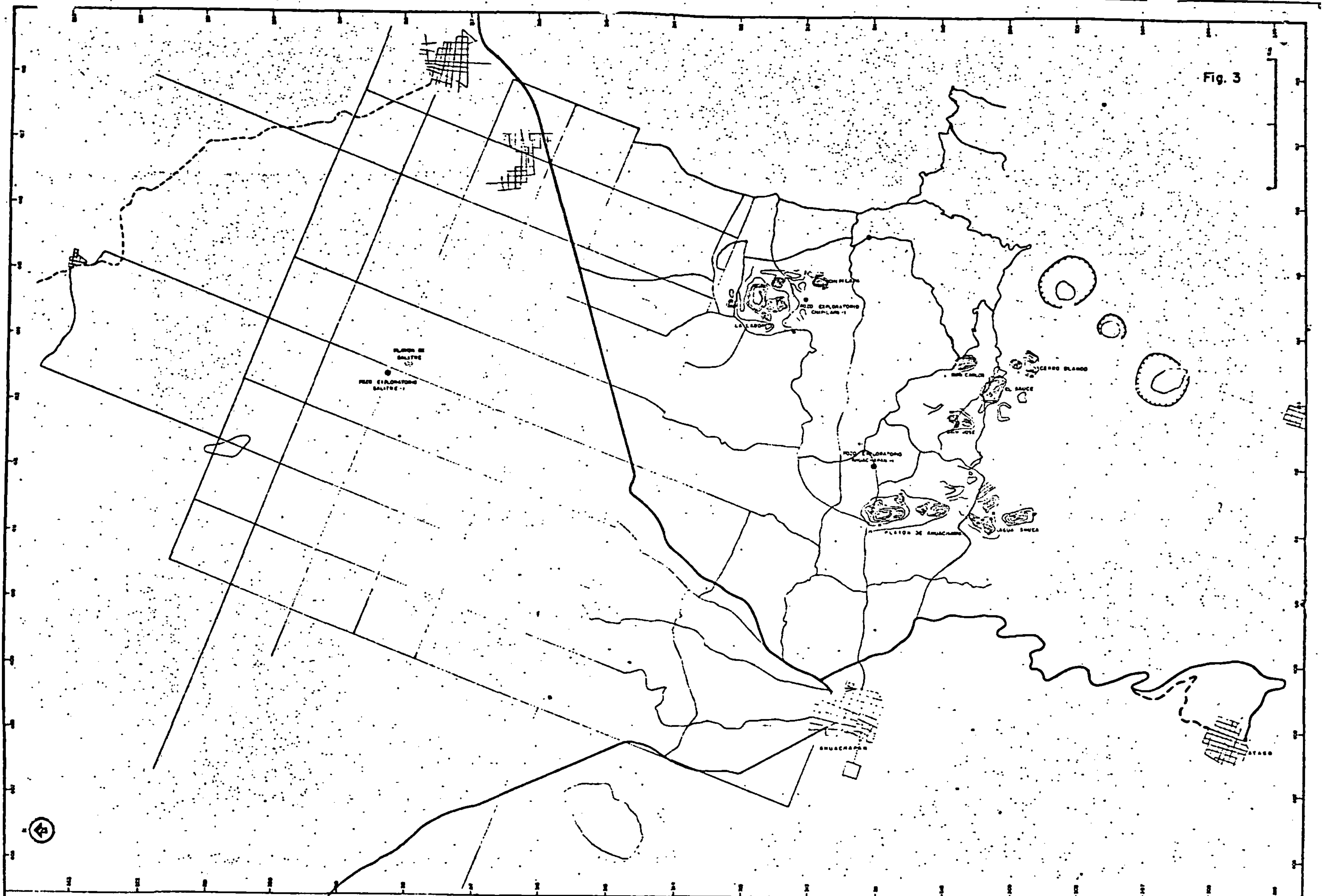


Fig. 3

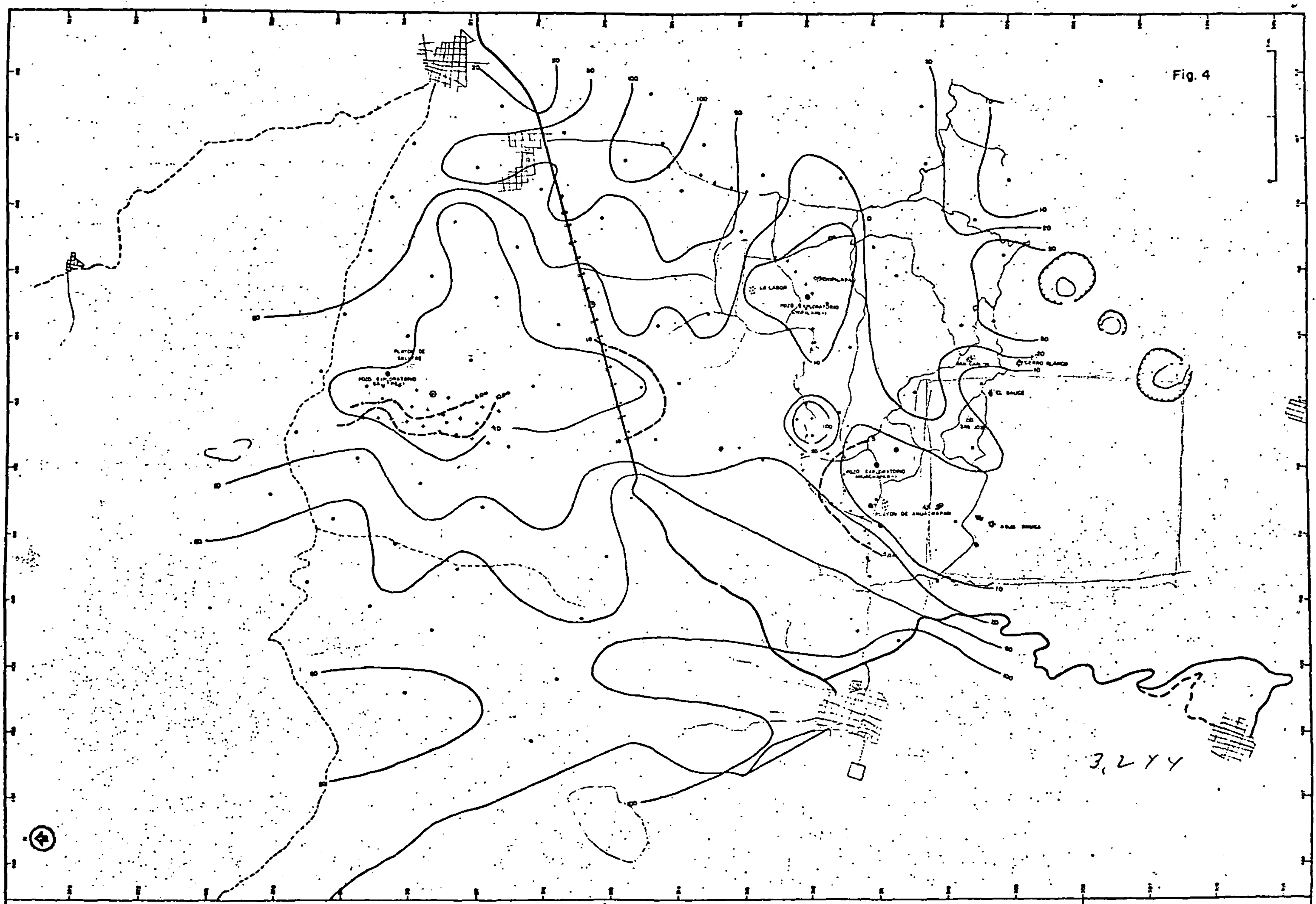
C E L O N U

ESTUDIOS GEOTERMICOS

ISOTERMAS A 1.5m DE PROFUNDIDAD
AREA DE AHUACHAPAN

SAN SALVADOR | [illegible] | P-23-A-81

Fig. 4



3,244

- PERFILES CONTINUOS A 100m. ENTRE CENTROS DE ELECTRODOS, CON INTERVALOS DE 200m., CONFIGURACION DIPOLO-DIPOLO (ARREGLO POLAR) (19[illegible])
- " " " " (19[illegible])
- PERFILES CONTINUOS A 100m. ENTRE ELECTRODOS DE CORRIENTE, CONFIGURACION SCHLUMBERGER (19[illegible])

○ SONDEO VERTICAL, CONFIGURACION DIPOLO-DIPOLO..

● " " " SCHLUMBERGER..

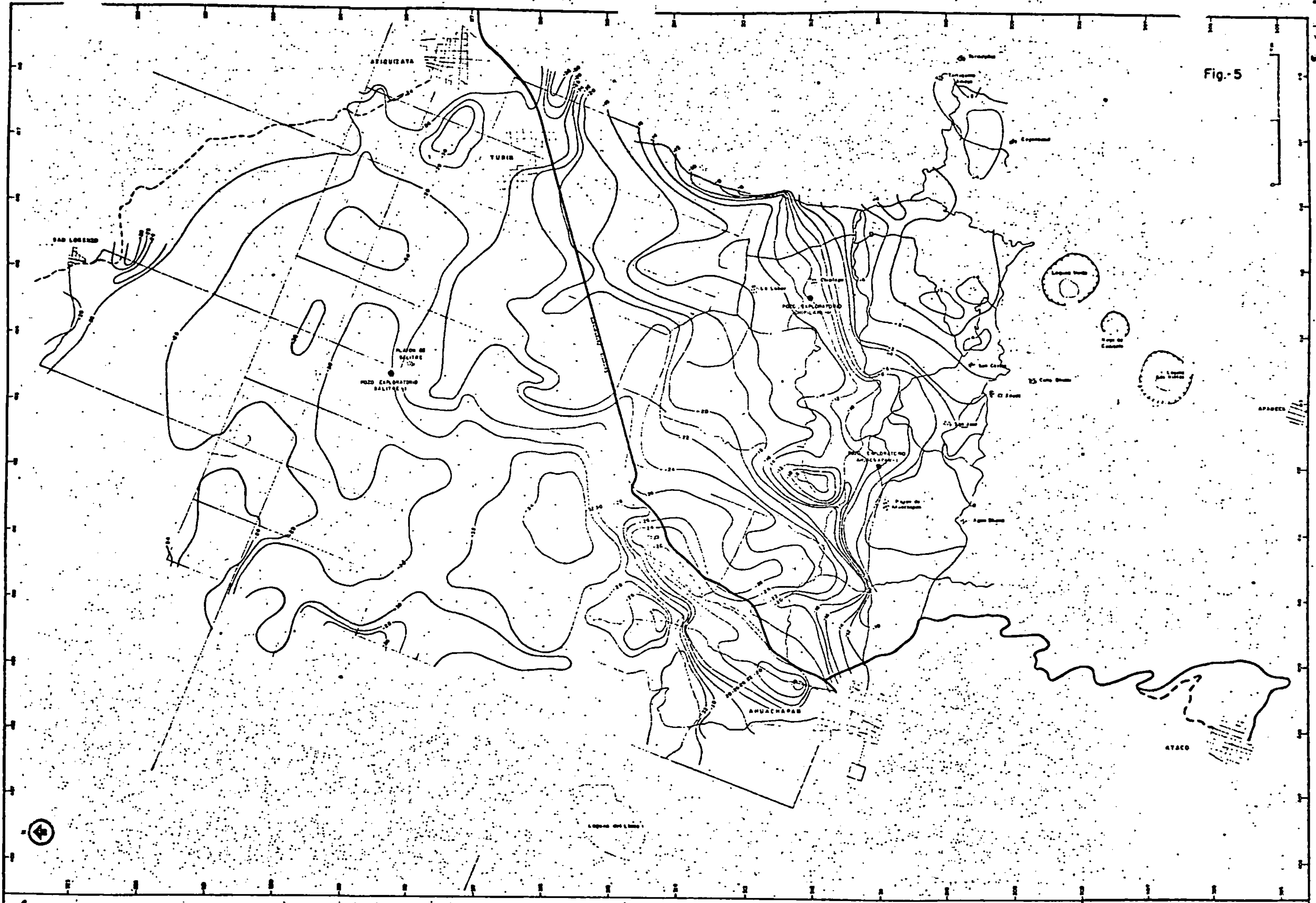
CURVAS DE ISORESISTIVIDAD EN Ω METROS

CEL ONU

ESTUDIOS GEOTERMICOS

LEVANTAMIENTO DE RESISTIVIDAD ELECTRICA

Fig.-5



CEL ONU

ESTUDIOS GEOTERMICOS

AREA DE AHUACHAPAN

LEVANTAMIENTO GRAVIMETRICO

ANOMALIA BOUGUER

DENSIDAD = 2.00

INTERVALO DE CURVAS 2 miligales

SAN SALVADOR	[illegible]	P-23-A-31

CEL - ONU
ESTUDIO DE LOS
RECURSOS GEOTERMICOS
EL SALVADOR

FECHA: 25 NOV. 1968.

Variación de la resistividad del terreno con la temperatura y la porosidad. El contenido de cloruros es asumido constante, y m (factor de cementacion) es tomado igual a 2.2.-

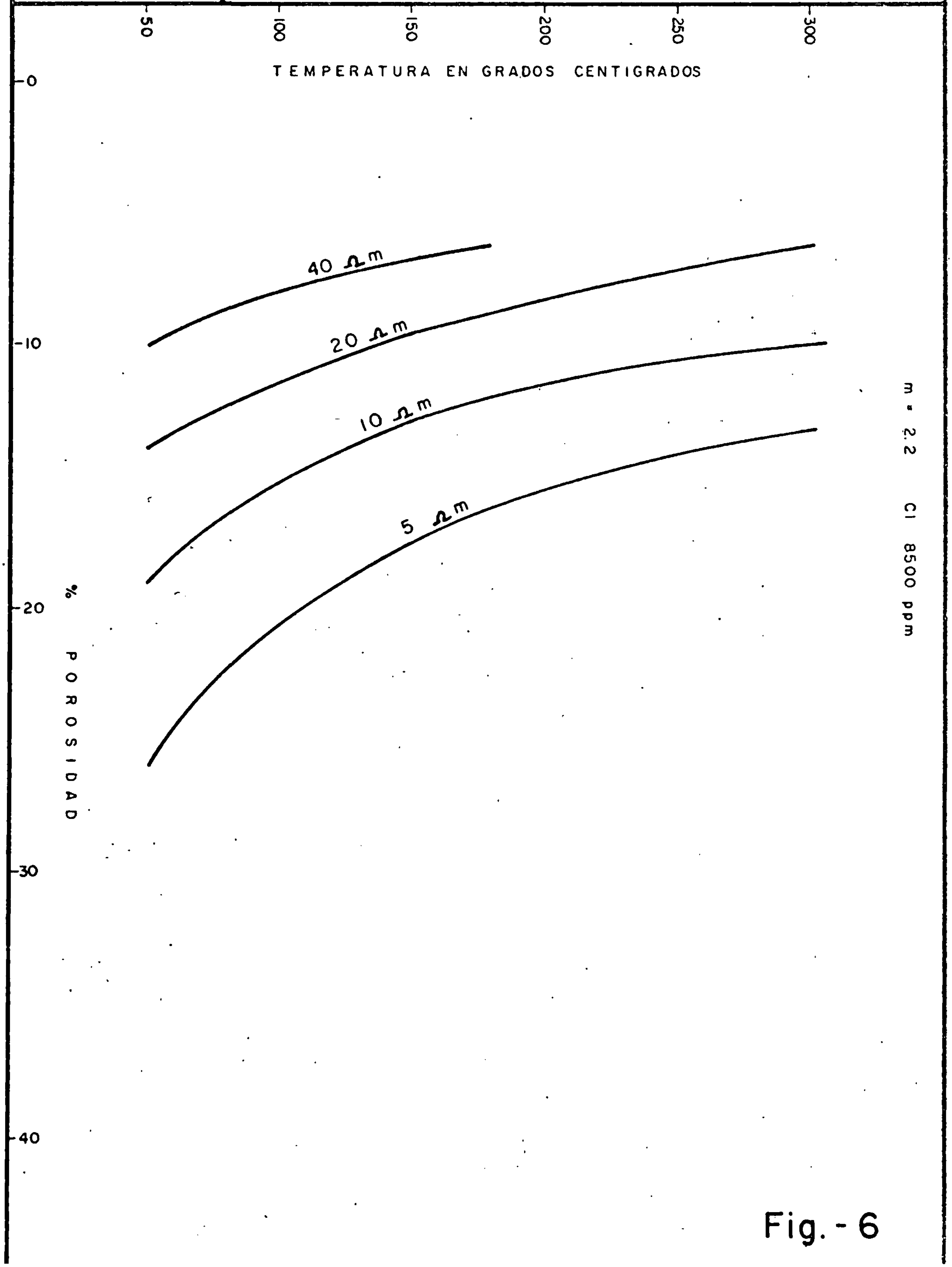


Fig. - 6

CEL - ONU
ESTUDIO DE LOS
RECURSOS GEOTERMICOS
EL SALVADOR

FECHA: Nov. 27-1968

Variación de la resistividad del terreno con la temperatura y la porosidad. El contenido de cloruros es asumido constante, y m (factor de cementacion) es tomado igual a 1.6.

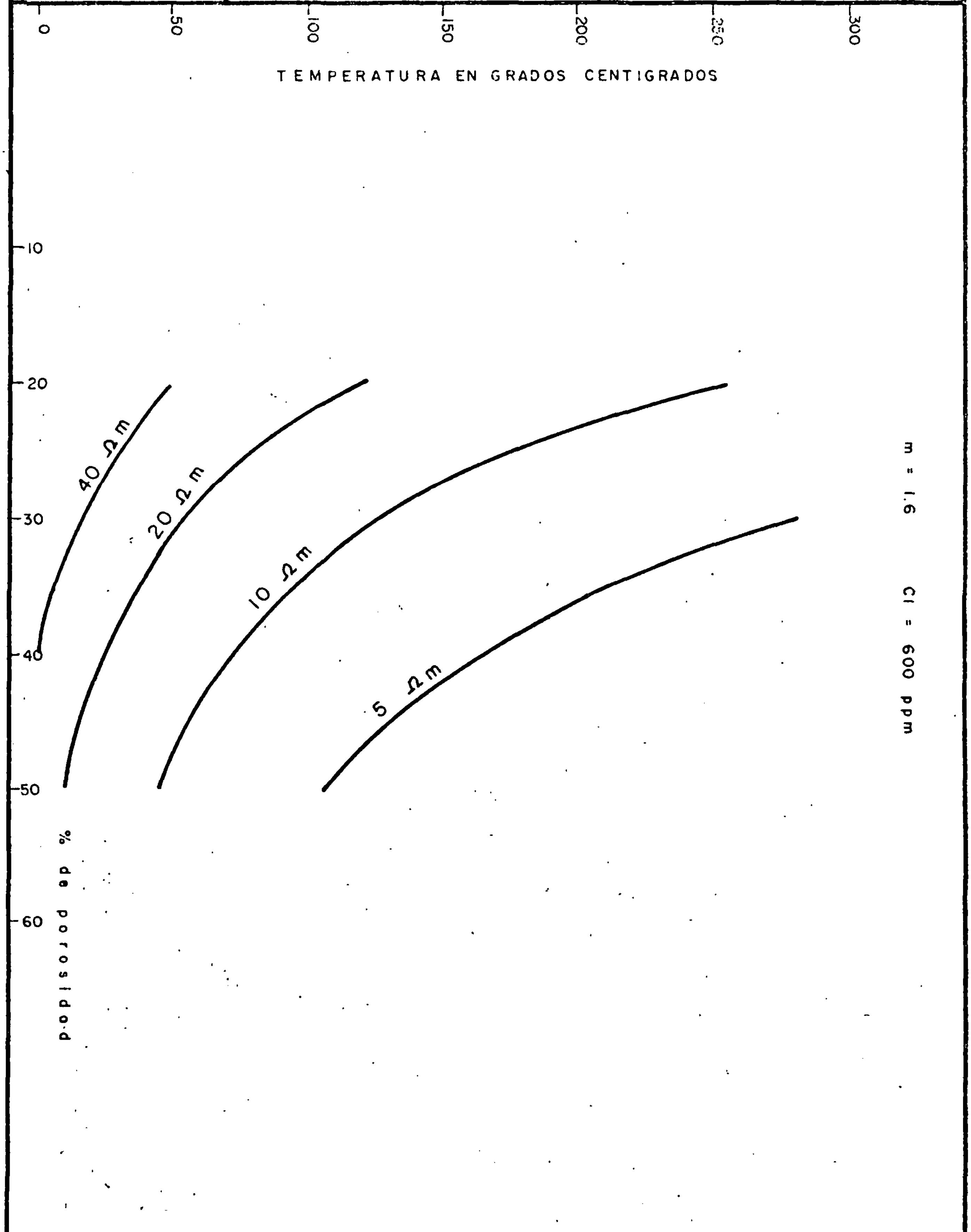


Fig.- 7

LEVANTAMIENTOS GEOFISICOS EN EL AREA GEOTERMAL DE AHUACHAPAN

Por José González G.

ABSTRACT

The results of geophysical surveys in the Ahuachapan area are reported. The following studies are covered: magnetic surveys, geothermal gradient measurements, and surveys of magneticals, geothermals and electric resistivity.

The magnetic and gravimetric measurements were made along a basic grid, which was layed out in the northern part of the area, as well as along roads located in the southern part of the same area. The approximate areal extent of the surveyed area is 200 Km^2. The results provide a general outline of the distribution of magnetic and gravity anomalies.

The magnetic values show the variation of the vertical intensity in the field. These values were measured using a flux-gate magnetometer, and the results are shown in the corresponding map by isogammas. The gravimetric data are shown in the Bouguer anomalies maps.

These gravimetric data were calculated using four different values of density, due to the fact that this information was lacking when the corresponding estimates were made.

A temperature survey was made at 1.5 m depth in the Ausoles area, covering 8 of the 11 existing fields in the southern part of this area. The maps with the isotherms showing the distribution of the temperature level, were prepared with the obtained data.

In order to obtain data regarding the geothermal gradient, 24 wells were drilled taking into account the available geological surveys, and distributed in order to cover the main area. The wells are 100 meters deep with a diameter of NX (3½"). A standard pipe line of 1" Ø was placed to facilitate the temperature measurements.

The measurements of electrical resistivity constitutes the major part of the basic information, which determines the location of the exploratory wells. The continuous profiles have been established along the basic grid and along some roads. Vertical soundings have been made in certain selected places.

The present results give indication of several low resistivity areas with resistivity values below 10 Ω. m. The largest of these areas, including the area around and towards south of the successful Ahuachapán Nº 1 drill hole, is 13.5 Km^2. Assuming that all low resistivity areas within the Ausoles area are interconnected at depth the total area of low resistivity in between 20-30 Km^2.

Suggestions for further work are presented.

1. INTRODUCCION

El presente informe incluye los resultados de los levantamientos geofísicos realizados en el área de Ahuachapán, los cuales comprendieron los siguientes estudios: Magnéticos, Gravimétricos, Geotérmicos y de Resistividad Eléctrica. La aplicación de estos resultados conjuntamente con los datos geológicos y geoquímicos, sirvieron de base para la localización de los sitios de los tres pozos exploratorios que se han perforado a la fecha en dicha área.

Las mediciones tanto magnéticas como gravimétricas se hicieron a lo largo de la cuadrícula básica que se trazó en el sector norte del área y de los caminos que cubren el sector sur de la misma, abarcando una superficie de 200 $Km.^2$ aproximadamente, obteniéndose en esta forma un cuadro general de la distribución de las anomalías características del área.

Los valores magnéticos muestran las variaciones de la intensidad vertical del campo, medidos por medio de un magnetómetro discriminador de flujo (flux-gate magnetometer), y los resultados son mostrados por medio de isogamas en el mapa correspondiente. Los datos gravimétricos aparecen en los mapas de anomalías Bouguer que se calcularon empleando cuatro valores distintos de densidad debido a que se carecía de este dato cuando se efectuaron los cálculos respectivos.

Se hizo un levantamiento de temperatura a 1.5 m. de profundidad en las zonas de los ausoles propiamente dicha, midiéndose 8 de los 11 campos existentes en la parte sur del área. Con los datos obtenidos se elaboraron los mapas con las isotermas mostrando la distribución de la temperatura a dicho nivel.

A fin de obtener los datos relacionados con el gradiente geotérmico, se perforaron 24 pozos distribuidos en forma de cubrir las zonas de interés y en base a los levantamientos geológicos disponibles. Los pozos tienen una profundidad de 100 mts. y un diámetro NX (3½"), habiéndose colocado tubería standard de 1" ∅ para facilitar las mediciones de temperatura.

Las mediciones de resistividad eléctrica constituyen la mayor parte de la información básica que determinó la ubicación de los pozos exploratorios habiéndose corrido en su mayoría perfiles contínuos a lo largo de la cuadrícula básica y de algunos caminos vecinales, así como también sondeos verticales en ciertos lugares escogidos. Sin embargo, es necesario hacer notar que el trabajo está incompleto, tal como se podrá apreciar en el mapa respectivo, y por consiguiente será necesario continuar dichas mediciones para poder contar con la mayor información posible, ya que según los resultados de los primeros pozos exploratorios, por lo menos en lo que respecta a temperatura, se han encontrado los valores predichos según los datos aportados por este método.

Tanto para los sondeos verticales como para los perfiles continuos se empleó inicialmente la configuración Schlumberger pero en julio de 1967 por recomendación del Dr. G. Bodvarsson y a fin de tratar de eliminar el efecto inductivo causado por la configuración mencionada, se cambió al sistema dipolo-dipolo (arreglo polar). Con esta última modalidad se han logrado medir sondeos verticales con expansión máxima de 4 km., que equivalen a 8 y 12 km. en las configuraciones Schlumberger y Wenner respectivamente.

Según las características encontradas en el área, se ha estimado que sería necesario correr perfiles continuos con mediciones cada 250 m. y un espaciamiento entre centros de electrodos, de 1 Km. y 1.5 Km. en ciertas zonas y cubrir detalladamente las áreas de interés, delineando la curva de 5 Ω.m. para la ubicación de los pozos exploratorios futuros.

2. Magnetometría

De acuerdo a la experiencia obtenida en otros países acerca de la aplicación del método magnético en la exploración geotérmica, se dispuso estudiar la factibilidad de su empleo aprovechando la visita que el Sr. G. Pálmason, Geofísico Islandés, hiciera a nuestro Proyecto en marzo de 1966 como experto de Naciones Unidas.

El Sr. Pálmason corrió perfiles en una longitud de 24 km abarcando los Ausoles de Ahuachapán, Agua Shuca, La Labor y parte del campo del Salitre, haciéndose mediciones cada 50 mts. El instrumento empleado fue un magnetómetro Canadiense tipo discriminador de flujo (flux-gate magnetometer), marca J. Sharpe, modelo MF-1 para medir la intensidad vertical del campo, que él trajo de Islandia para probar las posibilidades de aplicación del método.

De acuerdo a los datos obtenidos se encontraron variaciones de la intensidad magnética vertical del orden de las 1000 gamas, además de un decrecimiento gradual de esa intensidad partiendo del Salitre hacia la zona de los Ausoles al sur, decrecimiento que estaba entre las 500 y 600 gamas.

Aparte de los detalles antes mencionados se observaron muchas anomalías negativas en la zona sur de los Ausoles que podrían estar asociadas con la actividad termal característica de dicha zona.

En vista de los resultados obtenidos y según recomendación del Sr. Pálmason se adquirió el magnetómetro canadiense marca McPhar M700 del mismo tipo que el anteriormente mencionado y con una precisión de ± 5 gamas, habiéndose efectuado mediciones cada 50 mts a lo largo de las líneas comprendidas en la cuadrícula básica así como en las demás líneas medidas para proveer el control topográfico que serviría de apoyo para el levantamiento gravimétrico proyectado en el área.

Para controlar la variación diurna se estableció una estación base en un sitio escogido por sus condiciones de aislamiento de influencias perturbadoras, habiéndose comprobado que por lo menos en la época en que se efectuaron las mediciones, se registró un período tranquilo ya que la variación máxima de las lecturas en la base nunca pasó de las 40 gamas y por consiguiente no se aplicó ninguna corrección a las lecturas medidas.

Los datos provenientes de las lecturas en 5000 estaciones aproximadamente, aparecen mostrados en el mapa de isogamas de la variación magnética vertical, Nº P-23-A-45. De acuerdo a dicho mapa se definen las zonas de "bajas" magnéticas en los alrededores de los Ausoles así como también la "alta" en Salitre; se puede notar asimismo las "altas" entre los Ausoles de Ahuachapán y Chipilapa y que corresponderían a las coladas de lava que se encuentran en esa zona, sin embargo llama la atención la "baja" en la cúpula de "San Lázaro" que sería opuesto a lo esperado en dicha cúpula, por lo que se estima necesario conocer el magnetismo remanente para hacer las interpretaciones finales de los datos.

3. Gravimetría

Los primeros trabajos gravimétricos se llevaron a cabo en 1962, consistiendo en la medida de 4 perfiles paralelos de 5 km. de largo a 1 km de distancia entre sí, trazados en sentido normal a la dirección de una supuesta falla en el volcán Salitre, habiéndose utilizado un gravímetro Worden y efectuado las mediciones con un espaciamiento de 50 m; los trabajos los realizó la Dirección General de Cartografía en cooperación con el Servicio Geodésico Interamericano; los perfiles mostraron ciertos rasgos interesantes en las vecindades del volcán Salitre pero desafortunadamente no alcanzaban a cubrir la zona de interés y por consiguiente el trabajo quedó inconcluso.

En vista de estos resultados y ampliando la red antes mencionada se proyectó y ejecutó un levantamiento del área mostrada en los mapas respectivos, con estaciones cada 200 m. Para el control tanto horizontal como vertical se hizo un levantamiento de la zona apoyado en las estaciones de control de la Dirección General de Cartografía, utilizándose teodolitos autoreductores Wild RDS a fin de obtener la precisión necesaria para esta clase de levantamientos. Para las mediciones gravimétricas se empleó el gravímetro Worden Nº 397 con una constante de 0.3710 (3) miligales por división. Se tomó como estación de referencia el Punto "A" (B.M. S-9) de la red nacional medida por el Ing. J. Monges C.

en 1958 y la estación de triangulación "La Capilla" ligada esta última con el punto "A" antes mencionado; para los efectos de control de la "deriva" se estableció una estación intermedia en Atiquizaya.

El número de estaciones medidas llegó a 1100 comprendidas en los circuitos correspondientes a las distintas líneas de la red. Los resultados aparecen mostrados en los mapas Nos. P-23-A-50/53, con las anomalías Bouguer provenientes del empleo de los siguientes valores de densidad: 1.8, 2.0, 2.25 y 2.50 gr/cm^3, ya que en la época en que se hicieron los cálculos no se tenía mayor información acerca de las densidades de las rocas en el área de estudio. Los cálculos de las anomalías se efectuaron por medio de la computadora IBM 1620 de la Dirección General de Cartografía.

El cuadro de anomalías nos presenta ciertos rasgos que podrían interpretarse como indicadores de la distribución de algunas estructuras del subsuelo en la parte sur del campo, que nos servirían para tratar de conocer las condiciones de permeabilidad en esa zona; sin embargo de acuerdo a las recomendaciones del Dr. Bodvarsson sería deseable elaborar otro mapa de anomalías en base de una densidad de 2.7 gr/cm^3 y ampliar el levantamiento para cubrir de 5 a 10 km fuera del área termal con un espaciamiento de 1 km entre estaciones; con relación al valor de 2.7 gr/cm^3 deseo agregar que según comunicación personal del Ing. M. Jiménez, esto coincidiría con los valores encontrados por él en las muestras de rocas de la zona.

Al obtenerse esta información podría completarse el cuadro de anomalías del campo y tratar de conocerse así los rasgos estructurales prominentes con miras del estudio de las características de permeabilidad del reservorio.

4. Gradiente Geotérmico y Mediciones Superficiales de Temperatura

Tomando en consideración la importancia del conocimiento de las condiciones de temperatura en el subsuelo, se proyectó y ejecutó un plan de perforaciones de pozos para mediciones del gradiente geotérmico, utilizando a la vez los datos para correlacionarlos con los levantamientos de resistividad eléctrica; asimismo se llevó a cabo un levantamiento de temperatura superficial en las zonas de los Ausoles propiamente dichos, cubriéndose 8 de los 11 campos existentes en la parte sur del área.

El número de pozos perforados fue de 24 distribuidos en su mayor parte en la parte sur, con una profundidad de 100 m y un diámetro NX ($3^1/2$" ∅). Para las mediciones de temperatura se utilizaron sondas de termistores con dos conductores; los termistores empleados eran de 10000 ohmios de resistencia a 25°C y las lecturas se hicieron ya sea con un puente Wheatstone o bien con el teletermómetro marca Yellow Springs Instrument de lectura directa aplicando la corrección correspondiente a la resistencia empleada; a fin de facilitar la introducida de la sonda, se colocó tubería standard de 1" ø en los pozos, lográndose en esta forma los fines deseados.

La precisión de los valores medidos fue de ± 0.5°C de acuerdo a las pruebas hechas en el laboratorio del Proyecto, y los resultados aparecen mostrados en el mapa P-23-A-40-A-.

En relación a la conductividad calórica, se hicieron unas pruebas en los laboratorios del Bundesanstalt für Bodenforschung en Hannover, República Federal de Alemania; las muestras medidas provenían del pozo Tobar 1 obteniéndose los siguientes resultados:

Profundidad de la muestra	Conductividad calórica
35 m	2.8×10^{-3}(cal/cm./seg/°C)
40 m	3.5×10^{-3}
58 m	4.3×10^{-3}

la tendencia de menores conductividades a menores profundidades podría mostrar una meteorización en el basalto encontrado en dicho pozo.

En vista de la carencia de la información necesaria relativa a todos los pozos, se dispuso calcular el gradiente, utilizando unicamente los valores de temperatura medidos en la superficie y en el fondo, adoptándose un valor promedio de 23°C para el valor en la superficie.

Con el objeto de conocer la distribución de la temperatura superficial en las zonas de los Ausoles, se midió la temperatura en agujeros de 1.5 m de profundidad y 1" Ø. Para cubrir dichas zonas se trazó una cuadrícula con líneas orientadas Norte-Sur, Este-Oeste, separadas a 100 m y con agujeros cada 15 m. En ciertos lugares de interés el espaciamiento entre líneas se redujo a 50 m. Para las mediciones se emplearon sondas con termistores, aseguradas en varillas de madera para facilitar su inserción y debidamente aisladas, empleándose el mismo tipo de teletermómetro antes mencionado.

Los datos obtenidos de estas mediciones aparecen en el mapa P-23-A-81; según puede apreciarse, los ausoles del "Playón" y "La Labor" indican una mayor superficie con temperaturas superiores de 70°C en comparación con el resto de los otros ausoles medidos.

Según los datos mostrados en los dos mapas antes mencionados, las superficies en km^2 de las zonas en la parte sur del campo se resumen en la forma siguiente:

Datos básicos	Superficie en Km^2	
	Min.	Max.
Manifestaciones superficiales	21	30
Gradiente geotérmico:		
Area comprendida por la curva de 40°C/100m	21.5	

5. Resistividad Eléctrica

De acuerdo a la experiencia en otros países, principalmente en Nueva Zelandia, sobre la aplicación del método de resistividad en la exploración geotérmica, se dispuso emplear más intensamente dicho método en los trabajos exploratorios del Proyecto.

Las primeras mediciones se llevaron a cabo en marzo de 1966 bajo la dirección del Sr. G. Pálmason, utilizándose el equipo canadiense J. Sharpe, modelo SP5-R que había sido adquirido previamente por Naciones Unidas. Las pruebas se hicieron en el campo "El Salitre" en las proximidades de las fuentes termales y en los alrededores de "El Limón" en la Hacienda "La Labor". Según esas pruebas se vió claramente desde el principio que el instrumento no era suficientemente capaz de medir los valores relativamente bajos de las resistividades encontradas en dichas zonas termales aún en las capas superficiales, ya que con el tipo de configuración empleada -Wenner- apenas se había logrado una expansión de a = 26m, siendo imposible hacer más lecturas por la incapacidad del instrumento; en vías experimentales se improvisó un arreglo de baterías en serie a fin de aumentar hasta los 540 voltios el voltaje introducido, habiéndose logrado una expansión de a = 144m; sin embargo aún no era posible profundizar los sondeos a los niveles necesarios y por consiguiente se decidió adquirir un equipo que fuera lo suficientemente potente a fin de lograr medir los valores de resistividades bajas que se esperaba encontrar en las áreas termales investigadas y alcanzar las zonas profundas de interés.

En enero de 1967, fueron iniciadas las mediciones empleándose el equipo canadiense McPhar R203 dotado de un generador de 2.5 KVA, un transmisor de 850 voltios, 5 amperios y 0.3 ciclos por segundo, y un receptor con una sensibilidad máxima de 100 microvoltios a escala completa; la precisión del instrumento es del 2%.

De acuerdo a las primeras pruebas efectuadas en "El Salitre" y "Playón de Ahuachapán", bajo la dirección del Dr. O. Kappelmeyer, se decidió correr perfiles continuos con mediciones cada kilómetro o más, según las condiciones del terreno; la configuración empleada fue la Schlumberger con las características siguientes: distancia entre electrodos de corriente, 1 km y 50 m entre los de potencial; además de los perfiles continuos se midieron sondeos verticales en sitios escogidos, siempre con la misma configuración y una expansión máxima de 4 km.

Al examinar las curvas resultantes de los sondeos verticales se notaba en todas ellas un aumento pronunciado (mayor de 45°) en la curva de resistividad a partir de unos pocos centenares de metros (200 m aproximadamente), lo cual excedía los valores teóricos posibles; dicho aumento se manifestaba en todos los sondeos en una forma idéntica tal que hacía sospechar un efecto anómalo que desfiguraba sistemáticamente los valores medidos y que éstos no guardaban relación con los esperados según las condiciones geológicas de la zona. En julio de 1967 aprovechando la visita del Prof. G. Bodvarsson se estudió este problema, haciéndose mediciones no solamente dentro de las áreas termales sino que en las siguientes, fuera de dichas zonas: El Playón (Quezaltepeque), Guazapa y Playa de San Diego (La Libertad), llegándose a opinar que el problema era debido al efecto inductivo originado por el empleo de corriente alterna en el tipo de configuración empleada, habiéndose decidido por esas razones cambiar dicho tipo adoptándose desde entonces la configulación dipolo-dipolo con arreglo polar- para tratar de reducir a un mínimo dicho efecto.

De acuerdo con el Prof. Bodvarsson se hicieron las siguientes consideraciones en relación con los efectos originados por el empleo de corriente alterna en las mediciones: en dichas circunstancias los campos alternantes dan origen tanto a la inducción entre los circuitos de corriente y potencial, así como al llamado "efecto de cubierta" (skin effect), en las mediciones de resistividad los dos campos se suman o sea que los efectos inductivos aumentan la resistividad aparente, tal como quedó comprobado con los resultados de las mediciones experimentales llevadas a cabo en las áreas antes mencionadas; la proporción entre la fuerza electromotriz inducida y el campo conductor dependen tanto del tipo de configuración como de la profundidad en que se nota el "efecto de cubierta" y por consiguiente se considera que para poder reducir a un mínimo dicha influencia perturbadora es preferible usar la configuración dipolo-dipolo, ya que tanto la Schlumberger como la Wenner son las que presentan menores posibilidades para emplearse con corriente alterna aún con una frecuencia muy baja como en el presente caso.

Según las condiciones encontradas en las zonas termales se dispuso correr los nuevos perfiles con las siguientes características: 1 Km. entre centros de pares de electrodos y 500 m. entre electrodos tanto de corriente como de potencial.

Al regresar de mi viaje de estudios y poner en práctica las técnicas neozelandesas, se han iniciado corridas de nuevos perfiles siempre con la configuración dipolar pero con mediciones cada 250 m. y además en vías de experimentación se ha aumentado a 1.5 Km. la distancia entre centros de pares de electrodos para obtener mayor penetración; sin embargo, como se puede observar claramente en el mapa, las mediciones están incompletas, debiendo cubrirse el campo de La Labor y toda la parte sur del área para definir los límites de ella, así como en el sector oriente de la misma.

Además de los perfiles corridos a lo largo de algunos caminos, se hizo un levantamiento especial en "San Raimundo" para la localización del pozo "Salitre-I", trazándose 3 líneas paralelas separadas a 250 m y con un largo de 3.5 Km cada una, las mediciones se hicieron cada 250 m tal como aparece en el mapa mencionado; además se midieron 2 sondeos verticales en la carretera Santa Ana-Ahuachapán (Km 85-95) con una expansión máxima de 4 Km., lo cual equivaldría teóricamente a 8 y 12 Km en las configuraciones Schlumberger y Wenner respectivamente.

Debido a que tal como se indicó anteriormente el método de resistividad es el que practicamente sirvió de base para la localización de los sitios de los pozos exploratorios, dejaré para la parte final de este informe los comentarios respectivos, a fin de tratar más ampliamente los distintos aspectos encontrados al correlacionar las mediciones de resistividad con los datos obtenidos de los tres pozos exploratorios perforados hasta la fecha.

6. Discusión de los Resultados

En relación a los levantamientos magnéticos y gravimétricos, tal como se expuso en los capítulos correspondientes, puede decirse que han aportado datos interesantes aunque en una forma menos decisiva y concluyente comparados con los levantamientos de resistividad que son los que han constituido básicamente la casi totalidad de la información utilizada para la selección de los sitios de pozos.

Tal como ha sido aceptado por los resultados obtenidos en otros campos termales de diversos países del mundo, los dos parámetros fundamentales para un campo termal los constituyen la temperatura y la permeabilidad. En relación a la primera, y en el caso nuestro de reservorios con agua a altas temperaturas y un gran contenido de cloruros, el método de resistividad nos da una valiosa información acerca de las condiciones de temperatura en el subsuelo.

Al examinar el mapa de resistividades se pueden observar varias zonas "bajas" de extensión apreciable, destacándose la del "Salitre", sin embargo, al tomar en cuenta los datos provenientes de los pozos de gradiente, podemos diferenciar dos áreas que aunque sus resistividades son numéricamente iguales son producidas por condiciones distintas, tales serían "Salitre" en la parte norte y las zonas de los Ausoles en la parte sur.

Esto coincidiría con la opinión del Dr. G. Facca, de que la "baja" en "Salitre" sería interpretada como producida por un acuífero somero con alta permeabilidad y un sistema convectivo, en cambio las "bajas" en Playón y Agua Shuca no podrían interpretarse en forma similar ya que las condiciones hidrológicas y litológicas son completamente distintas a las del Salitre, por consiguiente unicamente en estas últimas "bajas" se encontrarían temperaturas altas.

Las razones anteriores fueron las que básicamente decidieron la ubicación de los dos primeros pozos: Ahuachapán-I y Chipilapa-I, cuando se seleccionaron en mayo de 1967.

A fines de mayo de 1968, se llevó a cabo el levantamiento de resistividad en la Hacienda "San Raimundo" que se describió anteriormente habiéndose ubicado en base a dicho levantamiento el pozo "Salitre-I" para comprobar la validez o no de la interpretación anterior.

Los resultados de los dos primeros pozos comprobaron plenamente la alta temperatura esperada y asimismo el último, las condiciones que se presumían en el acuífero somero.

Según los análisis químicos de las muestras obtenidas en los pozos Ahuachapán-I y Chipilapa-I, las aguas contienen una alta cantidad de cloruros: 8500 ppm y por consiguiente este detalle ha sido tomado en consideración para los cálculos de las curvas que se han elaborado para obtener la variación respecto a la temperatura, porosidad y resistividad según la fórmula de Archie y los valores tomados de International Critical Tables; según los cálculos que se han hecho, se adoptó un valor de m=2.2, tomando en consideración las condiciones indicadas por las muestras de los pozos mencionados y la temperatura medida en los mismos.

Para "El Salitre" el factor de cementación se calculó igual a 1.6, considerando un contenido de Cl = 600 p.p.m. (datos de las fuentes superficiales) y una temperatura de 80°C; sin embargo es necesario hacer notar que si aceptamos el valor de porosidad de 15% (según los datos del Ing. M. Jiménez), vemos que sería imposible obtener las resistividades medidas en dicha zona, y por consiguiente tendríamos que considerar la posibilidad de tener a mayor profundidad una cantidad mucho más elevada de cloruros para poder cumplir con la fórmula antes mencionada, ya que de la temperatura -el otro parámetro- no hay indicaciones de poderse obtener valores mayores en dicha zona.

De acuerdo a estos primeros resultados sería necesario llevar a cabo los siguientes levantamientos geofísicos: Mediciones detalladas de resistividad en la parte sur del área de Los Ausoles para definir las zonas de 5 a 10 Ω.m. así como los límites de la parte oriental del área y con igual detalle el campo La Labor-Chipilapa. Además se necesita calcular las anomalías Bouguer empleando una densidad de 2.7 y extender el levantamiento gravimétrico fuera del área termal hasta una distancia de 5 ó 10 Km.

Para detalles específicos deberán estudiarse los informes de los señores Consultores de Naciones Unidas: Profesores A. E. Beck y G. Bodvarsson, Doctores S. Bjornsson, G. Facca, O. Kappelmeyer, W. J. P. Macdonald, G. Pálmason y D. White.

La numeración de los planos mencionados en el orden correspondiente en este informe coincide respectivamente con las figuras Nos. 1, 2, 3, 4, 5, 6, 7 y 8.

Deseo expresar mi sincero agradecimiento al Sr. D.G. Fallen Bailey, así como también a los señores expertos de Naciones Unidas que con sus enseñanzas y sugerencias hicieron posibles los levantamientos mencionados.

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GEOTHERMAL DRILLING IN EL SALVADOR

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SUMMARY

In the course of this work a general description is given of how geothermal studies have been carried out in El Salvador, by means of surface and deep drilling until reaching the production phase in which we presently find ourselves. The most important technical problems faced in trying to reach the proposed objectives, by making use of the different types of drilling that have been done, and the goals reached in each one of them are examined.

INDEX

Section I

INTRODUCTION

The development of geothermal drilling in El Salvador dates from they year 1956, the date on which the preliminary drilling was started. Generally the drilling method has been rotary, which is also commonly used in other fields where subsurface explorations are done.

The drilling process, started with 11 preliminary sample wells (195601959) in different locations in the Ahuachapan area, which are examined in the first part of this report. Later geothermal gradient drilling (196601967), continuous samples (196801976), and deep drilling (1968-1976) are the object of analysis. The work has a chronological order that also gives the procedures for carrying out the required investigations.

Some shallow sample drilling has been done in other thermal areas, Ahuachapan as well as in the eastern part of the country.

After several years of activity, profiting from the continual development of drilling techniques and accumulated experience, a significant improvement has been achieved that has had notable repercussions in the area of economics and principally in understanding the geology and hydrology of the Ahuachapan geothermal field presently under exploitation. This improvement is mainly evidenced in the siting and completion of the wells drilled continuously for approximately only 2 years which presently make available more than 30 MW.

This knowledge also permits the solution of residual water problems that for the moment have been overcome by drilling reinjection wells.

From the start of these studies, up to the present, 99 wells with different geothermal purposes have been drilled. The main purpose of this report is to provide a general, technical description of the most characteristic features of the drilling methods used:

a) objective
b) technical information
    -geology
    -mechanics
c) results

There are immediate future plans for expansion of the geothermal drilling in the Chipilapa area near Ahuachapan and in the eastern part of the country.

Section 2

GEOTHERMAL DRILLING METHOD

2.1 Exploratory drilling

This label identifies the different smalldiameter and slightly deep drilling that in the course of the exploratory stage of geothermal fields have been developed and that, for your better understanding, have been separated according to their objective.

2.1.1 Preliminary drilling

Objective

In the period between 1956 and 1959 there were 11 exploratory holes drilled in the proximity of the thermal manifestations of Agua Shuca (3 wells), Playon de Ahuachapan (4 wells), with depths that went from 32 to 373 mts, which are shown in Figure 1; and Playon de Salitre (4 wells) all in the Ahuachapan area. The drilling carried out in those areas had a prospective character and it was the start of the endogenous knowledge of the country. Among its purposes was establishing the feasibility of capturing steam by intercepting known faults, and the geological-hydrological study of the subsoil.

Geology

The preparation of the lithological profiles was more feasible in the Playon de Ahuachapan area due to the greater recovery of cores which was very limited at Salitre and Agua Shuca. This situation, mainly resulted from the problems with the formations found in the area in which the outstanding characteristics could be given as: the alteration of rocks as a result of steam faults (Playon de Ahuachapan); kaolinization in sands, clays, and andesites; and intense mineral sedimentation consisting of pyrite, calcite and silica.

A special characteristic of the drilling at Playon de Ahuachapan was its definite purpose of verifying at depth the tectonic steam fault that causes the surface manifestations, which was intercepted by all the drilling in this area (Bearing N18°W). Outside of the problems encountered, we succeeded in getting valuable information in regards to temperature, stratigraphy, cavernous connections found with surface manifestations adjacent to the wells, caloric current, horizons of underground water, etc. with the best results from the Playon de ahuachapan field which is presently the steam producer.

Mechanical Process

All the drilling was done by continuous samples with the arrangements listed in the following general plan (depending on depth):

Ø Drilling	Ø Tubing
6-5/8"	6"
6" (5-1/2, 4-1/2)	NX (3")
BX 2-3/8"	BX (2-7/8")
AX 1-15/16"	AX (2-1/4")
EX 1-1/2"	EX (1-13/16")

There were two types of equipment used in this drilling: for the deep, Chicago Pneumatic diamond drill#8 with hydraulic feed; while for the shallow drilling, Christensen drills with screw feed were employed.

It could be said that the problems encountered in the mechanical area result from the slow rate of progress in drilling techniques in general, as well as from designing a test for this work and becoming acquainted with a new field.

As a result we found as the most important technical problems:

a) the impossibility of constructing raises because of high surface temperatures

b) the installation of a control valve, in the drilling column after the start of the initial drilling in order to prevent floods of steam or hot water

c) master valve, used instead of the preventative ones normally employed at the present

d) the use of pure water as a drilling fluid which created the additional problem of causing high temperatures in the tool, making it impossible to drill efficiently.

e) incomplete displacements in the cementations which eventually caused separation of the tubing within the well, and mainly developed from the lack of means for a rapid pumping of the cement, providing the opportunity for the intercalation of air pockets or water within the cementation column; lack of efficient and previous washings from the well in order not to contaminate the cement and reduced annular space for the cementation

f) inaccurate knowledge about the characteristics of the formations, especially the hydrothermal alteration, that were penetrated which had a major impact on the drilling - making it much more difficult

Results

The drillings that were carried out permitted:

1) initiating a study of the zone with the best prospects for potential exploitation (Playon de Ahuachapan) and that at the moment is the source for all the geothermal power used in El Salvador

2) correlating as far as possible the litho-stratigraphy that was encountered with the stratigraphy from the geological survey of the Ahuachapan area (which can be seen on page 13) for possible application in later drilling

3) confirming steam faults (NNW) and providing additional information about the fracturing of the formations, which has served as the basis for later studies.

2.1.2 Gradient drilling

Objective

Beginning in 1967 drilling at 100 depth was planned in the country, in conjunction with CEL and the Special Fund of the United Nations, in order to measure geothermal gradient, which is generally anomalous in the volcanic zones and to an even greater degree in volcanic geothermal areas. The drilling was distributed in the areas of Ahuachapan (24), Berlin (7), Chinameca (3), and in Santa Rosa de Lima (4).

Geology

The recovery of drilling cuttings was only partial, due to the fact that the purpose of the drilling was not specifically for obtaining geological information but was primarily for measurement of the geothermal gradient.

The drilling was designed to be done with bits, using water as the drilling fluid. There were constant losses of circulation.

Due to the geological conditions present in the area where these drillings were done, themeasurement of the gradient and its interpretation were problematic; this was because of the effect of the underground water across permeable volcanic deposits that covered the surface of the areas in question.

On the basis of the maximum temperatures measured up to 100 m depth in the Ahuachapan area, a map of isotherms (Fig. 2) has been prepared where, as one can observe, there are two interesting areas of geothermal structures located to the east of the city of Ahuachapan. In the first of these, known as the Ahuachapan area (Playon de Ahuachapan) exploitation of endogenous energy with a production capacity greater than 60 MW is being carried out at the present time; to the NE of the first, the Chipilapa area stands out, which presently is subject to exploration by means of test wells (±500 m deep) and where temperatures of 205°C at 400 m have been found. It is very possible in the Chipilapa area, that in the immediate future deep exploratory drilling will be carried out for the purpose of trapping subsoil steam.

Mechanical process

The drillings were done with a diameter of 3", placing at the time of completion 1" casing (galvanized) down to the bottom, through which the temperatures were measured.

Superficially, and as a protection for the holes, 4" diameter lining was installed (galvanized down to 3 meters depth).

The drilling processes at these depths were satisfactory. They were done by contracts with private firms, generally utilizing Long Year compact equipment which is easily installed even in places with difficult access.

Results

As was explained earlier, although these drillings were designed to measure the geothermal gradient, the results in this regard were not absolutely positive.

For the measurement of the geothermal gradient, it is considered essential to have the presence of an almost impermeable stratum, more or less uniform. With regards to the temperatures measured down to 100 m depth, these have been interesting factors in the individualization of thermal structures.

2.1.3 Continuous sample drillings

Objective

After the analysis of the results from the gradient drillings done in the country, the decision was tken to plan another type of drilling, with multiple purposes, including, of course, the measurement of geothermal gradient. This type of drilling has already been carried out in the area of Los Toles, Ahuachapan, and the Chipilapa area. Its purpose is to supply information on the following features:

-stratigraphic succession

-hydrological measurements (hydrostatic levels of different aquifers and permeability tests)

-measurements of temperature and pressure

-physical determinations like porosity and ensity of the cores

-production test when it is possible

The maximum depths reach up to the present are 451 mts in the Chipilapa area (Well Ch-E-1) with a minimum diameter of 3-7/8"

Geology

Between November/75 and June/76 two continuous sample wells (core) were drilled in the Los Toles area, to the west of the Ahuachapan area, down to a 400 m depth.

The two wells in question (TR-1 and TR-3) were located from the stratigraphic point of view in the "young agglomerates" series, they intercepted the indicated series, later the Ahuachapan andesites (largely fractured) and partially penetrated the tertiary agglomerates. Beginning with the interception of the andesites an aquifer emerged (cropped out) which had pressures up to 40 psi, discharging hot water with a small percentage of steam.

The maximum temperatures measured were 115°C. The definitive production tests will be carried out shortly.

Between June and August of this year, a continuous sample well was drilled in the Chipilapa area (Ch-E-1) to a depth of 400 mts. The lithological profile (see Fig. 3) shows a series of volcanic deposits, slightly similar to the one in the Ahuachapan area; it differs from the latter in the greater predominance of agglomerated tufa and agglomerates on the flows of andesite lavas. At 298 meters total losses of circulation persisted and the maximum temperature without stabilization was 205°C

The geological, hydrogeological and geothermal conditions in this zone, as evidenced in the Ch-E-1 well, are very encouraging, and for the moment it was decided to drill more deeply with the same system, to 500-600 meters; this process is currently being completed. The recovery of cores from these formations has been totally efficient.

Other wells (4) with a similar process, were drilled to complement the deep drilling in the Ahuachapan field under exploitation, towards the North and East of the same. The maximum depths were 300 meters, actually working as a piezometer.

-Mechanical method (process)

The continuous sample wells were drilled with TECKNO and Long Year rotary equipment; the first of these, with an incorporated tower and proper traction, has been efficiently used in the latest drilling.

In the chart shown below the completion corresponding to the recently drilled wells is given:

Ø Drilling (inches)	Ø Tubing (inches)
3½, 3; (8½, 9-9/8)	6-5/8
5-5/8	4
3 (3-7/8)	2 (grooved)

Generally drilling has been done with water. When technical problems have presented themselves, as for example in the instability of the walls of the well, bentonitic fluid with low viscosity and weight was used. When the elevated pressure prevented the normal execution of the drilling process (Los Toles) heavy mud with a baryta based was used.

All the wells finally drilled were equipped with blowout preventers similar to those in the deep wells. The depth of the pipe casing was generally determined in accordance with the characteristics of the intercepted rocks.

Results

Up to now, continuous sample drilling has been considered the most direct, efficient, system for multipurpose studies of the subsoil. The information, when correctly collected, means a considerable advance in the exploration programs.

2.2 Deep drilling

2.2.1 Exploration-production deep drilling

These were begun in 1968 after completing and evaluating in a generalized form the different studies (geological, geohysical, geochemical, shallow drilling, etc.) in the Ahuachapan and Berlin areas. This drilling, unlike the preceding, was done with larger diameters and at greater depths

Objective

The purpose of this drilling was to study the geology, hydrology chemism and temperatures at depths down to 1500 meters, as well as the feasibility of trapping available steam for generation of power in Ahuachapan as well as in the eastern part of the country.

Geology

The geological-tectonic layout, obtained from the surveys carried out previously in the Ahuachapan area, showed promising geothermal characteristics. The deep exploratory drilling, located in advantageous sites, from the geomineral point of view, made possible the direct testing of the geological and hydrogeological conditions in the structures that could store thermal fluids.

Ultimately, the geological data from the first wells drilled in the Ahuachapan area (CH-1, Ah-1, and Ah-9) were efficiently made use of and they formed the basic technical elements for geothermal development in the Ahuachapan area. The drilling cuts, systematically recovered, were prope ly identified by means of macroscopic analysis (binocular magnifying glass) and microscope (polarizing microscope), preparing the corresponding lithological profiles, through which it was possible to preliminarly determine the thicknesses of the formations that make up the surface volcanic cover, the neighboring impermeable horizons and those that definitely make up the principal reservoir of the field.

Some characteristics of the intercepted rocks, specifically the fracturing or jointing of the surface andesitic lavas create problems for the progress of the drilling by causing total losses of the drilling fluid. On the other hand, in the deep part of some wells permeability of the basal andesitic lavas was evident, getting the first productions of geothermal steam.

Outside of the important geological data determined in the course of the drillings, it was also possible to do continuous readings of temperature and pressure needed to supplement the geothermal evaluation.

The measurement of the hydrostatic levels, controlled during the course of the drilling, helped with correlation of those levels already established for the saturated underground horizon and defined the levels of the deep aquifer at pressure.

The systematic collection of samples (cuts) and the implementation of the "Geolograph" (penetration graph) in the drilling equipment, always helped with the completion of the lithological profiles of the wells. In some of them, the information obtained was incomplete due to the constant losses in circulation and the difficulty of stopping them. Below the zone of total deep losses, cores have been obtained approximately every 100 meters, which has been an indispensable factor in the exploration of the characteristics of the rocks of the reservoir and the pliocenic substratum.

With these first deep drillings, the following was completely defined:

-the characteristics of the surface volcanic deposits in order to decide on the placement of the anchoring pipe
-the young agglomerate-andesite contact zone of the reservoir in order to select the location for the production pipe
-the physical, petrographic characteristics and thicknesses of the young agglomerates, the determining formation of the geothermal field due to its confining function
-the petrographic conditions of permeability and thicknesses of the andesitic rocks of the reservoir
-the tertiary contact and the characteristics of the underlying rocks
-the production capacity of the deep aquifer

Mechanical process

Very little data with regard to the important problems or features observed during the drilling of these wells has been saved. In general, the progress with respect to the appropriate treatment for some of the problems, such as the losses in circulation, was little advanced; as a consequence, cement plugs were frequently used in small losses and the drill mud was even used in zones where presently it is normal to drill with water.

The arrangements used are, in part, very similar to those of present-day production or reinjection wells. Some variable characteristics were, in the first wells, the more superficial placement of the anchoring and production pipe (Ah-1= 23 m, Ch-1 = 28 m, Lempa-1 = 30 m, and Tronador = 65m) which seems logical if your consider the little knowledge of the geological situation at depth and the exploratory purposes of the wells in question, although some of them were producers. Current problems for the advance of exploratory drilling are the presence of shallow flows of andesitic lavas in most of them. Their fracturing and density causes total losses of circulation which is difficult to stop and low penetration. The technical designs for the objectives carried out during this stage of drilling are shown in the following chart:

Ø Drilling (inches)	Ø Casing (inches)
17½	13-3/8
12¼	9-5/8
8-3/4	7-5/8 (7")
6-1/4	

2.2.2 Deep production drill holes

Objective

These drill holeshave had essentially the same purpose of trapping steam originating from the andesitic formations which make up the principal reservoir of the Ahuachapan geothermal field; potentially available for the generationof electrical energy, with depths that vary between 600-900 meters depending upon the thickness of the producing stratum and, in addition, studying temperatures and pressures in the drillhole, chemistry of fluids, and flow characteristics.

Geology

The location of the production wells depended, on the one hand, on the geothermal structure evidenced by geomineral surface investigations and test holes. Also, the results of exploratory deep drilling done previously, which in this stage provide real values about the characteristics of the reservoir (permeability, temperatures, etc.) have been determining factors. The production drill holes support the information on the stratigraphy of the Ahuachapan area which is summarized in the following chart:

STRATIGRAPHY OF THE AHUACHPAN AREA

FORMATION	GEOLOGICAL CHARACTERISTICS	DEPTH IN METERS	GEOTHERMAL CHARACTERISTICS
Surface	Tufas, pumice, blocks, fractured andesitic lavas	0-250	No importance. Surface geothermal manifestations emerge.
Intermediate	Cohesive agglomerates, porous, fairly altered	250-450	Make up a seal (cap-rock) ideal because of their thickness and low permeability
Reservoir	Andesitic lavas, dense, fractured, sometimes with breccia.	450-800	Make a powerful reservoir
Depth	Massive, dense agglomerates, slightly fractured interbedded with lavatic lens	800-1500 or more	Behavior of impermeable substratum. Could be producing in isolated cases.

The final planned depth has been the object of lengthy study. At first wells were drilled to a depth of 150 meters within the andesitic reservoir. Later the criterion were varied, due to the heterogenousness of the formation with respect to permeability and at the present time the wells go down to the contact with the old agglomerates (tertiary), with depths of about 850 mts. Aften v rious years of deep drilling in El Salvador (600-1500 mts) XXX with ends of geothermal production testing has been done that can be summarized as follows:

-The collection of crushed samples (cuts) is best every 5 meters

-The cutting of cores (sample) every100-150 meters in the productive zone is essential

-The use of a geolograph (penetration recorder) is of primordial importance for the lithological determinations
-The wells should be drilled to the andesitic formation before installing the tubing
-The preparation of the lithological profile should be considred as a basic factor in the termination of the wells and should be carried out as efficiently as possible
-

There isn't any doubt that the drilling of production wells has provided sufficient and incalculably useful geological information, which without a doubt has had repercussions for the geothermal advances of the county.

In figure 4, the roof of the andesitic formation through which the saline aquifer that supplies the geothermal center of Ahuachapan circulates, is shown. In the figure one can observe similar conditions in many wells and the particulars of the volcanic deposits.

Mechanical process

In the course of these drillings, two drilling companies have participated (Loffland Brothers and Foramines, S.A.) with a participation of 30% and 70%, respectively and in chronological order. Therefore, the most important technical data are closely related to the characteristics of the equipment used (Ideco and Fred Cooper TD42010, respectively).

Drilling preparations

The preliminary preparations used for the start of the drilling can be summarized in this way:

- the location based on an interpolation-extrapolation between wells drilled previously or from some geotectonic sequence
- predicted lithological succession
- final projected depth
- constructed raise, which allows:
  - access for installation of B.O.P. andmud conductor pipe
  - drainage of residual fluids
  - installation of the head, which appears in the schematic drawing in Fig. 5.
  - an underground discharge by means of a 2" Ø outlet to a site at a distance from the well
- drilling programs and well design

In order to define the criterion followed for this purpose, one will start by giving the functions that the casing generally have in our field:

1) surface casing (anchor). placed and cemented at approximately 100 meters depth. It is designed to prevent the contamination of surface aquifers, to give security to the drilling operations, and the head assembly.

2) Intermediate or production. Installed and cemented to 400-600 meters depth. Its purpose is to protect the unstable walls principally plastic formations (young agglomerates), to prevent contaminations of the saturated regional aquifer or the influence of this on the deep aquifer and conducting the production flow to the surface.

3) Pipes in the production zone. In some cases the installation of blind and/or grooved, uncemented pipe has bee n necessary, generally in order to protect the well from slipping. These pipes were installed by means of hangers placed some 10-20 meters within the intermediate casing or tubing and their depth depended on the conditions in the producing zone.

On the basis of the given operations the following principal criterion have been adopted for the preparation of the piping program:

a) the final depth. The depth and number of pipes depends on this in part.

b) the nature of the formations that are expected to be encountered.

c) location of the shoes. An important criterion that refers to the placement of pipes on dense formations for the purpose of assuring optimal cementations

d) economic factor. The greater the drilling diameter and pipe, the greater the increment in the costs, which is reflected in the following:

-larger quantity of mud in order to raise the cuttings, which increases the cost of additives and the capacity required from the pumps

-slower drilling

-the cost of materials like pipe, drills, etc.

The drill program as well as its specifications are prepared on the basis of:

-the pipe program
-types of formations that are expected to be encountered
-the approximate depths

On the following page is a chart with the systems of completions carried out at Ahuachapan.

Test program

The test and special operations that have been foreseen can be summarized as follows:

a) pressure tests for the cementations, pipe, and head solderings
b) readings of deviations approximately every 100 mts down to the depth of the intermediate casing
c) taking of samples
d) permeability tests
e) readings of hydrostatic levels

Completion System and Pipe Specifications

System	Ø Drillholes (inches)	Ø Casing (inches)	Specifications
a	26	20	94 lbs/ft, API, E-40 (or K-55). Round thread
	17½	13-3/8	
	12¼	10-3/4	-40 lbs/ft, Range 3 trapezoidal thread. -API 5L, Grade 2 ASTM-A120, round thread.
		9-5/8	
b	17½	13-3/8	-54.5-61 lbs/ft, API, K-55, Range 3, trapezoidal thread -48 lbs/ft, API, P-40, Range 3, round thread
	12¼	9-5/8	-36.40 lbs/ft, API, K-55, Range 3, trapezoidal thread -36 lbs/ft, API, J-55, Range 3, round thread
	8½	7-5/8	26.4 lbs/foot, API J-55, Range 3, Hydril FJ-P thread
		7	23 lb/ft, API, H-40, Range 2, round thread

With respect to the required specifications, in the course of the drilling some changes were made that were considered advisable:

-casing with trapezoidal thread ("buttress"). In consideration of the greater efficiency of these compres ion joints, compared with the round thread (77% versus 49% for 13-3/8" pipe), the latter was used only in the first two producing wells, changing to butress pipe in the later ones, whenever possible

-valves. The use of standard gate valves was changed because of problems with leaks to "through conduit" valves, in spite of the greater cost.

-pipes in the production zone. "J Slots" have been used and ultimately double casing slip hangers for threaded pipe on which the upper casing slip was removed prior to their insertion in the well in order to facilitate the later extraction of the pipe, if it should benecessary

Drilling operations

A notable characteristic in the drilling of the majority of the wells has been the high instances of hardness and difficulty in drilling the first 100 mts due to the eluvial formations on the surface, the more or less unbroken flow of lava, and the low weight of the drilling column by inch of diameter of the available drill.

This has given the equipment an excessive vibration that any lighter equipment would not be capable of overcoming. The approximate feed has been 0.5 to 1.5 mts/hour.

The drilling for the 9-5/8 (12-1/4) casing has generally been more rapid, with an increment in the weight leading to feeds of 2 to 4 mts/hour, except in occassional lava flows. The downhole drilling of the production pipe has shown considerable variations and is considered as the productive zone. These variations belong more than anything to the characterisitcs of hydrothermal alteration in some cases, fracturings in others, density of the rocks in others. Nevertheless, the rate of penetration has been up to 5 mts/hour, except in some wells that have only reached 2.5 mts/hour.

The average total time to drill the different diameters has varied with the contractors, but in general it decreased, going from 25 to 30 days in the completions for the first wells to 2 or 3 months in the later ones.

The drilling technique with water in zones with total losses of circulation (production zone) has been established in all of the drilling successfully, with the occassional use of mud in order to lift out cuts from the bottom of the hole toward the fractured formations, a technique that is econimically justified.

Circulation losses

This is one of the problems that has always presented itself in the drilling of geothermal fields.

The most serious problem has occurred in drilling for 9-5/8 (approx. 500 mts). Many attempts were made in the first drillings to seal these losses with cement plugs; nevertheless, only a temporary sealing was accomplished which disappearred upon drilling the plugs in question. Based on this experience, plugging materials like coffee bark, nuts, rice, etc. added to the benitonic mud were successfully used for partial losses while cement was used only when there wasn't any success with the plugging materials or for total losses, which is a practice used up to the present.

A balance has been achieved between the excessive costs and the need for a good return during the cementations. Aldo, due to the limitation of cores, maintaining the circulation and the recovery of cuttings provide the only means for identifying the penetrated formations. Nevertheless, the danger of instability in the formations always exists when drilling with water; the use of mud stoppers to clean the hole of any slump or accumulation of cuttings, makes possible drilling without difficulty. It is necessary to take some precautions and look out for possible accumulations of cuttings.

Drill mud

During the drilling process, many of the original problems due to lackof materials and test equipment have been overcome.

The main additives used for the loosening of fresh (sweet) bentonite water have been:

1) bentonite: local up to the cementation of the anchor pipe.
   USA up to the total losses of the productive zone
2) lignosulfate
3) caustic soda
4) baryta
5) ASh soda
6) CMC
7) plugs: coffee bark, rice chaff, etc.

The basic philosophy in the manufacture of the mud has been to provide the simplest and most economical mud that would make possible drilling a well in the shortest time possible with a nimimum of problems, which has been more or less fairly well accomplished, even though lacking some results on some properties of the mud (real viscosity, filtration, etc.)

In the first drillings, chemical agents that produced a partially viscous fluid were used, increasing the viscosity with the concentration, but they proved to be unstable with the temperature becoming an aqueous fluid after approximately 36 hours.

Large concentrations were useful for sealing some circulation losses, but they proved to be excessively costly.

The normal drill mud used subsequently was a fluid with low to medium viscosity (30-33 centipoises) with a small solid content, made up of Wyoming Bentonite and water. Caustic soda has always been used to thicken the fluid, increase the pH and reduce the water losses.

CMC was originally used, rather infrequently, in order to increase the viscosity and control the fluid losses. At present it use has been suspended.

Diesel oil has not been used as an additive for the mud in order to reduce fluid losses, but has been used to facilitate doing the complicated cementations.

Due to the low availability of Wyoming bentonite (USA) it was necessary to use lower quality Guatemalan bentonite in non-critical zones (called "local" in this report).

For a few years, materials (1), (2), (3), (5), and (7) have been elements used primarily in the mud, keeping on the average the following characteristics:

-specific gravity: 1.03-1.08
-"fannel" viscosity: 38-40 seconds
-gel: reduced to zero prior to the cementations
-temperatures: 50-70°C (maximum)
-low solid content, by desanding and no use of baryta

The temperatures of the mud in the bottom have not generally exceeded 100°C. This has made possible the utilization of the mud with little altered properties. Nevertheless, the extreme salinity of the thermal water has sometimes affected the properties of the mud, making it necessary to treat it with means of the addition of chromium lignosulphonates; which are also used as stable thinners under temperature. The low hydrostatic level of the deep aquifer has only one advantage, which is the entrance of saline waters into the hole are difficult during the drilling operations.

The characteristics of the equipment, such as the drill weight on the drill and RPM have had generally low values, limited by the capacity of the equipment and, in some cases, by the formations. Average values oscillate between 4 to 6 tons and 50 to 70 rpm, respectively, reaching an average feed of 0,5 - 1 m/h down to apprxoimately 100 mts and 1.5-2.5 m/h in the rest, with maximum values up to 7 m/h in zones with small thickness.

Operations for cementation of casing

The necessity of getting a complete return of the cement through an annular space to the surface has always been one of the main aims in order to insure successful cementations.

In the majority of the wells, the cementation of the 13-3/8" casing has been satisfactory. Some problems have been enountered initially in trying to maintain uniformity in the cementation operations, originating in part from hardened fractures of the cement, causing delays. Nevertheless, the final results are considered satisfactory.

The cementation of the 9-5/8" casing has presented generally major problems due to the continuous losses in circulation which necessitate doing supplementary cementations. This experience has led to the practice of using a quantity of cement in excess of the theoretical calculation (200-400%) in order to overcome the known loss zone and to supplement it with a subsequent filling or cementation from the surface to the annular space. The cementation processes, when losses occur, indicate theneed for a pumping, sufficiently high, in order to fill the annular space completely down to the zones or losses or above these; also they necessitate lateral pumpings at gradually increasing intervals, for the purpose of permitting the partial setting of the cement. When these processes have taken place, the complete cementation has taken about 28 hours (against 3 hours approximately in normal cementations) but finally success has been achieved.

The use of the additional percentage, sufficient to assure the return to the surface for any reason, is one way of guaranteeing no formation of water pockets within the cement column (in cementations completely by gravity or pumping from the surface) which can have effects on expansions with the temperature and cause collapses in the pipe or damages to a more or less satisfacoty cementation.

The cementation operations are always susceptible to circulation losses due to the greater hydrostatic pressure of a cement column (specific gravity 1.8) as compared with that of a mud drilling column even though larger. The ideal solution seems to be the use of a lightweight cement with perlite, for example; but this normally can only be done when there are service companies available for mix and effective pumping.

A test program, in order to determine the ideal proportions and additives necessary in order to guarantee the use of local Portland cement, under the proper conditions has not been carried out. Nevertheless, in the latest drillings, the local cement seems to have been giving satisfactory results. Imported cements mixed with 39% silica floud and retarders have been designed for a setting time of 3 hours at approximately 212°C which doesn't correspond with our conditions and were used in only the first cementations.

The compression tests in cylinders taken during the cementation of wells Ah-5, Ah-6, Ah-7, after 7 and 28 days of setting, show low values (92-174 kg/cm2) for the imported cement; besides, this was found soft after 16 hours for which reason the later cementations used this cement with a ratio of 1:2 or 1:4 (imported:local)

In order to adapt to local conditions, additives like 1% Wyoming Bentonite and Hallybruton Retarder HR 4 were used as additives only when the return temperatures exceeded 40°C with a concentration of 0.2% to 0.4% per cement weight.

For some time the cementations have been totally carried out with local cement, utilizing a special Hallyburton pump in order to insure a better mix and rapid pumping of the cement.

There has been a limit to the number of additives that could be added and dispersed due to the limitations of space and lack of guarantee of a complete mix. The additives for the cementations most commonly employed have been: Retarder HR 4 and calcium chloride as an accelerator of cement setting.

Explosions

Compared with other geothermal fields where high temperatures offen appear at the surface and the wells remain under pressure, the Ahuachapan fields have shown few problems in this regard (T 70°C during the drilling) for the low hydrostatic levels as well as for the relatively cold, upper formations. Nevertheless, the price of installing and testing of B.O.P. has always been maintained.

On ocassions, the floods of gases, whose escape has not produced greater problems, have caused explosions. Only in a few wells, have frequent explosions been faced and which have always been controled by closure of the BOP on the drilling pipe and the injection of cold water, without having caused any damage to personnel or equipment.

READINGS

Deviation

One has maintained the practice of carrying out readings of variations in the wells by means of "Tocto", approximately every 100 mts of depth down to the zone in which drilling is done with mud, which approximately coincides with 400-500 mts. When such variations have consistently shown up, the use of cement plugs has always been a favorable solution or modifying the drilling techniques (psb, rpm) in small ways.

The values obtained in some wells can be seen in the table that follows (representative for the rest of the wells); showing the maximum deviation and the corrections in those cases where later readings were taken

WELL	MAXIMUM DEVIATION IN HEXAGONAL DEGREES	DEPTH (mts)
Ah-21	1-3/4	472.5
Ah-22	2	348.5
	1-3/4	482
Ah-24	7-1/2	344.21
	3	430
Ah-25	3	285
	3/4	338
Ah-29	2	226.5
	0	550
Ah-17	1/2	449.26

Injection tests

These tests have been carried out in the productive zone a little before the completion of the drilling of the well.

They consisted of pumping into the wells increasing fixed flows between 0-50 lts/sec and measuring the fluctuations in pressure by means of percolation, located at a fixed depth within the hydrostatic column of the well. Generally, drilling equipment pumps have been utilized.

It must be pointed out that the interpretation of this data doesn't directly give the permeability value of the well but, since both parameters (permeability-injectibility) come from the fracturing characteristics of the formations of the wells, it is possible through these tests and their respective index to anticipate the production characteristics of the well.

An example that illustrates the recorded data and their processing in order to determine the injectibility index is seen in Fig. 6

Hydrostatic levels

In the course of the drilling and in the case of major losses, measurements of the hydrostatic level were done by means of float systems. The purpose is to detect variations in the horizons of underground water that would contribute to the hydrological understanding of the field and to foresee some problems in drilling.

Samples

As has already been indicated, this is some of the main information that in conjunction with the geological criterion were taken at definite depths for lithostratigraphic tests. The samples or cores are presently done with a diamond drill bit 5-5/8", drilling 4-5 mts; the recoveries are variable but in the producing wells are maintained above 50%.

The frequent taking of samples from the productive zone for the understanding of the characteristics of the rocks from the roof of the reservoir has always been considered important. The taking of cores should be done only when there is an important need, due to the high costs, risks in these unstable zones, and because of the precautions that should be taken before proceeding to drill them.

Drilling program for a well

For the purpose of showing more clearly the aims of a drilling program in a well, see Annex No. 1 which is representative of the latest programs. Also, in Fig. No. 7 one can see the drilling characteristics that have been described previously, applied in Ah-26 as a typical example.

Results

Based on the experience gained and made use of by the experts that have participated in the development of geothermal drilling in El Salvador, it is believed that deep drilling for the definite purpose of trapping available steam for the generation of elecgric energy requires the support of a geological understanding prior to the drilling and an efficient supervision of the mechanical process during the drilling; without leaving room forerror in these two respects. A strict coordination and collaboration between both disciplinesis completely esential.

About the general results obtained, one cold summarize them as follows: 14 wells for production have been drilled of which 8 have proven successful; 2 with predictible success due to the temperature and pressure conditions (Ah-24 and Ah-25); 1 well utilizable only for observation (Ah-3); one that has high pressures and restricted production (Ah-13); and 2 wells (Ah-2 and Ah-8) that due to their location are used for reinjection (see the following table)

Of the 10 wells considred successful, 7 of them have been drilled according to the (b) system of completion and 3 wells (Ah-4, Ah-20 and Ah-21) according to the (a) system (see table, page 17 and Annex No. 2). The 8 producing wells and Ah-1 of the exploration-production classification, maintain a capacity of 69 MW presently feeding 2 units with a nominal capacity of 30 MW each.

Elesewhere operations in previously drilled wells have had to be done inorder to improve by means of deepening the production characteristics. These operations have always proved more difficult than a normal drilling and have led to doing complicated repairs (Ah-24), elevating the costs considerably; nevertheless, the success achieved (Ah-21) has compensated for the problems.

The following table is a summary of the objectives with which each one of the deep wells were drilled.

TABLE OF DISTRIBUTION OF DEEP WELLS ACCORDING TO THEIR OBJECTIVE

Exploration-Production	Boundaries of field	Production	Reinjection
CH-1	Ah-11	Ah-2 V	Ah-17
Ah-1	Ah-12	Ah-3	Ah-29
Tronador 1	Ah-14	Ah-4	
Lempa 1	Ah-15	Ah-5	
Salitre 1	Ah-16##	Ah-6	
Ah-9		Ah-7	
Ah-10#		Ah-8V	
		Ah-13	
		Ah-20	
		Ah-21	
		Ah-22	
		Ah-24	
		Ah-25	
		Ah-26	

#Exploration-Reinjection

##Productive

V Presently reinjection

Total wells

Exploration-production	7
Boundaries of field	5
Production	14
Reinjection	2

Deep reinjection drilling

Purpose

These have been done with the aim of injecting residual water, originating from the producing wells in the zone of the Ahuachapan andesitic bed or within the old agglomerates (approx. 800-1200 mts) in depth). The reinjection at these depths has as its purpose reducing the possibility of interference with the producing aquifer by cooling.

The drilling carried out with the indicated purpose of reinjection has in reality been planned as "double purpose" drilling (production-reinjection), while the other wells (Ah-2 and Ah-8) were drilled with the purpose of production and due to the disfavorable results and their marginal location at the field, reinjection was done; solving in this way the difficulties in the generation of geo-thermoelectric energy.

Geology

With respect to geological and hydrogeological conditions, two basic factors represent the specific difference between production and reinjection double purpose wells:

-the location of the latter in the environs of the exploitation zone in order to avoid possible interaction. T is aim has been emphasized more as of late.

-the final depth for these wells (approx. 1200 m) conforms with the decision to go beyond the thickness of the andesitic reservoir (approx. 800 mts) and to go sufficiently underneath in order to assure the reinjection of the greater part of the residual water in the old agglomerates thus allowing a greater amount of time for heating of the fluid before reaching the upper stratum.

Mechanical process

There aren't any important differences between the process for drilling reinjection wells (double purpose) except for the completion, which tends to insulate the producing formation with blind pipe. In the reinjection wells (Ah-17 and Ah-29), 7-5/8" casing has been installed, hung until reaching the roof of the old agglomerates. In the producing wells, it is a question of the casing functioning as protection for the unstable formations, covering in the least way possible the productive zone (see Annex 2 on well completion)

It can be easily understood that the head installation in reinjection (double purpose) wells, should use the same specifications as those for the producing wells, although these aren't as vital in the producing as the reinjection wells.

The other specifications for the mechanical process are similar to those mentioned in the section on production drilling.

Results

With these drillings it has been possible to begin an economic decompensation stage after little more than a year of geothermoelectric generation. In conjunction with the generation,studies were done in order to understand the possible effects. Two reinjection wells have been drilled with completion corresponding to the "b" system (see page 17) and two production wells (completion system "a") - both sets successful; in addition, the recent deepening of one of them (Ah-2) has been carried out in order to try to improve its characteristics as a reinjector.

Other wells previously drilled for delimitation of the field are also possible reinjectors.

The estimated costs for a double purpose well (reinjection-production) at a depth of 1200 meters is $450,000 of which 55% is for drilling operations and 45% for materials. The drilling of a production well of approximately 800 mts. means about 75% of the above-mentioned cost.

Conclusions

According to the results successively examined in the different parts of this report, the drilling operations carried out from the start of exploration until the phase of steam production have been important to geothermal advances in El Salvador.

The sample drillings are considered totally necessary in the preliminary stages for direct verification of petrographic characteristics, hydrogeological and thermal properties of the subsoil. Their siting depends more than anything on the specific purposes of the study.

Continuous sample drillings, which can reach depths down to 600-800 mts, without major problems, efficiently controlled, are good for multiple studies. Their cost is around $40,000 per 400 mts well which is not onerous considering the value of the basic information that they supply. Future explorations will have a better foundation if this type of drilling is done first.

In the Ahuachapan and Chipilapa areas, continuous sample wells with depths of 300-450 meters have been drilled and in the latter area exploration will go down to 600 mts. In the geothermal zones in the eastern part of the country drilling for geological, hydrogeological and geophysical prospecting is being planned.

-Deep drilling, done with maximum diameters of 26" and generally with 17½", have reached their objectives in our country and especially in Ahuachapan, where they have been utilized as means of deep exploration, production and reinjection.

Normally the termination (completion) have not presented special problems. Isolated cases (Ah-24) of rupture of casing and special cementations were handled efficiently

The producing wells have depths averaging 800 m in order to totally intercept the andesitic reservoir in which ~~it is~~ were planned, to leave the formation totally open and only in special cases to put in grooved pipe if the stability conditions merit it. This latter it was decided to get a final depth with specific tests to this purpose

The reinjection or double wells were drilled at the present time up to 1200 meters in depth penetrating approximately 400 mts within the old agglomerates, leaving conveniently insulated the andesitic formation up to the proximity with the aglommeratic contact

Basic condition for the successes achieved in the drilling of the wells has been especially the technical, mechanical-geological cooperation.

Annex 3 summarizes all the drilling processes carried out in the country and that have been described in this work.

DRILLING PROGRAM FOR A WELL

Objective: To drill with 8½" a production-reinjection well to a depth of approximately 1200 m

Data: Coordinates of the raise:

Latitude: 311.096.39

Longitude: 412.516.53

Elevation: 794.75 m

Casing: 13-3/8" O.D. x 54.5? lb. X 55, Range 3, API round thread up to approximately 85 m

9-5/8" O.D. x 36 lb, K-55, Range 3, API ITC thread up to approximately 500 m

7-5/8" O.D. x 26.4 lb, K-55, Range 3, ? up to 800 m, grooved up to 1000 m

Centralizers: Centralizers for pipe of 13-3/8" will be placed in the first pipe on the casing shoe and every 25 m

For casing of 9-5/8" they will be placed in the first casing on the shoe and every 5 pipes up to the 13-3/8" pipe

Pressure test:

1) solder the head of 13-3/8" and to test with 70 kg/cm2 for 15 minutes

2) A pressure test of the pipe will be done with 50 kg/cm2 for 15 minutes

Drill Mud: The circulation of mud should be maintained while it is econimically justified based on the opinion of the supervisor. The quality of the mud will be advised during the work process but "gel" should be diminished to zero before running the casing

Losses of circulation: All the partial losses of circulation should be sealed with plugging materials. Cement mixed with coffee bark will be utilized when total loss is encountered.

Cementation of the casing: All casing will be completely cemented according to the program that will be suitably prepared.

Verticality: A record of dip will be taken every 100 mts drilled or in the changes of drill that are considered necessary

Geology: Lithological succession that is expected to be found:

0-240 m	Intercalation of lava flows with pyroclastics and tuffs
240-550 m	Young agglomerates
550-750 m	Basal andesitics
750	Old agglomerates

Samples: Samples will be taken at the depth indicated by the geologist

Program:

1) Drill with 17-1/2" up to approximately 85 m and run 13-3/8" casing to approximately 85m and cement the same

2) After 15 hours, cut the 13-3/8" pip, weld the 13-3/8" head; test it with 70/kg/cm2 and install B.O.P

3) Drill with 12-1/4" Ø to apprxoimately 500 m, runn 9-5/8" O.D. casing and cement the same. Do a pressure test of the pipe with 50 kg/cm2.

4) Continue drilling with 8-1/2" Ø and "jets" to 100 m below the total loss. The minimum depth of the well should be 1000 m and the maximum 1200 m

5) Take special care at all times to note all the falls of the wall or pipe traps

6) From the 9-5/8" O.D. casing shoe one should drill with an 8-1/2" Ø bit and "Jets" in order to try and open the fractures of the well. In total losses, drill with water. Occassionally mud could be used with previous authorization from the supervisor

7) When all the data has been collected, according to (5), it can be decided if it is necessary to install a "liner" or not.

8) Proceed to wash the well with closed B.O.P.

9) Mobilization

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SIMPOSIO INTERNACIONAL SOBRE LA ENERGIA GEOTERMICA EN AMERICA LATINA

Ciudad de Guatemala

PERFORACIONES GEOTERMICAS EN EL SALVADOR

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El Salvador

Octubre de 1976.

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RESUMEN

En el transcurso de este trabajo se hace una descripción general de como se encausaron las investigaciones geotermales en El Salvador, por medio de perforaciones superficiales y profundas, hasta lograr la fase de producción en que actualmente nos encontramos. Se examinan los problemas técnicos más importantes afrontados para lograr los objetivos propuestos aprovechando los diferentes tipos de perforaciones realizadas y las metas alcanzadas en cada una de ellas.

INDICE

SECCION 1

INTRODUCCION

El desarollo de perforaciones geotermales en El Salvador data desde el año 1956, fecha en que se iniciaron las denominadas en este trabajo, perforaciones preliminares. Generalmente el método de perforación ha sido rotativo, que también es común a otros campos donde se realizan exploraciones del subsuelo.
El proceso de perforación, comenzó con 11 pozos de investigación preliminar (1956-1959) en diferentes ubicaciones del área de Ahuachapán, los cuales se examinan en la primera fase de este trabajo; posteriormente, son objeto de análisis las perforaciones de gradiente geotérmico (1966-1967), testigo contínuo (1968-1976) y perforaciones profundas (1968-1976) obedeciendo a una secuencia cronológica que al mismo tiempo pone de manifiesto la respuesta a los requerimientos de la investigación.

Han sido realizadas también algunas perforaciones de investigación de poca profundidad en otras áreas termales tanto en Ahuachapán, como en el Oriente del país.

Después de varios años de actividades, aprovechando el contínuo desarrollo de las técnicas de perforación y la experiencia acumulada, se ha logrado una significativa superación, que ha repercutido notablemente en lo económico y principalmente, en el conocimiento geológico e hidrológico del campo geotérmico de Ahuachapán, actualmente en explotación, lo cual se manifiesta evidentemente en la ubicación y terminación de los pozos perforados continuamente desde hace solamente unos 2 años aproximadamente y que permiten la disponibilidad de más de 30MW en la actualidad.
Este conocimiento permite también, la solución de problemas del agua residual, que al presente ha sido superado con la perforación de pozos de reinyección.

Desde el inicio de las investigaciones, hasta el presente, se han perforado 99 pozos con fines geotermales diversos. El propósito esencial de este trabajo, se dirige a proporcionar una descripción técnica general en los aspectos más característicos de los procesos de perforación efectuados:

.../

a) Objetivo

b) Información técnica

  - Geología
  - Mecánica

c) Resultados

Existen planes futuros inmediatos de expansión geotérmica, en el área de Chipilapa, próxima a la de Ahuachapán y la parte de Oriente del país donde perforaciones geotérmicas serán programados.

SECCION 2

PROCESO DE PERFORACIONES GEOTERMALES

2.1 Perforaciones de investigación

Con esta denominación se identifican las diferentes perforaciones de pequeño diámetro y poco profundas que en el curso de la etapa exploratoria de los campos geotérmicos del país han sido desarrolladas y que, para su mayor comprensión, han sido separadas según su objetivo.

2.1.1 Perforaciones preliminares

- Objetivo

En el período comprendido entre 1956 y 1959 fueron perforados 11 agujeros de investigación con profundidades que van de los 32 a los 373 mts., en proximidad de las manifestaciones termales de Agua Shuca (3 pozos), Playón de Ahuachapán (4 pozos), que están mostrados en la figura 1, y Playón de Salitre (4 pozos), todos en el Departamento de Ahuachapán. Las perforaciones efectuadas en las 3 áreas mencionadas, tuvieron carácter prospectivo y fué el inicio de los conocimientos endógenos en el país. Entre sus propósitos estaba, el de establecer la factibilidad de captar vapor interceptando fallas conocidas, y la investigación geológica-hidrológica del subsuelo.

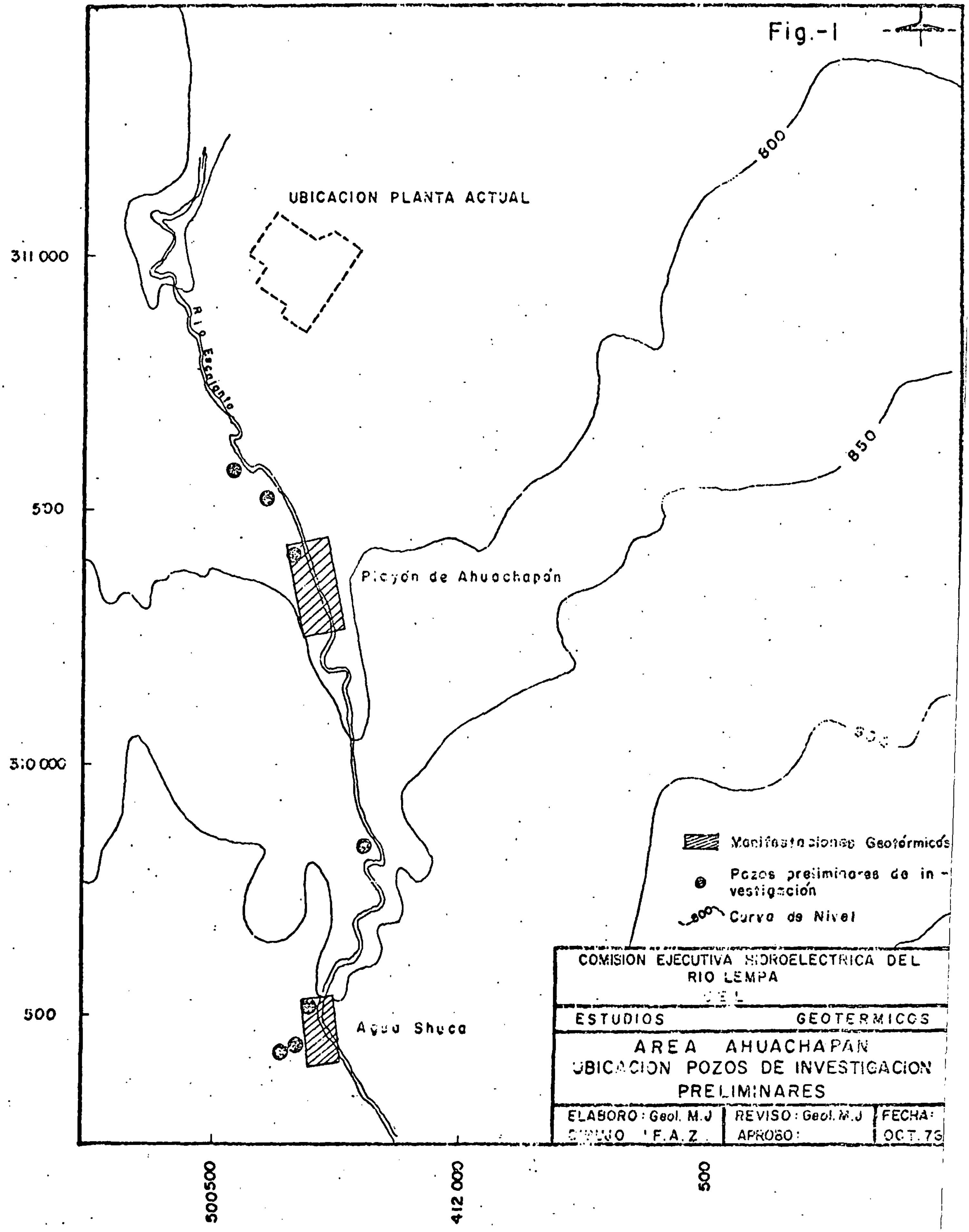
- Geología

La preparación de los perfiles litológicos fué más factible en el área Playón de Ahuachapán por la mayor recuperación de núcleos, la cual fué muy limitada en Salitre y Agua Shuca. Esta situación, dependió grandemente de los problemas de las formaciones encontradas, en las cuales se pudo apreciar como características sobresalientes: La alteración de las rocas por efectos de fallas vaporíferas (Playón de Ahuachapán); la caolinización en arenas, arcillas y andesitas; la intensa depositación mineral consistente en Pirita, Calcita y Sílice.

Característica especial para las perforaciones en Playón de Ahuachapán, fué su propósito definido de comprobar en profundidad la falla tectónica vaporífera que origina las manifestaciones superficiales, la cual fué interceptada por todas las perforaciones en esta área.(Rumbo N18°W). Fuera de los problemas encontrados, se logró la obtención de informa-

....../

Fig.-1



COMISION EJECUTIVA HIDROELECTRICA DEL RIO LEMPA

CEL

ESTUDIOS GEOTERMICOS

AREA AHUACHAPAN
UBICACION POZOS DE INVESTIGACION PRELIMINARES

ELABORO: Geol. M.J	REVISO: Geol. M.J	FECHA:
DIBUJO: F.A.Z.	APROBO:	OCT. 75

ción valiosa respecto a temperaturas, estratigrafía, conexión de las cavernizaciones encontradas con manifestaciones superficiales adyacentes a los pozos, corriente calórica, horizontes de agua subterránea, etc.. obteniendo los mejores resultados en el campo Playón de Ahuachapán que es actualmente el productor de vapor.

- Proceso mecánico

Todas las perforaciones se hicieron a testigo contínuo con completamientos comprendidos en el siguiente esquema general (dependiendo de su profundidad):

Ø Perforación "	Ø Entubamiento "
6 5/8"	6"
6" (5½, 4½)	NX (3")
NX 3"	BX (2 7/8")
BX 2 3/8"	AX (2¼")
AX 1 15/16"	EX (1 13/16")
EX 1½"	

Los equipos empleados en estas perforaciones fueron de 2 tipos: para las profundas, perforadora a diamante Chicago-Pneumatic # 8 con avance hidráulico; mientras para las perforaciones someras, se usaron máquinas de tipo Cristensen con avance de tornillo.

Los problemas encontrados en el aspecto mecánico puede decirse que provinieron, tanto del bajo grado de avance de las técnicas de perforación en general, como del hecho de estar construyendo una experiencia en este trabajo y conociendo un campo nuevo.

Así encontramos, como problemas técnicos más importantes:

a) Imposibilidad de construir contrapozos por las altas temperaturas superficiales.

b) Instalación de válvula de control, en la columna de perforación, después del inicio de las primeras perforaciones para prevenir venidas de vapor o agua caliente.

c) Válvula maestra, sustituyendo a los preventores usados normalmente en la actualidad.

d) Uso de agua pura como fluído de perforación que llevó al problema adicional de encontrar temperaturas altas en la herramienta, impo-

..../

sibilitando maniobrarlas con eficiencia.

e) Desplazamientos incompletos en las cementaciones que originaron eventualmente separación de los entubamientos dentro del pozo, lo cual provino en gran medida de la falta de medios para un bombeo rápido del cemento, dando posibilidad a la intercalación de bolsas de aire o agua dentro de la columna de cementación, falta de lavados previos y eficientes del pozo para no contaminar el cemento y reducido espacio anular para la cementación.

f) El conocimiento impreciso de las características de las formaciones penetradas que influyen grandemente en la perforación haciendola más difícil, especialmente la alteración hidrotermal.

Resultados

Las perforaciones efectuadas permitieron:

1) Iniciar el conocimiento de la zona de mayor perspectiva para un aprovechamiento potencial (Playón de Ahuachapán) y que al presente constituye la fuente de toda la generación geotérmica que El Salvador aprovecha.
2) Correlacionar hasta donde fué posible la lito-estratigrafía encontrada con la estratigrafía proveniente del levantamiento geológico del área de Ahuachapán (la cual puede verse en pag. 13) para su posible aplicación en las perforaciones posteriores.
3) Confirmar fallas vaporíferas (NNW) y proporcionar información adicional sobre el fracturamiento de las formaciones, que ha servido de base para estudios posteriores.

2.1.2 Perforaciones de gradiente

-Objetivo

A partir de 1967 fueron programadas en el país, según el Proyecto conjunto de CEL y el Fondo Especial de las Naciones Unidas, perforaciones de 100 mts. de profundidad para mediciones del gradiente geotérmico, que generalmente en las zonas volcánicas es anómalo y, en mayor grado, en áreas geotérmicas volcánicas. Las perforaciones fueron distribuidas en las áreas de Ahuachapán (24),Berlín (7), Chinameca (3) y en Santa Rosa de Lima (4).

...../

-Geología

La recuperación de recortes de perforación fué parcial, debido a que los propósitos de las perforaciones no fueron específicamente para obtener información geológica, sino mas que todo para medición del gradiente geotérmico.

Las perforaciones fueron programadas a realizarse con barrena, utilizando agua como fluído de perforación. Hubo constantes pérdidas de circulación.

De acuerdo a las condiciones geológicas presentes en las áreas donde se realizaron estas perforaciones, la medición del gradiente o su interpretación resultó problemática, por la influencia del agua subterránea através de depósitos volcánicos permeables que cubren superficialmente las áreas mencionadas.

Ha sido elaborado en base a las temperaturas máximas medidas hasta 100 m. de profundidad, en el área de Ahuachapán, un mapa de isotermas (Fig. 2), donde como puede observarse se evidencian 2 áreas interesantes de la estructura geotérmica localizada al Este de la ciudad de Ahuachapán. En la primera de ellas, conocida como área de Ahuachapán (Playón de Ahuachapán) se realiza al presente, explotación de energía endógena con capacidad de producción mayor de 60 MW; al NE. de la 1ª se destaca el área de Chipilapa, que actualmente está sujeta a exploración por medio de pozos de investigación (± 500 m. de profundidad) y donde se han encontrado temperaturas de 205°C a 400 mts. Muy posiblemente en el área de Chipilapa, se realicen en un futuro inmediato, perforaciones profundas exploratorias con fines de captar vapor del subsuelo.

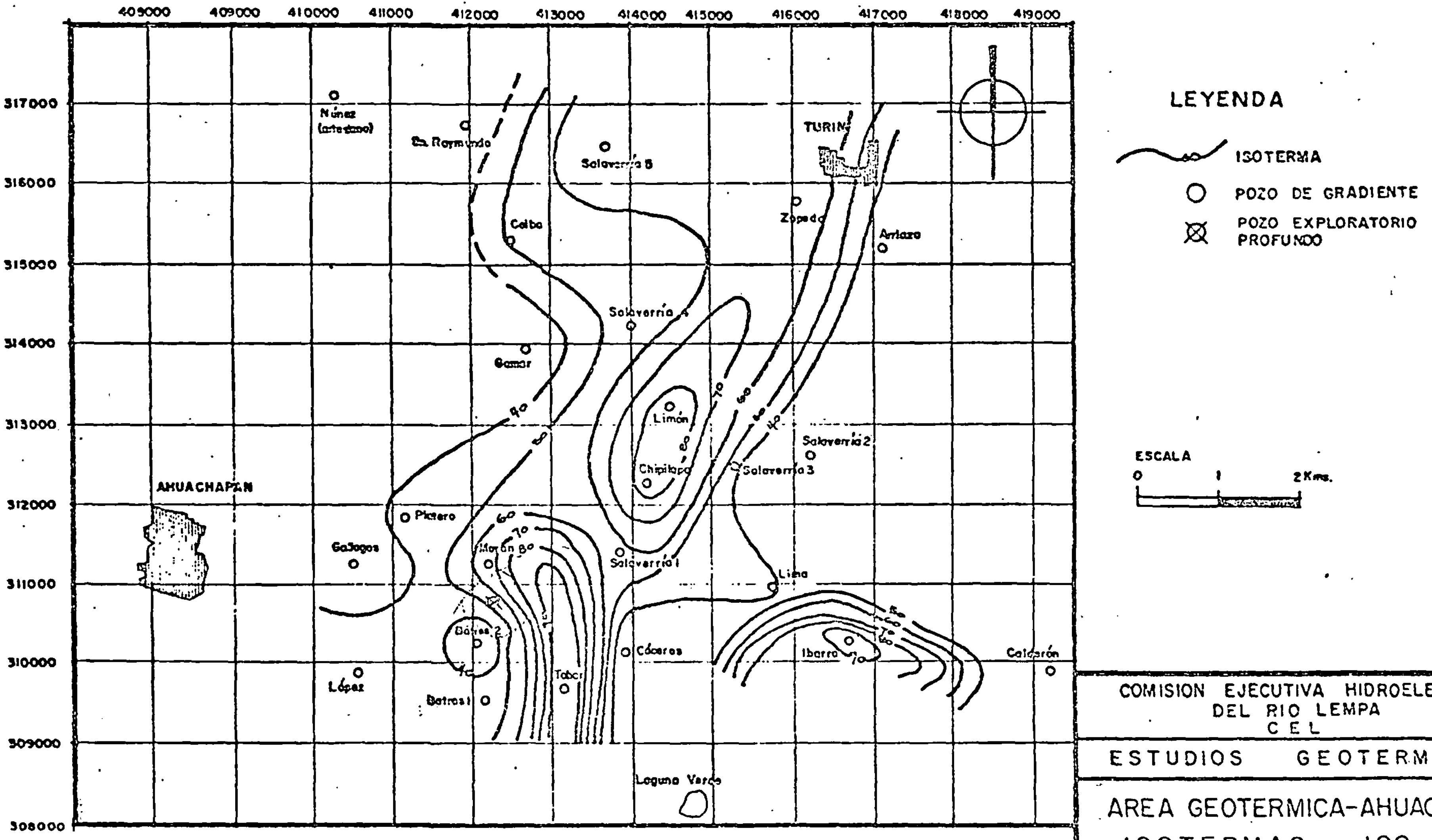
-Proceso mecánico

Las perforaciones se realizaron con diámetro de 3", colocando a su finalización tubería de revestimiento de 1" (galvanizada) hasta el fondo, siendo através de ésta que se midieron las temperaturas.

Superficialmente, y como protección del agujero se instaló en cada uno de ellos, revestimiento de 4" de diámetro (galvanizada), hasta 3 metros de profundidad.

...//

Fig.- 2



COMISION EJECUTIVA HIDROELECTRICA
DEL RIO LEMPA
C E L

ESTUDIOS GEOTERMICOS

AREA GEOTERMICA-AHUACHAPAN
ISOTERMAS a 100 mts.

ELABORO Geólogo M. JIMENEZ	APROBO	FECHA
DIBUJO M. E. M. N.	REVISO Geólogo M. JIMENEZ	OCT. 19[illegible]

Los procesos de perforación a estas profundidades fueron satisfactorias; se realizaron por contratos con firmas privadas utilizando generalmente equipos compactos Long Year, los cuales son fácilmente instalables aún en sitios de acceso difícil.

Resultados

Según se explicó antes, aunque estas perforaciones fueron planificadas para medir el gradiente geotérmico, los resultados a este respecto no fueron absolutamente positivos.
Para la medición del gradiente geotérmico se considera indispensable - la presencia de capas casi impermeables, más o menos uniformes.
Con respecto a las temperaturas medidas hasta 100 mts. de profundidad, éstas han significado elementos interesantes en la individualización - de estructuras termales.

2.1.3 Perforaciones a testigo contínuo

-Objetivo

Después del análisis de los resultados de las perforaciones de gradiente realizadas en el país, se tomó la decisión de proyectar otro tipo de perforaciones, con propósitos múltiples, incluyendo por supuesto la medición del gradiente geotérmico. Este tipo de perforaciones ya ha sido realizado en las áreas de los Toles, Ahuachapán y en el área de Chipilapa. Tienen como objetivo, aportar información sobre los siguientes aspectos:

- Sucesión estratigráfica
- Mediciones hidrológicas (niveles hidrostáticos de diferentes acuíferos y ensayos de permeabilidad).
- Mediciones de temperatura y presión.
- Determinaciones físicas como porosidad y densidad de los núcleos.
- Prueba de producción cuando es posible.

Las profundidades máximas alcanzadas hasta el presente son de 451 mts. en el área de Chipilapa (Pozo Ch-E-1) con diámetro mínimo de 3 7/8"

- Geología

Entre Noviembre/75 y Junio de 1976 se perforaron 2 pozos a testigo(núcleo) contínuo en el área de los Toles, al Oeste del área de Ahuachapán, hasta la profundidad de 400 mts.

....../

Los 2 pozos mencionados (TR-1 y TR-3) se ubicaron desde el punto de vista estratigráfico en la serie "Aglomerados Jóvenes", interceptaron dicha serie, posteriormente las andesitas de Ahuachapán (ampliamente fracturadas) y parcialmente penetraron a los aglomerados terciarios. - A partir de la intercepción de las andesitas afloró un acuífero, el cual levantó presiones hasta de 40 psi., fluyendo agua caliente con un pequeño porcentaje de vapor.

Las temperaturas máximas registradas fueron de 115°C. Las pruebas definitivas de producción serán realizadas en breve.

Entre Junio y Agosto del corriente año, se perforó siempre a testigo contínuo un pozo en el área de Chipilapa (Ch-E-1) hasta una profundidad de 400 mts. El perfil litológico (ver fig. 3) presenta una serie de depósitos volcánicos, ligeramente similar a la que corresponde al área de Ahuachapán; difiere de esta última en la mayor predominancia de tobas aglomeráticas y aglomerados sobre los flujos de lavas andesitas.

Desde 298 metros persistieron pérdidas totales de circulación y la temperatura máxima sin estabilización fué de 205°C.

Las condiciones geológicas, hidrogeológicas y geotérmicas de esta zona, evidenciadas en el pozo Ch-E-1 son muy alentadoras, y por el momento se dicidió profundizarlo con el mismo sistema, hasta 500-600 metros, estando en realización dicho proceso. La recuperación de núcleos en estas formaciones ha sido totalmente eficiente.

Otros pozos (4) de similar proceso, fueron perforados como complemento a las perforaciones profundas del campo de Ahuachapán en explotación, hacia el Norte y Este del mismo. Las profundidades máximas fueron de 300 metros, funcionando actualmente como piezómetros.

-Proceso mecánico

Los pozos de testigo contínuo fueron perforados con equipos rotativos TECKNO y Long Year; el primero de éstos, con torre incorporada ~~[illegible]~~ y tracción propia, ha sido utilizado eficientemente en las últimas perforaciones.

En el esquema abajo mostrado se presenta el completamiento correspondiente a los pozos recientemente perforados.

Ø Perforación (pulg.)	Ø Entubamiento (pulg.)
3½, 3; (8½, 9 7/8)	6 5/8
5 5/8	4
3 (3 7/8)	2 (ranurado)

...../

AREA CHIPILAPA
POZO DE INVESTIGACION CHE-1

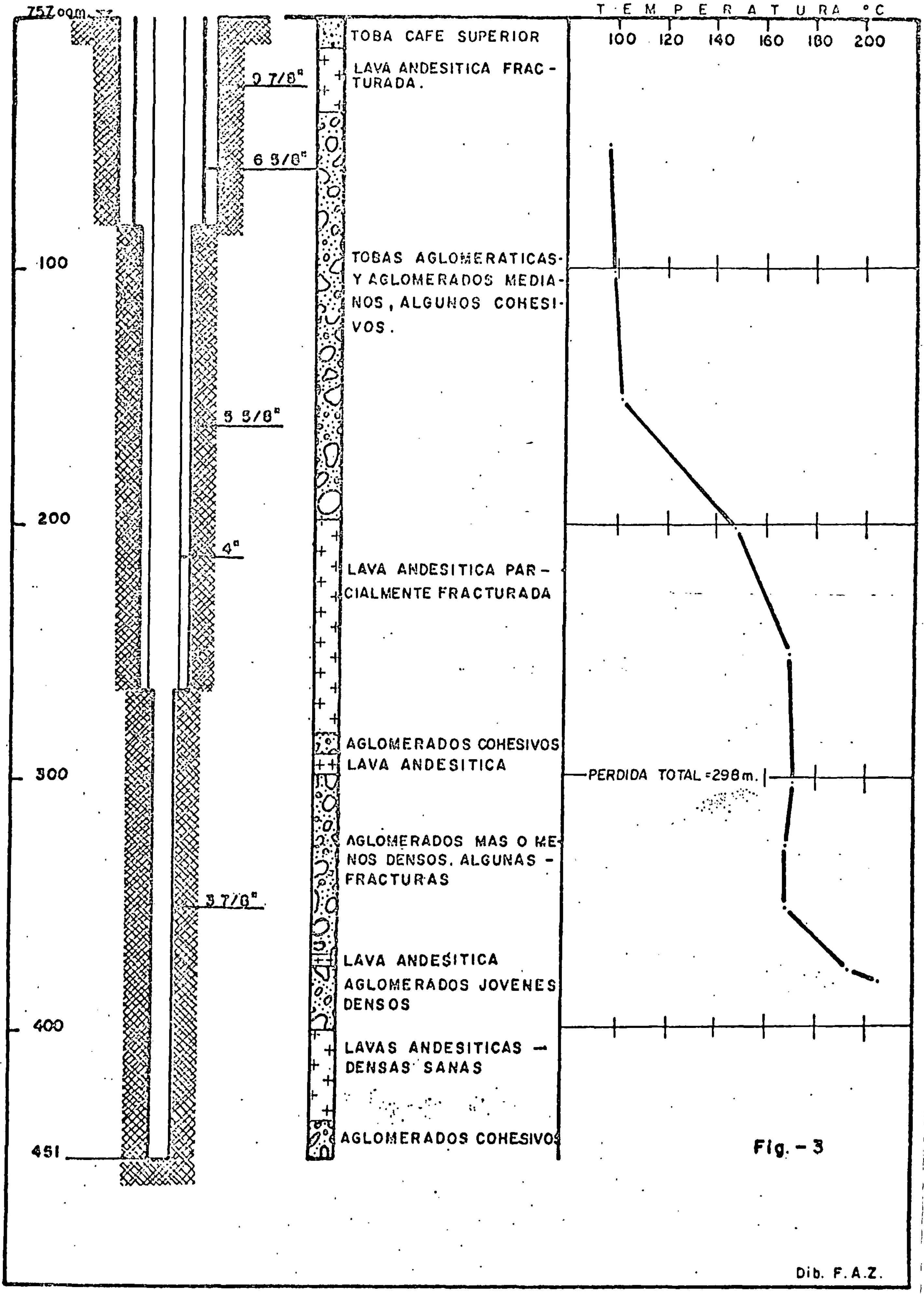


Fig. - 3

Dib. F.A.Z.

Generalmente se ha perforado con agua. Cuando problemas técnicos se han presentado, como por ejemplo inestabilidad de las paredes del pozo, se utilizó fluído bentonítico de baja viscosidad y peso. Cuando las presiones elevadas impidieron el desarrollo normal del proceso de perforación (Los Toles), se usó lodo pesado a base de Barita.
Todos los pozos últimamente perforados fueron equipados con preventor de reventones similar al de los pozos profundos. La profundidad de las tuberías de ademe fué determinada generalmente de acuerdo a las características de las rocas interceptadas.

Resultados

Hasta el presente, se consideran las perforaciones a testigo contínuo como el más eficiente sistema directo de investigación múltiple del subsuelo. La información, correctamente colectada, significa un avance considerable en los programas de exploración.

2.2 Perforaciones profundas

2.2.1 Perforaciones profundas de Exploración-Producción

Fueron iniciadas en 1968 después de completar y evaluar en forma generalizada los diversos estudios (Geológicos, Geofísicos, Geoquímicos, perforaciones someras, etc..) en las áreas de Ahuachapán y Berlín. Estas perforaciones a diferencia de las precedentes, se efectuaron con diámetros grandes y a profundidades mayores.

-Objetivo

Estas perforaciones tuvieron los propósitos de investigar la geología, hidrología, quimismo y temperaturas a profundidades hasta de 1500 metros, así como también la factibilidad de captar vapor aprovechable para generación, tanto en Ahuachapán, como en el Oriente del País.

-Geología

El esquema geológico-tectónico, obtenido de los levantamientos efectuados con anterioridad en el área de Ahuachapán, mostraba características geotérmicas promisorias. Las perforaciones exploratorias profundas, localizadas en sitios ventajosos desde el punto de vista geominero, hicieron factible la comprobación directa de las condiciones geológicas e hidrogeológicas en las estructuras que pudieran almacenar fluídos termales.
Definitivamente, los datos geológicos procedentes de los primeros po--

.../

zos perforados en el área de Ahuachapán (Ch-1, Ah-1 y Ah-9), fueron eficientemente aprovechados y constituyeron los elementeos técnicos básicos del desarrollo geotérmico en el área de Ahuachapán. Las muestras de canal o recortes de perforación, recuperados sistemáticamente, fueron convenientemente identificados mediante el análisis macroscópico (lupa binocular) y el microscópico (microscopio polarizante), elaborándose los perfiles litológicos correspondientes, por medio de los cuales fué posible determinar preliminarmente los espesores de las formaciones que constituyen la cubierta volcánica superficial, los horizontes impermeables confinantes y las que en definitiva constituyeron el reservorio principal del campo.

Algunas características de las rocas interceptadas, específicamente el fracturamiento o agrietamiento de las lavas andesíticas superficiales constituyen problemas para el avance de la perforación, al ocasionar pérdidas totales de fluído de perforación. Por otro lado, en la parte profunda de algunos pozos , fué notoria la permeabilidad de las lavas andesíticas basales, obteniéndose las primeras producciones de vapor geotérmico.

Fuera de los datos eminentemente geológicos determinados en el curso de las perforaciones, fué posible también realizar los registros contínuos de temperatura y presión necesarios para complementar la evaluación geotérmica.

La medición de los niveles hidrostáticos, controlados en el curso de las perforaciones, facilitó su correlación, con los ya establecidos para el horizonte subterráneo saturado y definió los niveles del acuífero profundo a presión.

La colección sistemática de muestras (recortes) y la implementación del "Geolograph" (gráfico de penetración) en el equipo de perforación, propició actualizar permanentemente el perfil litológico de los pozos. En algunos de ellos, la información obtenida fué incompleta por las constantes pérdidas de circulación y la dificultad de obturarlas. Abajo de la zona de pérdidas totales profundas se han obtenido núcleos aproximadamente cada 100 metros, lo cual ha sido factor indispensable en la exploración de las características de las rocas del reservorio y del subestrato pliocénico.

Con estas primeras perforaciones profundas, se definieron completamente:

.../.

- Las características de los depósitos volcánicos superficiales para decidir la colocación de la tubería de anclaje.
- La zona de contacto aglomerado joven-andesitas del reservorio, para diseñar la ubicación de la tubería de producción.
- Las características petrográficas, físicas y espesores del aglomerado joven, formación determinante del campo geotérmico por su función confinante.
- Las condiciones petrográficas, de permeabilidad y espesores de las lavas andesíticas del reservorio.
- El contacto terciario, y las características de las rocas subyacentes.
- La capacidad de producción del acuífero profundo.

-Proceso mecánico

Pocos datos se conservan respecto a problemas o factores importantes observados durante la perforación de estos pozos. En general, los progresos respecto al conveniente tratamiento de algunos problemas, tales como las pérdidas de circulación, estaban poco avanzados; en consecuencia, tapones de cemento se usaron con frecuencia en pérdidas pequeñas y el lodo de perforación se usó aún en zonas donde actualmente es normal perforar con agua.
Los completamientos usados son en parte muy similares a los de actuales pozos de producción o reinyección. Algunas variantes características fueron, en los primeros pozos, la colocación más superficial de las tuberías de anclaje (Ah-1=23m, Ch-1=28m, Lempa-1=30m y Tronador=65m), y de producción, lo que parece lógico si se considera el poco conocimiento de la situación geológica en profundidad y la finalidad explorativa de dichos pozos, aunque algunos de ellos fueron productores.
Problemas corrientes en el avance de las perforaciones exploratorias lo constituyeron la presencia de flujos someros de lavas andesíticas en la mayor parte de ellas. Su fracturamiento y densidad ocasionaron pérdidas totales de circulación de difícil obturación y baja penetración.
Los diseños técnicos para las terminaciones efectuadas durante esta etapa de perforación, están enmarcadas en el cuadro siguiente:

.../

Ø Perforación (pulg.)	Ø Revestimiento (pulg.)
17½	13 3/8
12¼	9 5/8
8 3/4	7 5/8 (7")
6¼	

2.2.2 Perforaciones profundas de producción

-Objetivo

Estas perforaciones han tenido el propósito esencial de captar vapor, proveniente de las formaciones andesíticas que constituyen el reservorio principal del campo geotérmico de Ahuachapán, aprovechable potencialmente para la generación de energía eléctrica, con profundidades que oscilan alrededor del rango 600-900 metros dependiendo del espesor del estrato productor; y además, estudiar temperaturas y presiones del agujero, química de fluídos y características del flujo.

-Geología

La ubicación de pozos de producción dependió por una parte de la estructura geotérmica evidenciada por investigaciones geomineras de superficie y pozos de investigación. También han sido elementos determinantes los resultados de perforaciones exploratorias profundas previas, las cuales en esta etapa, son las que proporcionan valores reales sobre las características del reservorio (permeabilidad, temperaturas, etc.). Las perforaciones de producción complementaron la información sobre la estratigrafía del área de Ahuachapán, de la cual se presenta una síntesis en el siguiente cuadro:

.../

ESTRATIGRAFIA DEL AREA DE AHUACHAPAN

FORMACION	CARACTERISTICAS GEOLOGICAS	PROFUNDIDAD EN METROS	CARACTERISTICAS GEOTERMICAS
Superficial	Tobas, pómez, bloques, lavas andesíticas fracturadas.	0-250	Sin importancia. Afloran manifestaciones térmicas superficiales.
Intermedia	Aglomerados cohesivos, porosos, alterados medianamente	250-450	Constituyen un sello (cap-rock) ideal por su espesor y baja permeabilidad.
Reservorio	Lavas andesíticas, densas fracturadas, algunas veces brecciadas.	450-800	Constituyen un potente reservorio.
Profunda	Aglomerados masivos densos, poco fracturados intercalados a lentes lávicos.	800-1500 o más.	Comportamiento de subestracto impermeable. Puede ser productor en casos aislados.

La profundidad final programada, ha sido objeto de detenido estudio.- En principio se perforaron pozos penetrando unos 150 metros dentro - del reservorio andesítico. Posteriormente se varió el criterio, debido a lo heterogéneo de la formación con respecto a la permeabilidad y por el momento los pozos se llevan hasta el contacto con los aglomerados antiguos (terciarios), con profundidades de aproximadamente 850 mts. Después de varios años de perforación profunda en El Salvador (600- - 1500 metros), con fines de producción geotérmica se han obtenido experiencias que se pueden resumir así:

- La colección de muestras trituradas (recortes) resulta conveniente cada 5 metros.
- El corte de núcleos (testigo), cada 100-150 metros en la zona produc

../

tiva es indispensable.

- El uso de geolograph (registrador de penetración) es de primordial importancia para las determinaciones litológicas.
- Los pozos deben perforarse hasta la formación andesítica antes de colocar la tubería de producción.
- La elaboración del perfil litológico debe considerarse como el factor básico en la terminación de los pozos y debe ser lo más eficientemente realizado.

No hay duda que la perforación de pozos de producción ha aportado información geológica suficiente y de incalculable utilidad, lo que sin duda ha repercutido en los progresos geotérmicos del país.
En la fig. 4 está representado el techo de la formación andesítica, a través de la cual circula el acuífero salino que abastece la Central Geotérmica de Ahuachapán. En dicha figura pueden observarse condiciones comunes en muchos pozos y las particularidades propias de los depósitos volcánicos.

-Proceso mecánico

En el proceso de estas perforaciones, han participado 2 compañías perforadoras (Loffland Brothers y Foramines, S. A.) con una participación del 30% y 70% respectivamente y en orden cronológico. Por lo tanto, los datos técnicos más importantes guardan una relación estrecha con las características de los equipos usados (Ideco y Fred Cooper TD42010 respectivamente).

-Preparativos para la perforación

Las condiciones previas establecidas para el inicio de las perforaciones pueden resumirse así:

a) La ubicación proveniente de interpolación-extrapolación entre pozos perforados con anterioridad o bien de algún ordenamiento geotectónico.
b) Sucesión litológica prevista.
c) La profundidad final proyectada.
d) Contrapozo construido, el cual permite:

-Acceso para instalación de B.O.P. y tubo conductor de lodo.

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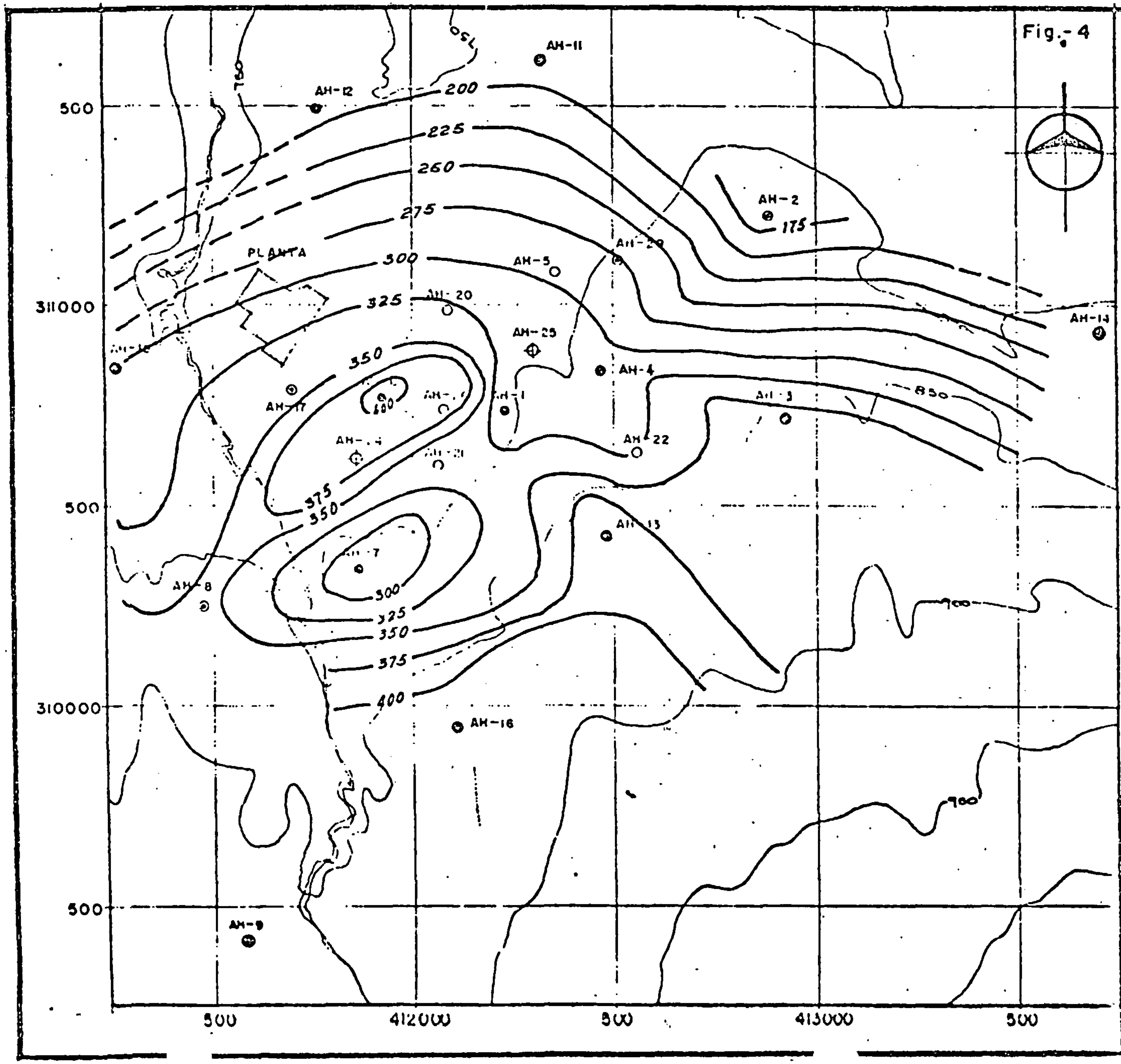
Fig.- 4



CAMPO GEOTERMICO AHUACHAPAN

SIMBOLOGIA

- ◉ POZOS 1a. UNIDAD
- ○ POZOS 2a. UNIDAD
- ◎ POZOS REINYECCION
- ◉ POZOS EXPLORATORIOS
- ⊕ POZOS RESERVA

Escala

0 500 mts.

COMISION EJECUTIVA HIDROELECTRICA
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ESTUDIOS GEOTERMICOS

MAPA ESTRUCTURAL DEL TECHO DE LA FORMACION ANDESITICA DE AHUACHAPAN

ELABORO Geol M JIMENEZ	APROBO G CUELLAR	FECHA
DIBUJO F A Z	REVISO Geol M JIMENEZ	[illegible]

-El drenaje de los fluídos residuales.
-Instalación del cabezal, del cual aparece un plano esquemático en la fig. 5
-Una descarga subterránea por la salida de 2" Ø hasta un sitio alejado del pozo.

e) Programas de Perforación y diseño del pozo:

Para definir los criterios seguidos para este propósito, se comenzará exponiendo las funciones que los revestimientos desempeñan por lo general en nuestro campo:

1) Revestimiento de superficie (anclaje).Colocado y cementado aproximadamente a 100 mts. de profundidad, está destinado a evitar la contaminación de acuíferos superficiales, a dar seguridad a las operaciones de perforación y al montaje del cabezal.
2) Intermedio o de producción.Instalado y cementado hasta 400-600 metros de profundidad, tiene el propósito de proteger las paredes inestables, principalmente formaciones plásticas (Aglomerado joven), evitar contaminaciones del acuífero saturado regional o la influencia de éste sobre el acuífero profundo y, conducir el flujo de producción a la superficie.
3) Tuberías en zona de producción. En algunos casos ha sido necesaria la colocación de tuberías ciegas y/o ranuradas no cementadas,generalmente para proteger el pozo de desprendimientos. Se instalaron éstas por medio de colgadores colocados unos 10-20 metros dentro del revestimiento intermedio o de producción y su profundidad dependiente de las condiciones en la zona productiva.

En base a las funciones descritas se han adoptado los siguientes criterios principales para la elaboración del programa de revestimiento:

a) La profundidad final. De ésta depende en parte la profundidad y número de revestimientos.
b) La naturaleza de las formaciones que se espera encontrar.
c) Ubicación de las zapatas. Criterio importante que se refiere a la colocación de revestimientos sobre formaciones densas, con el objeto de asegurar cementaciones óptimas.

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Fig:5

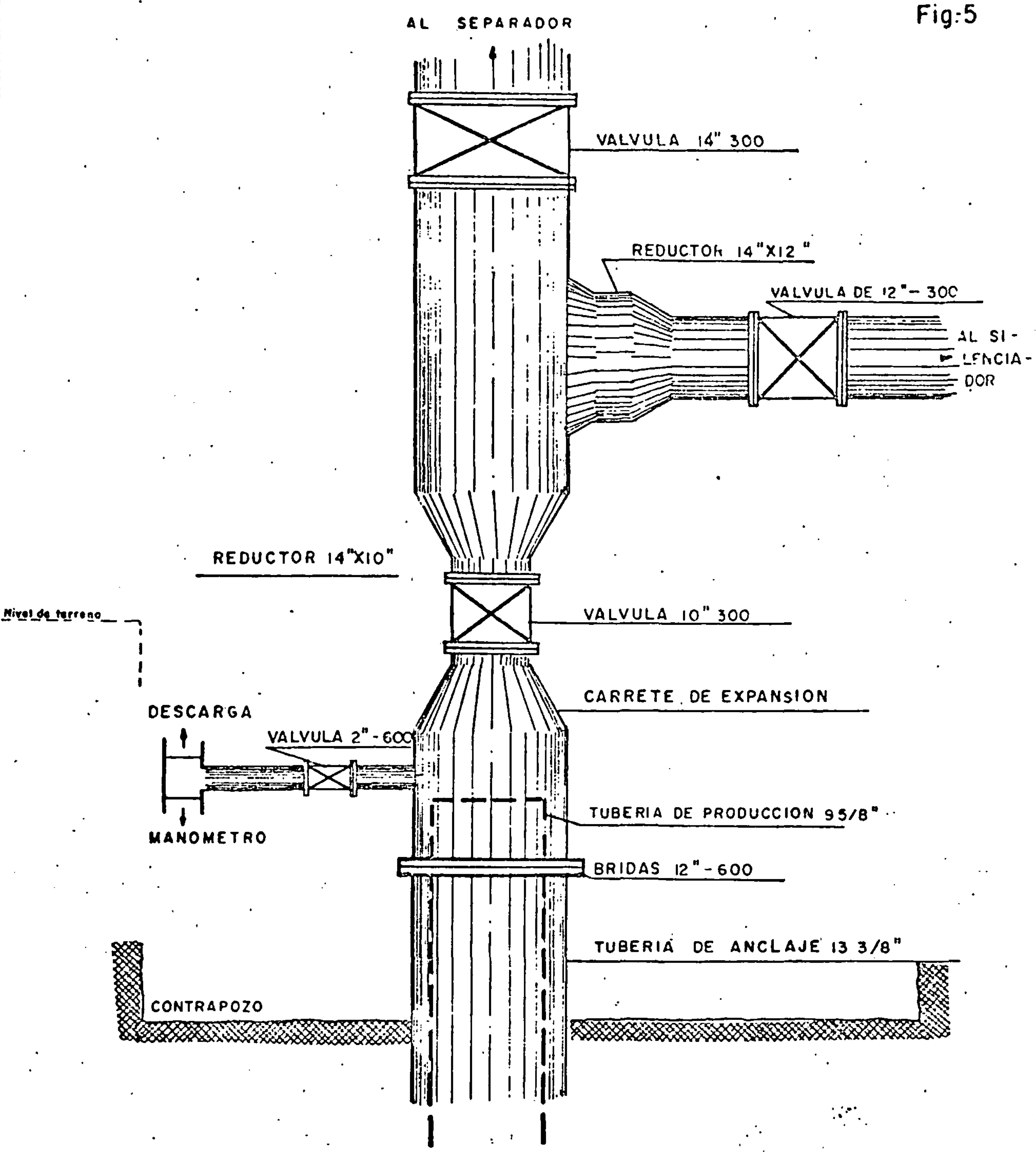

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DIAGRAMA TIPICO DE CABEZAL

d) Factor económico. Cuanto mayor es el diámetro de perforación y revestimiento, el incremento de costos se refleja en lo siguiente:

-Mayor cantidad de lodo para subir los recortes, lo que eleva el costo de aditivos y la capacidad requerida de las bombas.
-Más lentitud en la perforación.
-El costo de materiales como tuberías, barrenas, etc.

El programa de barrenas así como también sus especificaciones, se elaboran entonces, en base a:

-El programa de revestimientos.
-Tipos de formación que se espera encontrar.
-Las profundidades aproximadas.

En la página siguiente se muestra un cuadro, con los sistemas de completamientos efectuados en Ahuachapán.

Programa de pruebas

Las pruebas y operaciones especiales que se han previsto pueden resumirse así:

a) Pruebas de presión para las cementaciones, revestimientos y soldaduras de cabezal.
b) Registros de desviación cada 100 mts. aproximadamente hasta la profundidad del revestimiento intermedio.
c) Toma de testigos.
d) Pruebas de permeabilidad.
e) Registros de niveles hidrostáticos.

Sistema de Completamientos y Características de Tubería

Sistema	Ø Perf. (pulg.)	Ø Revest. (pulg.)	Especificaciones de Tub.
(a)	26	20	94 $\frac{\text{lb}}{\text{pié}}$, API, H-40 (ó K-55) Rosca redonda.
	17½	13 3/8	
	12¼	10 3/4	-40 $\frac{\text{lb}}{\text{pié}}$, Rango 3, rosca trapezoidal. -API 5L, Grado 2, ASTM-A120, rosca redonda.
		9 5/8	
(b)	17½	13 3/8	-54.5-61 $\frac{\text{lbs}}{\text{pié}}$, API, K-55, Rango 3, Rosca trapezoidal -48 $\frac{\text{lb}}{\text{pié}}$, API, H-40 Rango 3, rosca redonda.
	12¼	9 5/8	-36.40 $\frac{\text{lbs}}{\text{pié}}$, API, K-55, Rango 3, rosca trapezoidal. -36 $\frac{\text{lb}}{\text{pié}}$, API, J-55, Rango 3, rosca redonda
	8½	7 5/8	26.4 $\frac{\text{lb}}{\text{pié}}$, API, J-55, Rango 3, rosca Hydril FJ-P
		7	23 $\frac{\text{lb}}{\text{pié}}$, API, H-40, Rango 2, rosca redonda.

En relación con las especificaciones requeridas, se hicieron en el transcurso de las perforaciones algunos cambios que se conside-

.../

raron recomendables:

- Tuberías de revestimiento con rosca trapezoidal ("Buttress"). En vista de la mejor eficiencia de estas juntas en compresión, comparadas con la rosca redonda (77% vrs. 49% para tubería 13 3/8"), esta última fué usada solamente en los primeros 2 pozos productores, cambiándose a la rosca Buttress en los posteriores, siempre que fué posible.
- Válvulas. Fué cambiado el uso de válvulas de compuerta standards, - por sus problemas de fugas, por válvulas "Through Conduit" a pesar de su mayor costo.
- Tuberías en zona de producción. Se han usado "J Slots" y últimamente colgadores de doble cuña para tuberías roscadas a los que se les ha quitado la cuña superior previa su introducción al pozo, para facilitar la extracción posterior de la tubería si fuera necesario.

Operaciones de perforación

Una característica notable en la perforación de la mayoría de los pozos ha sido las altas condiciones de dureza y dificultad para - perforar los primeros 100 mts, debido a las formaciones eluviales superficiales, a los flujos de lava mas o menos sanos y al bajo peso de la columna de perforación por pulgada de diámetro de la barrena disponible.

Esto ha llevado al equipo a una vibración excesiva que cualquier equipo mas liviano no habría sido capaz de superar. El avance aproximado ha sido de 0.5 a 1.5 mts/hora.

La perforación para el revestimiento de 9 5/8 (12¼) ha sido generalmente más rápida, con incremento en el peso llevando a avances de 2 a 4 mts/hora, excepto en ocasionales flujos de lava. La perforación abajo de la tubería de producción ha mostrado considerables variaciones y se considera como la zona productiva. Estas variaciones se deben mas que todo a características de alteración hidrotermal en algunos casos, fracturamientos en otros, densidad de las rocas en otros. Sin embargo la razón de penetración ha sido hasta 5 mts/hora, excepto en algunos pozos en que se ha llegado sólo a 2.5 mts/hora.

El tiempo promedio total para perforar en los diferentes diámetros,

ha variado con los contratistas, pero en general se ha declinado en esto aspecto pasando de 25 a 30 días en las terminaciones de los pozos primeros a 2 ó 3 meses en los últimos.
La técnica de perforar con agua en zonas de pérdidas de circulación total(zonas de producción) ha sido establecida en todas las perforaciones con éxito, incorporando el uso ocasional de lodo para levantar recortes del fondo del agujero hacia las formaciones fracturadas, técnica que se justificó económicamente.

Pérdidas de circulación

Este es uno de los problemas que siempre se han presentado en la perforación de campos geotérmicos.
El problema más serio ha ocurrido en la perforación para 9 5/8 (aprox. 500 mts.). Muchos intentos se hicieron en las primeras perforaciones por sellar estas pérdidas con tapones de cemento, sin embargo sólo se logró un sello momentáneo que desaparecía al perforar dichos tapones.
De acuerdo a esta experiencia, materiales obturantes como cascarilla de café, nuez, arroz, etc. adicionados al lodo bentonítico se usaron para pérdidas parciales con éxito, usando el cemento solamente cuando no se tuviere éxito con los obturantes o por pérdidas totales, la cual es una práctica conservada actualmente.
Se ha logrado un balance, entre los costos excesivos y la necesidad de un buen retorno durante las cementaciones. También debido al limitado de núcleos, el mantener la circulación y la recuperación de recortes provee el único medio para identificar las formaciones penetradas.
No obstante, existe siempre el peligro de inestabilidad de las formaciones cuando se perfora con agua; el uso de tapones de lodo para limpiar el agujero de cualquier derrumbe o acumulación de recortes, posibilita la perforación sin dificultad. Es necesario tomar algunas precauciones y observar frecuentemente los posibles acumulamientos de recortes.

Lodo de Perforación

Durante los procesos de perforaciones, se han superado bastante los problemas originales derivados de la falta de materiales y equipos de prueba.

Los aditivos mayormente usados para el lodo de agua dulce-bentonita han sido:

1) Bentonita: Local hasta la cementación de tubería de anclaje.
   USA hasta las pérdidas totales de la zona productiva
2) Lignosulfato
3) Soda cáustica
4) Barita
5) Soda ASh
6) C M C
7) Obturante: Cascarilla de café, granza de arroz, etc.

La filosofía básica en la fabricación del lodo, ha sido proveer el más simple y económico sistema de lodo que haga posible perforar un pozo en el más corto tiempo posible con el mínimo de problemas, lo cual se ha logrado más o menos razonablemente, aún careciende de resultados de prueba sobre algunas propiedades del lodo (viscosidad real, filtración, etc.).

En las primeras perforaciones se usaron agentes químicos que produjeron un fluído parcialmente viscoso, incrementando la viscosidad con la concentración, pero resultaron inestables con la temperatura convirtiéndose luego en un fluído acuoso después de aproximadamente 36 horas.

Al usar concentraciones grandes fueron útiles para sellar algunas pérdidas de circulación, pero resultaba excesivamente caro.

El lodo de perforación normal usado subsecuentemente fué un fluído de baja a media viscosidad (30-33 centipoises) de bajo contenido de sólidos, consistente en Bentonita Wyoming y agua. La soda cáustica se ha usado siempre para espesar el fluído, incrementar el PH y reducir las pérdidas de agua.

C M C fué usado originalmente con poca frecuencia para incrementar la viscosidad y controlar las pérdidas de fluído. Actualmente se ha suspendido su uso.

Aceite diesel no se ha usado como aditivo de lodo para reducir pérdidas de fluído, pero si para facilitar la realización de cementaciones complicadas.

Debido a poca disponibilidad de bentonita Wyoming (USA), fué necesario usar en zonas no críticas bentonita Guatemalteca (llamada "local" en este trabajo), de menor calidad.

Desde hace pocos años los materiales (1), (2), (3), (5) y (7), han -

sido elementos usados primordialmente en el lodo, manteniendo en promedio las características siguientes:

- Gravedad específica: 1.03-1.08
- Viscosidad "fannel": 38-40 segundos
- Gel: reducida a cero, previamente a las cementaciones
- Temperaturas: 50-70° C (máximas)
- Descontaminación por cemento mediante soda ASh
- Bajo contenido de sólidos, por desarenación y no uso de barita.

Las temperaturas del lodo en el fondo no han excedido en general los 100°C. Esto ha posibilitado la utilización del lodo, conservando las propiedades pocos alteradas. Sin embargo, la extrema salinidad del agua termal ha afectado algunas veces las propiedades del lodo haciendo necesario el tratamiento mediante adición de lignosulfonatos de cromo, que son usados también como adelgazadores estables bajo temperatura. El bajo nivel hidrostático del acuífero profundo tiene una sola ventaja, en cuanto a que las entradas de agua salina al agujero son difíciles durante las operaciones de perforación.
Las características de equipo, tales como el peso sobre barrena y RPM han tenido en general bajos valores, limitados por la capacidad del equipo y en algunos casos por las formaciones. Valores promedio oscilan en 4 a 6 ton. y 50 a 70 rpm. respectivamente, logrando avances promedio de 0.5-1 m/h hasta los 100 m aproximadamente, y 1.5-2.5 m/h en el resto, con valores máximos hasta 7 m/h. en zonas de poco espesor.

Operaciones para cementación de revestimientos

La necesidad de obtener un retorno completo del cemento a través del espacio anular hasta la superficie, siempre ha sido uno de los más firmes propósitos para lograr cementaciones exitosas.
En la mayoría de los pozos, la cementación del revestimiento 13 3/8" ha sido satisfactoria. Algunos problemas se encontraron inicialmente para mantener uniformidad en las operaciones de cementación, originados en parte por fracciones endurecidas del cemento, sobreviniendo retrasos; sin embargo, los resultados finales se consideraron satisfacto

rios.

La cementación del revestimiento 9 5/8" ha presentado por lo general mayores problemas debido a contínuas pérdidas de circulación que obligaron a efectuar cementaciones complementarias. Esta experiencia ha conducido a la práctica de proveer una cantidad de cemento en exceso al cálculo teórico (200-400%) a fin de sobrepasar la zona de pérdidas conocida y complementar con un llenado subsiguiente o cementación desde la - superficie al espacio anular. Los procesos de cementación cuando ocu-- rren pérdidas implican un bombeo suficientemente alto inicialmente para llenar el espacio anular completamente hasta las zonas de pérdidas o arriba de éstas; también implican bombeos posteriores a intervalos - incrementados gradualmente, con el objeto de permitir el fraguado parcial del cemento. Cuando estos procesos han tenido lugar, la cementa-- ción completa ha invertido hasta 28 horas (contra 3 horas aprox. en cementaciones normales), pero finalmente se ha logrado éxito.

El uso del porcentaje adicional suficiente para asegurar el retorno a la superficie, por cualquier razón, es una manera de garantizar la no formación de bolsas de agua dentro de la columna de cemento (en cementaciones completamente por gravedad o bombeando desde la superficie), que puedan repercutir en expansiones con la temperatura y originar colapsos en la tubería o daños a una cementación mas o menos satisfactoria.

Las operaciones de cementación están siempre propensas a las pérdidas de circulación debido a la mayor presión hidrostática de una columna de cemento (gravedad específica: 1.8) comparada con la de una columna de lodo de perforación aún más grande. La solución ideal parece ser el uso de un cemento de peso ligero, con Perlita por ejemplo; pero esto - normalmente solo puede hacerse cuando hay compañías de servicio disponibles para un mezclado y bombeo efectivo.

Un programa de pruebas, para determinar las proporciones ideales y aditivos necesarios para garantizar el uso de cemento local Portland bajo - las condiciones propias de nuestro campo no ha sido efectuado; sin embargo en las últimas perforaciones, el cemento local parece haber dado resultados satisfactorios. Cementos importados mezclados con 39% sílica flour y retardadores, han sido diseñados para un tiempo de fraguado de 3 horas a aproximadamente 212°C que no corresponden con nuestras condiciones y fueron usados en las primeras cementaciones.

Las pruebas de compresión en cilindros tomados durante la cementación

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de los pozos Ah-5, Ah-6 y Ah-7, después de 7 y 28 días de fraguado, mostraron valores bajos (92-174 kg/cm^2) para el cemento importado; además este se encontró blando después de 16 horas de colocado, por lo que para las cementaciones posteriores este cemento se usó con proporción 1:2 ó 1:4 con cemento Portland local.
Con el propósito de adaptarse a las condiciones locales, se usaron aditivos como 1% Bentonita Wyoming y Retardador Hallyburton HR 4 solamente cuando las temperaturas de retorno excedieron los 40°C con una concentración de 0.2% a 0.4% por peso de cemento.
Desde hace algún tiempo, las cementaciones se han efectuado totalmente con cemento local, utilizando una bomba especial Hallyburton para asegurar un mejor mezclado y rápido bombeo del cemento.
Ha existido un límite al número de aditivos que puedan agregarse y dispersarse debido a las limitaciones de espacio y falta de garantía sobre un mezclado completo. **Los aditivos para las cementaciones más comunmente empleados han sido: Retardador HR 4 y Cloruro de calcio como acelerador de fraguado.**

REVENTONES

Comparado con otros campos geotermales donde a menudo se presentan altas temperaturas desde la superficie y los pozos permanecen bajo presión, los pozos de Ahuachapán han mostrado pocos problemas en este aspecto (T≤70°C durante la perforación), tanto por los bajos niveles hidrostáticos como por las relativamente frías formaciones superiores. Sin embargo, siempre se ha mantenido la práctica de instalación y pruebas del B.O.P.
En ocasiones las venidas de gases, cuyo escape no ha producido mayores problemas, han aparentado reventones. Solamente en pocos pozos, se ha afrontado reventones frecuentes que siempre se han controlado con el cierre del BOP sobre la tubería de perforación y la inyección del agua fría, sin haber ocasionado nunca daños al personal ni al equipo.

REGISTROS

-Desviación

Se ha mantenido la práctica de efectuar registros de desviación del pozo por medio de "Tocto", aproximadamente cada 100 mts.

de profundidad hasta la zona en que se perfore con lodo, que coincide aproximadamente con los 400-500 mts. Cuando tales desviaciones se han manifestado severamente la inclusión de tapones de cemento ha constituído una solución que siempre ha sido favorable, como modificar la técnica de perforación (psb, rpm) en desviaciones pequeñas.

Los valores obtenidos en algunos pozos pueden observarse en el cuadro siguiente (representativos para el resto de pozos); mostrando la desviación máxima y la evidente corrección en los casos en que se han tomado registros posteriores.

POZO	DESVIACION MAX. EN GRADOS SEXAG.	PROF. (mts.)
Ah-21	1 3/4	472.5
Ah-22	2 1 3/4	348.3 482
Ah-24	7½ 3	344.21 430
Ah-25	3 3/4	285 338
Ah-29	2 0	226.5 550
Ah-17	½	449.26

Pruebas de inyectividad

Estas pruebas se han efectuado en la zona productiva un poco antes a la finalización de la perforación del pozo.
Han consistido en bombear al pozo flujos crecientes fijos comprendidos entre 0-50 lts/seg., y medir las fluctuaciones de presión mediante la amerada, situada a una profundidad fija dentro de la columna hidrostática del pozo. Generalmente se han utilizado las bombas del equipo de perforación.
Es de notar que la interpretación de estos datos no proporcionan directamente el valor de permeabilidad del pozo; pero ya que ambos parámetros (permeabilidad-inyectividad) provienen de las características de fracturamiento de las formaciones del pozo, que es en definitiva lo que interesa, es posible a través de esta pruebas y su índice respectivo anticiparlas características de producción del pozo.
Un ejemplo que ilustra los datos registrados, y su procesamiento para determinar el índice de inyectividad se muestra en la fig. 6.

Niveles hidrostáticos

En el transcurso de las perforaciones y caso de pérdidas importantes, se hacen mediciones del nivel hidrostático mediante sistemas de flotador. El propósito es detectar variaciones en los horizontes de agua subterránea que contribuyan al conocimiento hidrológico del campo y a prever algunos problemas de perforación.

Testigos

Como ya se ha indicado, esta es uno de las informaciones directas que de acuerdo con el criterio geológico se toman a profundidades definidas para comprobaciones litoestratigráficas. Los testigos o núcleos son tomados actualmente con corona de diamante 5 5/8", perforando 4-5 mts., las recuperaciones son variables, pero en los pozos productores se conserva arriba del 50%.
Se ha considerado siempre más importante para estas perforaciones, la frecuente toma de testigos a partir de la zona productiva para el conocimiento de las características de las rocas desde el techo del reservorio. La toma de núcleos debe estar respaldada por una necesidad

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importante, debido a los altos costos, riesgos en esas zonas inestables y a las precauciones que se deben tener antes de proceder a perforarlos.

Programas de perforación de un pozo

Con el objeto de exponer con mayor claridad los aspectos contemplados en el programa de perforación de un pozo, puede verse el anexo Nº 1, que es representativo de los últimos programas efectuados. Así también en la fig. Nº 7 puede verse características de perforación que se han descrito anteriormente, aplicadas en Ah-26 como ejemplo típico.

Resultados

Es experiencia ganada y aprovechada por los técnicos que han participado en el desarrollo de las perforaciones geotérmicas en El Salvador, que cualquier propósito de hacer perforaciones profundas con el objeto definido de captar vapor aprovechable para la generación de energía eléctrica, requiere el respaldo de un conocimiento geológico razonablemente fundamentado previo a la perforación y una eficiente supervisión del proceso mecánico durante la perforación, siendo sin lugar a dudas igualmente crítica cualquier falla en estos dos aspectos. Una estrecha coordinación y colaboración entre ambas disciplinas es completamente indispensable.

Sobre los resultados generales obtenidos puede resumirse lo siguiente:

Se han perforado 14 pozos para producción, de los cuales 8 han tenido éxito comprobado; 2 con éxito predecible por la condición de presiones y temperaturas (Ah-24 y Ah-25); 1 pozo utilizable solamente para observación (Ah-3); 1 que tiene altas presiones y producción restringida (Ah-13); y 2 pozos (Ah-2 y Ah-8) que por su ubicación se utilizan para reinyección (ver cuadro siguiente).

De los 10 pozos considerados exitosos, 7 de ellos han sido perforados según el sistema (b) de completamiento y 3 pozos (Ah-4, Ah-20 y Ah-21), según el sistema (a) (ver cuadro pag. 17 y anexo Nº 2). Los 8 pozos productores mencionados y Ah-1 de la clasificación Exploración-Producción, mantienen una capacidad $\geq$ 69 MW alimentando actualmente 2 unidades con capacidad nominal de 30MW cada una.

Por otra parte, intervenciones en pozos previamente perforados han tenido que efectuarse para tratar de mejorar mediante la profundización sus-

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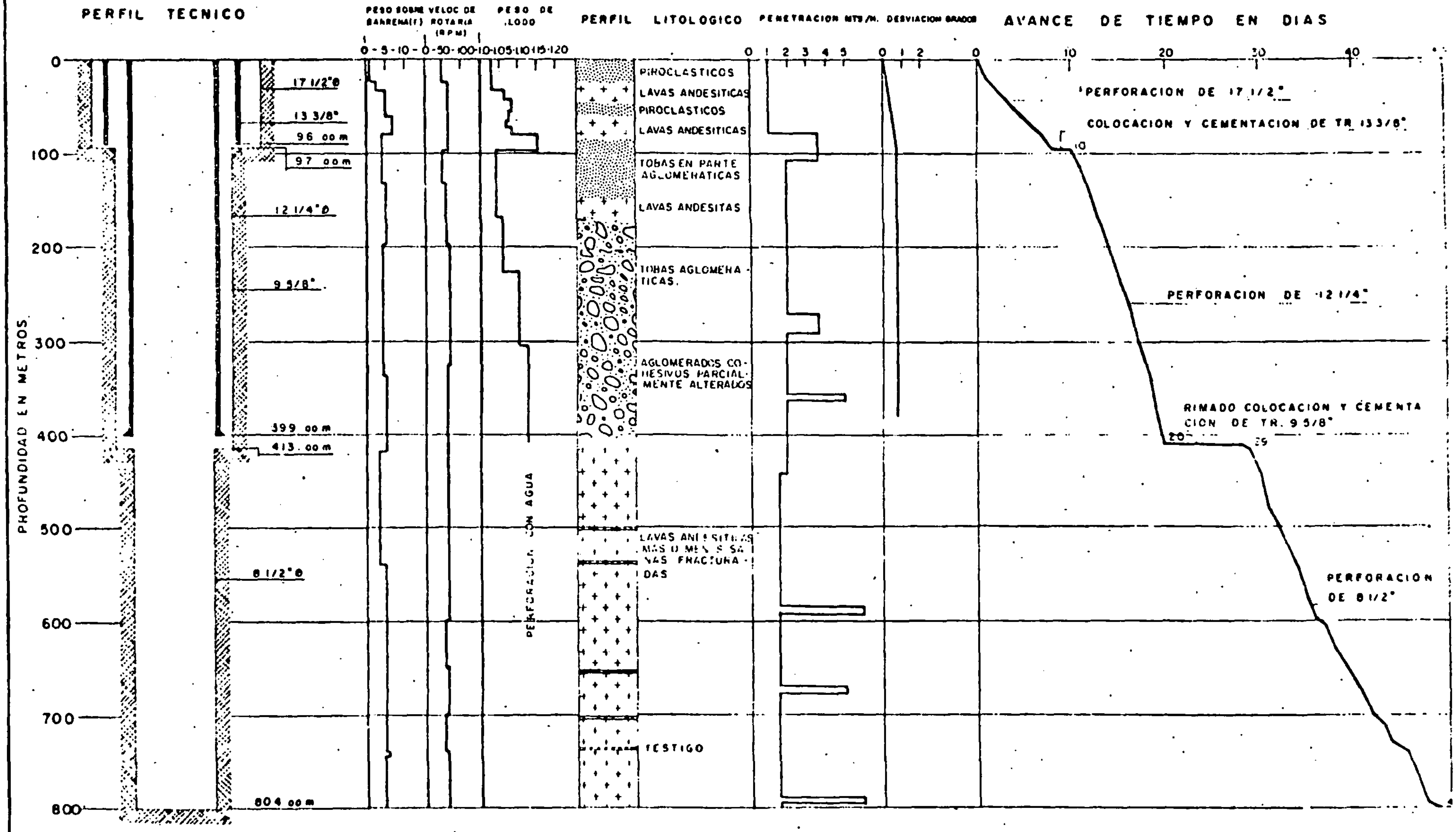
Fig.- 7

AH-26
CARACTERISTICAS DE LA PERFORACION



características de producción parcial poco aprovechable. Estas operaciones siempre han resultado más difíciles que una perforación normal y han conducido a efectuar reparaciones complicadas (Ah-24), elevando considerablemente los costos; sin embargo, el éxito logrado (Ah-21) ha compensado los problemas.

El siguiente cuadro es un resumen de los objetivos con los cuales se perforaron cada uno de los pozos profundos.

CUADRO DE DISTRIBUCION DE POZOS PROFUNDOS SEGUN SU OBJETIVO

Explorac-Produc.	Delimitación de campo	Producción	Reinyección
CH-1	Ah-11	X Ah-2 ∇̄ →	Ah-17
P Ah-1	Ah-12	X Ah-3	Ah-29
Tronador 1	Ah-14	P Ah-4	
Lempa 1	Ah-15	P Ah-5	
Salitre 1	P Ah-16 # #	P Ah-6	
X Ah-9		P Ah-7	
X Ah-10 #		X Ah-8 ∇̄ →	
		X Ah-13	
		P Ah-20	
		P Ah-21	
		P Ah-22	
		[illegible] Ah-24	
		'' Ah-25	
		P Ah-26	
# Explorac-Reiny.	# # Productivo	∇̄ Actualmente reinyectores	

Total de pozos

Exploración-Producción = 7

Delimitación del campo = 5

Producción = 14

Reinyección = 2

12 product

24 desllo

11/20

2.2.3 Perforaciones profundas de reinyección

-Objeto

Se han realizado con el fin de inyectar el agua residual proveniente de los pozos productores en la zona del lecho andesítico de Ahuachapán o dentro de aglomerados antiguos (Aprox. 800-1200 mts. de profundidad).La reinyección a esas profundidades tiene como finalidad, reducir la posibilidad de interferencia con el acuífero productor por enfriamiento.

Las perforaciones efectuadas con el propósito señalado de reinyección han sido en realidad proyectadas como perforaciones de "Doble Propósito" (producción-reinyección), mientras que otros pozos (Ah-2 y Ah-8), fueron perforados con el propósito de producción, y debido a su resultado desfavorable para ese propósito y a su ubicación marginal al campo, se hicieron reinyectores solucionando así dificultades de generación de energía geotermoeléctrica.

Geología

Con respecto a condiciones geológicas e hidrogeológicas, 2 factores básicos representan las diferencias específicas entre pozos de producción y de reinyección o doble propósito:

- La ubicación de estos últimos en los alrededores de la zona de explotación para evitar posible interacción. Esta tendencia ha sido más acentuada en la actualidad.

- La profundidad final para estos pozos (aprox. 1200m),obedece al criterio de sobrepasar el espesor del reservorio andesítico (aprox. 800 mts.), e ir lo suficientemente abajo para asegurar la reinyección de la mayor parte del agua residual en los aglomerados antiguos facilitando un mayor tiempo de calentamiento del fluido antes de alcanzar las capas superiores.

Proceso mecánico

No existen diferencias importantes en el comportamiento de la perforación para pozos de reinyección (doble propósito), excepto

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por el completamiento, el cual tiende a aislar con tubería ciega la formación productora. En los pozos de reinyección (Ah-17 y Ah-29), se ha colocado tubería de revestimiento de 7 5/8"colgada hasta alcanzar el techo del aglomerado antiguo. En los pozos productores, se trata de que los revestimientos cumplan solamente con su función de protección para las formaciones inestables, cubriendo al mínimo posible la zona productiva (véase anexo 2 de completamientos de pozos).
Puede entenderse fácilmente que las instalaciones de cabezal en pozos de reinyección (doble propósito), deben prever las mismas especificaciones que las de los pozos productores, no siendo este tan vital en los pozos productores usados como reinyectores.
Las demás características del proceso mecánico son similares a las mencionadas en la sección correspondiente a las perforaciones de producción.

Resultados

Con estas perforaciones se ha logrado comenzar una etapa de compensación económica al haber permitido la generación geotermoeléctrica (parcial) desde hace poco más de un año. Paralelamente a la generación se encaminan estudios para conocer sus posibles efectos.
Se han efectuado 2 perforaciones de reinyección (doble propósito)con completamiento correspondiente al sistema "b" (ver pag.17) usadas con éxito en la reinyección actualmente y 2 pozos de producción (sistema completamiento "a") se usan para la reinyección también favorablemente; además se ha efectuado recientemente la profundización de uno de ellos (Ah-2) para tratar de mejorar sus características como reinyector.
Otros pozos previamente perforados para delimitación del campo están en la línea de posibles reinyectores.

Los costos estimados para un pozo de doble propósito (reinyección-producción) y profundidad de 1200 metros es de $ 450,000 de los cuales un 55% corresponde a operaciones de perforación y un 45% a materiales. La perforación de un pozo de producción de aprox. 800mts. significa alrededor de un 75% del costo arriba mencionado.

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CONCLUSIONES

De acuerdo a los resultados sucesivamente examinados en las diferentes secciones del presente trabajo, las operaciones de perforación efectuadas desde los inicios de la exploración hasta la etapa de producción de vapor, han significado un factor determinante en los logros geotermales de El Salvador.

-Las perforaciones de investigación, se consideran totalmente necesarias en la etapa de estudios para la comprobación directa de las características petrográficas, hidrogeológicas y térmicas del subsuelo. Su localización depende más que todo de los propósitos específicos de la investigación.

Perforaciones a testigo contínuo, las cuales pueden alcanzar profundidades hasta de 600-800 mts. sin mayores problemas, eficientemente controladas, son medios de investigación múltiple. Su costo del orden de $ 40,000 por pozo de 400 mts. no es oneroso para lo valioso de la información básica aportada. Futuras exploraciones estarán mejor fundamentadas si previamente se efectúa este tipo de perforaciones.

En las áreas de Ahuachapán y Chipilapa han sido perforados pozos a testigo contínuo con profundidades de 300-450 mts., y en la última área mencionada se tratará de explorar hasta los 600 m. En las zonas geotérmicas de Oriente del país están programadas perforaciones en la etapa de desarrollo de las prospecciones geológicas, hidrogeológicas y geofísicas

- Perforaciones profundas, realizadas con diámetros máximos de 26" y generalmente con 17½", han logrado sus objetivos en nuestro país y especialmente en Ahuachapán, donde se han utilizado como medios de exploración profunda, producción y reinyección.

Normalmente las terminaciones (completamientos) no han representado problemas especiales. Casos aislados (Ah-24) de rotura de revestimiento y cementaciones especiales, fueron afrontados eficientemente.

Los pozos productores tienen profundidades medias de 800 m. para interceptar totalmente el reservorio andesítico, en el cual está programado, dejar totalmente abierta la formación y solo en casos especiales colocar tubería ranurada, si las condiciones de estabilidad así lo ameritan. Esto último se decide al llegar a la profundidad final,

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con pruebas específicas a ese propósito.

Los pozos reinyectores o de doble propósito se perforan al presente hasta 1200 metros de profundidad penetrando aproximadamente 400 mts. dentro de los aglomerados antiguos, dejando convenientemente aislada la formación andesítica hasta la proximidad con el contacto aglomerático.

Condición básica para los éxitos logrados en la perforación de los pozos ha sido especialmente la cooperación técnica, mecánica-geológica.

El anexo Nº 3 resume todo el proceso de perforación efectuado en el - país y que se ha descrito en este trabajo.

PROGRAMA DE PERFORACION DE UN POZO (A[illegible]-2[illegible])

Objetivo:

Perforar con 8 1/2" pozo de producción-inyección a la profundidad aproximada de 1200 m.

Datos:

Coordenadas del contrapozo:

Latitud: 311.09[illegible].3[illegible]

Longitud: 412,526.[illegible]

Elevación: 794.75 m.

Tubería de Revestimiento:

13 3/8" O.D. x 54.50 lb. K 55, Rango 3 Api Round thread hasta 85 m. aprox.

9 5/8" O.D. x 36 lb. K 55, Rango 3 Api LTC thread hasta 500 m. aprox.

7 5/8" O.D. x 26.4 lb. J 55, Rango 3, tubería ciega hasta 800 m., ranurada hasta 1000 m.

Centralizadores:

Centralizadores para tubería de 13 3/8" se colocarán en la primer tubería sobre la zapata y cada 25 m.

Para tubería de 9 5/8" se colocarán en la primer tubería sobre la zapata y cada 5 tubos hasta la tubería de 13 3/8".

Prueba de Presión:

1) Soldar cabezal de 13 3/8" y probar con 70 kg/cm^2 durante 15 minutos.
2) Se hará prueba de presión de la tubería con 50 kg/cm^2 durante 15 minutos.

Lodo de Perforación: Circulación de lodo debe ser mantenida mientras se justifique económicamente bajo la opinión del supervisor. La calidad del lodo se aconsejará durante el proceso de trabajo, pero "gel" deberá ser disminuído a cero antes de correr la tubería de revestimiento.

Pérdidas de Circulación: Todas las pérdidas parciales de circulación deben ser tapadas con materiales obturantes. Se utilizará cemento con adición de cascarilla de café, cuando se encuentre pérdida total.

Cementación de tubería de revestimiento: Toda tubería será cementada completamente según el programa que será elaborado oportunamente.

Verticalidad: Se tomará registro de inclinación cada 100 mts. perforados o en los cambios de barrena que se considere conveniente.

Geología: Sucesión litológica que se espera encontrar:

0-240 m.	Intercalación de flujos de lava con piroclásticos y tobas.
240-550 m.	Aglomerados jóvenes.
550-750 m.	Andesíticas basales.
750	Aglomerados antiguos.

Testigos: Se tomarán testigos a la profundidad que indique el Geólogo.

PROGRAMA:

1) Perforar con 17½" hasta 85 m. aprox. y correr T.R. de 13 3/8" O.D. hasta 85 m. aprox. y cementar la misma.

2) Después de 15 horas, cortar la tubería de 13 3/8", soldar el cabezal de 13 3/8"; se probará con 70 kg/cm^2 y se instalará B.O.P.

3) Perforar con 12¼" Ø hasta 500 m. aprox., correr T.R. de 9 5/8" O.D. y cementar la misma. Se hará prueba de presión de la tubería con 50 kg/cm^2.

4) Se continuará perforando con 8½" Ø y "Jets" hasta unos 100 m. abajo de la pérdida total. La profundidad mínima del pozo será de 1000m. y la máxima de 1200m.

5) Se tendrá especial cuidado, en todo momento de anotar todas las caídas de pared o atrapes de tubería.

6) A partir de la zapata de 9 5/8" O.D. se deberá perforar con barrena de 8½" Ø y "Jets" para tratar de abrir las fracturas del pozo. En pérdidas totales, se perforará con agua. Ocasionalmente se podrá usar lodo previa autorización del Supervisor.

7) Con los datos recabados, según (5), se decidirá si es necesario colocar "liner" ó no.

8) Se procederá a lavar el pozo con B.O.P. cerrado.

9) Movilización.

.../

ANEXO Nº 2

CARACTERISTICAS DE POZOS PROFUNDOS AREA AHUACHAPAN

POZO	ELEVAC.	PERFORACION (pulgs.)						REVESTIMIENTO (pulgs.)										OBSERVACIONES	FUNCION ACTUAL
								20	13 3/8	10 3/4		9 5/8		7 5/8		7			
		26	17½	12½	12¼	9 3/4	8½			Ciega	ran.	ciega	ran.	ciega	ran.	ciega	ran.		
Ah-1	812.73		35.05		189.9	1195.17			23.21			406.40							Productor.
Ah-2	828	96	700		1200			94	406										Reinyector
Ah-3	555.5	105	475		892.2			80	472				696.4					J-Slot 9 5/8" a 334.4	Observación, sin presión
Ah-4	812.23	52	405		642			50	401.55										Productor
Ah-5	791.45		404.6	469.8		951.63			90.19			456.93							Productor
Ah-6	792.97		25.75	455.23		591.16			90.60			454.3							Productor
Ah-7	824.79		103.63	404.35		950			96.73			403.36							Productor
Ah-8	810.27	110	467		299		710.7	107	463.75	380.44	434		502					Colgador 10 3/4 a 356.4-Reducc. 9 5/8 a 434.4	Reinyector
Ah-9	871.33		94.74		499.1				90.03			404.47					976.73	J-Slot 7" a 739.27	Observación, sin presión
Ah-10	723.7		102.11	422.07		1524			96.37			405.59		1162.14	1524			J-Slot 7 5/8 a 409.31-canasta a 1162.14 m.	Observación, sin presión
Ah-11	752.3	100	464		943.3			96.6	462										Observación, sin presión
Ah-12	720.9	100	409.56	728.47		1003		96	426										Observación, sin presión
Ah-13	959.6	99	420		931			97	410	479.96	812							Colgador 10 3/4 a 451.52	Observación, con presión (producción parcial)
Ah-14	821.77	97	542		570	800		96	448			464.6			628			Colgador 9 5/8 a 298 - Colg. 7 5/8 a 448	En profundización
Ah-15	772.48	22.7	495		704			98	491										Observación, sin presión
Ah-16	869.76	101	510		700			100	506		698.6								Observación, con presión (producción parcial)
Ah-17	773		505		452		1200		404.5			450		800				Colgador 7 5/8 a 351 canasta a 790 mts.	Reinyección
Ah-20	732.	96	455		600			84	449.5										Productor
Ah-21	735	25	477		942.6			94	472				632.6					Colgador 9 5/8 a 444	Productor
Ah-22	912		93		517		659.5		89.5			500.62							Productor
Ah-23	825.4																		En proyecto
Ah-24	793.1		99		454		850		95			254.02			845	434		Colgador 7" a 234.5 - Reducc. - 7 5/8 a 434	Productor
Ah-25	729.5		99.8		507		943		94.8			506							Pendiente pruebas de producción
Ah-26	771.1		97		413		804		96			399							Productor
Ah-29	794.75		94		550		1200		99			545		816				Colgador 7 5/8 x 9 5/8 a 495 mts	Reinyector

ANEXO Nº 3

Resumen General de Perforaciones Efectuadas en El País desde 1956 hasta 1976

INVESTIGACION						PROFUNDAS							
Preliminares		Gradiente		Testigo contínuo		Explor-Prod.		Delimitación		Producción		Reinyección	
Cant	Area	Cant	Area	Cant	Area	Cant	Area	Cant	Area	Cant	Area	Cant	Area
3	Agua Shuoa	7	Berlín	3	Playón	1	Chipilapa	5	Ahuachapán(Playón)	14	Ahuachapán(Playón)	2	Ahuachapán(Playón)
4	Salitre	3	Chinameca	1	Salitre	1	Salitre						
4	Ahuachapán (Playón)	4	Sta. Rosa	2	Los Toles	2	Oriente del País						
		24	Ahuachapán (Playón-Chipilapa-Salitre)	1	Chipilapa	3	Ahuachapán(Playón)						
TOTALES													
11		38		7		7		5		14		2	
56						28							
84													

NOTA:

15 Perforaciones someras que fueron efectuadas en el área Norte-Noroeste de Ahuachapán no se analizaron en este trabajo.

FRENCH GUIANA
FRENCH POLYNESIA
GABON
GERMAN DEMOCRATIC REPUBLIC
GERMANY, FEDERAL REPUBLIC OF
GHANA
✓ GREECE
GREENLAND
GRENADA
GUADELOUPE
✓ GUATEMALA
GUINEA-BISSAU
✓ GUYANA
HAITI
HONDURAS
HONG KONG
✓ HUNGARY
✓ ICELAND
✓ INDIA
✓ INDONESIA

✓ MALT
MART
✓ MAUR
✓ MEXIC
✓ MONG
✓ MORC
MOZA
NETH
✓ NETH
NEW
NEW
✓ NICAR
✓ NIGER
NORW
✓ PAKIS
✓ PANA
✓ PARA
PAPU
PENIN
✓ PERU

METHODOLOGY OF GEOTHERMAL EXPLORATION

Reconnaissance and prefeasibility phases

INDEX

1. Introduction

In keeping with the observations and recommendations listed by the VIII Reunion de Ministros de la OLADE, which took place in Quito, Ecuador, from the 5th to the 8th of last September, the Permanent Ministry is placing special emphasis on a new alternative source of energy which offers to satisfy energy requirements in a reasonable period of time: Geothermics.

The incorporation agreement, signed in Lima, Peru, the 2nd of November, 1973 for OLADE, considers as fundamental objectives of the Latin American Energy Organization, the promotion, coordination, and orientation of Member States with respect to new energy sources in accordance with the terms contained in Chapter II; in line with this Agreement, the Permanent Ministry believes that geothermal energy has wide prospects in Latin America in the area of development of non-traditional energy sources.

In accordance with the above, the Permanent Ministry of OLADE prepared a program of action that establishes as an objective the planned development of geothermics in the Latin American countries. In order to accomplish this, and as a first step in this plan, a general outline of methodology for geothermal exploration was completed, adaptable to the conditions and characteristics of each country, permitting OLADE to coordinate efforts in order to optimize technical, human and financial resources. These would be relied on in the area to set up a continuous interchange of experiences and multilateral support between the countries undertaking a search for or exploration of this resource.

Therefore, the Permanent Ministry assembled a group of experts that were requested to prepare a preliminary document about the methodology of geothermal exploration. That program was participated in by Dr. Thomas Casadevall, Geochemist, who was assistant professor in the National Polytechnical School of Ecuador, and presently Resident Geochemist for the U.S. Geological Survey in the vulcanology observatory of Hawaii; Engineer Salvador Garcia Duran, Geophysicist with the Comisión Federal de Electricidad de Mexico, current Superintendent of the Geothermal Project of the Smokejacks in the State of Puebla and the former Chief Geophysicist for the Cerro Prieto field; and Dr. Andrea Merla, Geologist, who presently is Director of AQUATER Geothermal Exploration, a subsidiary company of the Italian ENI Group. The geothermal program of OLADE and the work of the group of experts were coordinated by Engineer Elizarras from the Technical Department of OLADE.

The preliminary document was entitled: "Plan for a Methodology of Geothermal Exploration". This is the same one that was circulated among the Latin American countries and among some official institutions of other countries and international organizations interested in Geothermics.

Because of the interest shown by OLADE's iniative, a Seminar on Geothermal Exploration was organized that would allow revising and completing the issuance of the document. This seminar took place in Quito, Ecuador the 27 to 31 of March, 1978, with the attendance of 10 Latin American countries, the United States and Italy, as weel as Observers from institutions of higher education and companies in the business of geothermal exploration (see the attached list of participants).

The geothermal program of OLADE, from its beginning, relied on the valuable support of the Instituto Italo-Latino Americano (IILA) who provided the presence of Dr. Andrea Merla in the group of aforementioned experts and at the same time IILA cosponsored the Seminar. For these reasons, OLADE was very happy to have joined its efforts with the IILA for the start of the program and especially for the Cooperation Agreement signed between the two organizations, an act that would provide for joint action in common areas in the energy field.

Given the splendid possibilities that Geothermics offers the countries in the Andean area as an alternative energy source, the Corporation Andina de Fomento (CAF) was added as cosponsor to the Seminar.

Also, because of the experience that has been gained on the subject and as a further support for getting Latin American energy integration, the Comision Federal de Electricidad and Petroleos Mexicanos (PEMEX) contributed to the cosponsorship of the Seminar.

The main result of that meeting is this paper and in it is proposed:

-to outline the development of a geothermal type project
-to describe the methodology that could be used during the different phases of surface exploration
-to present a preliminary evaluation of the human and financial resources required for a geothermal type project in order to reach the stage of deep exploration and to place the different phases of the project in a schedule

Therefore, this paper tries to serve as a reference guide for planning specific geothermal projects and directing their development during the first stages of activity, by making use of the best information available and the technical resources of the countries themselves.

It is important to point out that the attention given to geothermics by the Permanent Secretary of OLADE, is based on technical-economic plans that could be adapted for any country in the area; and that by carrying them out, following programs such as this one, they could help in the search for and acquisition of funds which managed by OLADE will insure the start of new geothermal projects or the enlargement and support for those already in progress.

Finally, OLADE wants to express its appreciation to the aforementioned experts that made up the OLADE Geothermal Group and extend its thanks in a special way to their respective institutions for their cooperation in agreeing to the temporary absence of their experts without any profit except the experienced gained by them in this work.

The Permanent Secretary acknowledges the effort put out by the administrative personnel who helped with this part of the program and especially those of Mrs. Elvia Ortega de Andrade who was in charge of proofreading and the final document.

Quito, April 1978

2. PROPOSED METHODOLOGY FOR EXPLORATION

The methodology for exploration that is proposed, gives a general idea of what a geothermal type project is, the exploratory methods to be made use of, and the necessary personnel; all of this for each one of the stages, and finally, the amount of required investment. The proposed methodology is the result of the revision of a certain quantity of geothermal exploration projects, completed or in progress, in the recent areas of volcanism in Mexico, Italy and various Latin American countries, and is in agreement with the most advanced scientific progress in techniques for geothermal exploration.

This work has as its principal objective directing those countries where geothermal exploration is in its first stages and for which a special emphasis is placed on low cost exploration tools; in addition, the importance of complete reconnaissance studies is pointed out. In determining the exploration sequence an effort has been made to minimize, in the first stages, the intensive use of methods that would require large investments.

With the lack of a 'universal method', capable of resolving the problems related to the different exploration phases and automatically permitting the identification of a geothermal field, the preparation of a methodology has as it most wary feature the selection and combination of techniques that are suitable for the particular objectives of each project. In effect, the wide variety of possible local conditions can demand substantial changes in the sequence, and/or the manner os use of the proposed exploration techniques. In the computation of time and investment requirements, one has taken into account variables like: the size of the exploration area, the local availability of personnel, logistic support and the geographic conditions. In fact, the exploration philosophy proposed here focuses on the average geological conditions of Latin America and the Carribbean.

2.1 Development of a Geothermal Type Project

A first approach to the establishment of objectives of geothermal interest are the borders of the lithoferric slabs, characterized by tectonic and recent magmatic activity (e.g.: the Andean system, the Central American mountain range, the Carribbean area, etc.)

Nevertheless, the simple fact that a country or region belongs geographically to these parts of continents, does not guarantee finding 'a priori', geothermal fields with industrial value. As a result, in order to develop a geothermal project in little studied geological areas, it will be necessary to begin exploration activities with a Reconnaissance Study in areas that can vary between 10,000 and 100,000 square kilometers.

This initial study would allow one to set up the first work program as well as select choice areas, whose extension would be defined as being between 500 and 2,000 km2, thus more easily permitting the development of a geothermal project.

In general, a geothermal type project consists of two main parts (fig. No. 1): the first ahs a predominantly high risk, associated with the exploration of any mineral or energy source, and its objective is the identification of the field (geothermal field), including a study of possible applications; the second is a mixed type (exploratory, technological and energy risks) and is concerned with the development and exploration of the field. The first part has high levels of economic risk and should be met by progressively increasing investments; nevertheless, in all it makes up a small sum as will be seen later on in the estimates for required expenditures; the second part, on the contrary involves less risks but requires much greater outlays.

From the practical point of view, it is important to divide the geothermal type project into 5 different stages, of which the first three - 1) reconnaissance study, 2) prefeasibility study and, 3) feasibility study, refer to the exploratory part of the project; the other two - 4) development, and 5) working, are directed towards the systematic production of endogenous fluid, its industrial applications and the problems of managing the field.

The schematic drawing of the development of a geothermal type project is shown in the flow chart in Fig. No. 1.

STAGES IN A COMPLETE GEOTHERMAL PROJECT FIGURE 1

Reconnaissance study
Area: 10,000-100,000 km2

Prefeasibility study
Area: 500-2,000 km2

Exploration

Feasibility study
Area: 10-100 km2

Development

Working

Experience gained to date has shown that the average dimensions of a 'field' are found to be between 10 and 100 km2. If, as already stated, the geothermal project is located in a region of around 10,000-100,000 km2, the localization of the possible field will require intermediate stages of exploration that will allow: first, delineation of the 'area of interest' (500-2,000 km2) on the basis of the reconnaissance study, and later, the selection of one or more promising areas not greater than 100 km2 where the sites for the deep exploratory drill holes will be situated.

In keeping with the above, the prefeasibility study will have as its main objective the localization of the sites where the deep drilling will take place and should be subdivided into different phases, which should be carried out in reasonable periods of time since the expenditures grow proportionately with the progress of the progress. Therefore, it is necessary to begin with studies and explorations of a regional character whcih involve relatively low costs, leaving the more detailed study and exploration only for the areas of greater interest, and which, as already stated, normally are found between 500 and 2,000 km2.

These criterion facilitate the interpretation, systematically and in an integrated manner, of the results of the explorations and to disgard the unfavorable portions of territory, and also evaluate the expediency of going on to thenext stage of work.

2.2 Reconnaissance study

This would consist of the evaluation, for geothermal purposes, of all of the available information in conjunction with a series of preliminary investigations on a local scale. It would help to set up the first work conditions, to select the most promising areas, and to lay out in a concrete manner the courses of action for the following phases of the project (prefeasibility and feasibility)

2.2.1 Objectives

-Preliminary evaluation of the geothermal possibilities on a national or regional level

-Selection of the areas of interest

-Determination of a preliminary geothermal plan and subsequent detailed study of exploration in each area

These objectives represent the technical data,that, together with socioeconomic and political considerations, will form the basis for making the following decisions:

a) What priority should be given, on a national or regional level, to geothermics commensurate with alternate energy sources (ex: hydroelectricity, fossil fuels, etc.)

b) Defining areas of maximum priority in planning future explorations, taking into consideration the technical factors (indications of geothermal potential resulting from the reconnaissance study) as well as the economic ans social factors. Some local factors could play an important role in this stage; such as is the case of the possible exploitation of geothermal energy in an area in which there isn't any other energy sources available for generating power in this area or other activities that need local availability of energy at a low price (example: mining or certain types of industries, etc.)

c) Determining the amount of investment and technical data necessary in order to evaluate the geothermic potential of the area that has been established as having the greatest priority

2.2.2 Methodology

Speaking in general terms, a reconnaissance study at a national or local level can be summed up in the following manner:

Phase 1 - Evaluation of all the relative existing information.

In this stage all the basic documentation would be collected. This documentation would include:

- -Geological maps, detailed and on a local scale
- -Local geological study, including stratigraphy, structural geology, volcanic history, etc.
- -Satellite pictures and/or aerial photography
- -Topographical maps, detailed as well as regional
- -Information about the presence and characteristics of the thermal sources and hydrothermal conditions
- -Data obtained from wells that have been drilled for other purposes (oil, water, etc.)
- -All the available geophysical information

The evaluation of this information outlining geothermal areas (geologically homogenous areas) and selecting the areas where the following phase will take place (field exploration).

Phase II. -Field exploration and laboratory analysis

On the basis of the results in Phase I, a field reconnaissance study will be planned.

The main object of this study would be to collect specific information related to:

1) the possible presence of a thermal anomaly at surface levels of the terrestrial crust

2) the local hydrogeological conditions; and,

3) the nature of the thermal manifestations

In volcanic regions it would be very important to concentrate the geological observations on the following points:

-Identifying the areas in which there is a concentration of recent volcanic episodes. This concentration is clear evidence of the persistence of an important thermal anomaly in the subsoil

-Evaluating the relative quantity of acid volcanic products that are caused by differentiation of basic magmas or by anatexis.

-Explaining, at a local level, the relations existing between the volcanic structures and the regional tectonics.

-Investigating the possible presence of craters of phreatic explosion

-Collecting samples, of the greatest possible number, of lithological types for subsequent analytical work. At this stage, the petrographic work will be limited, in most of the samples, to studies of thin laminas.

-Collecting samples of xenoliths of the pyroclastics for studies in thin laminas

-Determining the absolute age in selected samples.

-Studying in a preliminary form all the possible formations, cover and reservoir

As far as the the geochemical and hydrogeological field work are concerned, it would be necessary to sample a representative number of the waters in the reconnaissance zone (cold or thermal springs, surface or well water).

The study to be done in this stage should be chosen based on the availability of: 1) personnel; 2) financing; 3) equipment; and 4) time. Depending upon the availability of the 4 previously mentioned factors, two plans can be set up: one that we will call mimimum and another that would be optimum, both trying to fulfill the objectives of the reconnaissance study. These are:

		MINIMUM	OPTIMUM
DATA REQUIRED:	Field	T°C pH	T°C pH Cl or conductivity
		visual estimate of flow	visual estimate of flow
		collection of samples	collection of samples
	Laboratory	K;Na;Ca;Mg;Cl; SO_4/ SiO_2	K;Na;Ca;Mg; Cl;SO_4; NH_4; SiO_2 (diluted)
	Personnel	Personnel not necessarily specialized in chemistry	Person(s) trained in field chemistry

	MINIMUM	OPTIMUM
Equipment	Thermometer	Thermometer
	pH paper	pH paper or pH meter
		Cl- paper or conductivity meter
	Flasks for samples and collection system	Flasks for samples and collection system

The chemical analyses will allow the calculation of subsoil temperatures by means of the use of geothermometers such as SiO_2, K/NA/Ca, etc. Flow estimates (l/sec or l/min) will be required for the application of models in order to determine the possible rate of mix between thermal fluids and other waters of the soil and subsoil.

2.2.3 Results

The work in phases I and II, in combination with the subsequent evaluation of all the data, should give as a result the following:

a) Determination of the main geothermal areas. (example: areas of geothermal interest related to recent volcanism or magmatic intrusions, areas of normal gradient)

b) Selection of areas of interest, indicating the probable existence of fluids with high heat contents in the subsoil, that is, areas in which the exploitation of geothermal energy would be feasible with presently used techniques.

Also the areas in which it would only be possible to find fluids with low heat content would be specified. Their exploitation could be: energy by binary systems or, non-energy in agricultural, industrial or residential situations.

The selected areas should have an area between 500 and 2000 km2.

c) Determination of the scale of priorities. Those areas which offer the most favorable geological conditions for the presence of a geothermal field at an economically exploitable depth should be of top priority. This scale of priorities should be determined on the basis of 'technical' considerations.

d) Determination in each area of a preliminary geothermal plan. This plan will take into consideration the features relative to the presence of a superficial thermal anomaly and the geological and hydrological conditions of the zone, and

e) Establishment of a detailed exploration program (Prefeasibility Study)

A plan for the in depth studies needed in order to better define the geothermal pattern of each area will be laid out. The objective of this plan will be to locate sites for drilling deep exploration holes in diameters suitable for production tests.

2.2.4 Personnel requirements, time and costs

The initial part of the geothermal exploration in any area requires highly experienced personnel, since it is during this stage that the guidelines for future exploration are established.

Data collection (Phase I) can be done by technical personnel not specially trained in geothermics.

The evaluation of the collected data should be, nevertheless, done by extremely qualified technical personnel with a lot of experience in geothermal exploration. This staff will be, therefore, responsible for the second phase of the work and will include a structural geologist, a volcanologist, a geochemist, and a geohydrologist.

The amount of time required to complete Phase I and Phase II can vary according to the size of the area to be explored and the amount of available information

On the average, for the reconnaissance of an area of 10,000 to 100,000 km2, it shouldn't exceed a 9 to 16 month interval, estimating 2 to 4 months time for the collection and evaluation of data; 2 to 3 months for field reconnaissance; 1 to 3 months for laboratory analyses and 4 to 6 months for the evaluation of the results and preparation of the final reconnaissance report.

The cost of the reconnaissance study, assuming the aforementioned areas, could be between a minimum of 100,000.00 U.S. dollars and a maximum of 250,000.00 U.S. dollars. These estimates are dependent on many factors that will explained in more detail in the chapter on the costs of prefeasibility studies.

2.3 Prefeasibility Study

It has as its main object identifying the most promising areas, in which the costs would be sufficiently low to advise moving from superficial exploration to deep exploration. This phase carries out the preliminary evaluation of possible resources.

2.3.1 Objectives

a) To determine the preliminary geothermal plan of the selected area.

The 'geothermal plan' of an area will be determined when there is available detailed information regarding: 1) the presence and origin of thermal anomalies; 2) the characteristics of the cover formation or seal rock; 3) the pattern of general water circulation; and 4) the type and characteristics of the "reservoir".

b) Laying out the sites for deep exploratory drilling with diameters suitable for production tests.

A three dimensional model of a selected area would allow planning an adequate drilling program, directed towards testing the validity of the model.

2.3.2 Methodology

The detailed exploration plan for each given area, whose principal geothermal characteristics were already outlined during the Reconnaissance Study, will generally consist of investigations of varying costs. The emphasis given to low cost exploration seeks, as a result, maximum efficiency in the investment for higher costing investigations.

A. Geology-Hydrogeology-Geochemistry

A-1) Geology and Volcanology

The work will generally start off with an interpretation of a geological aerial photograph; working towards the determination of faults, mapping of volcanic structures, definition of volcanic-tectonic relations and fault systems related to buried intrusions, and towards the integration of existing geological maps.

The second step will be a geological and vulcanological survey. Its principal objectives will be:

a) to investigate the presence of a thermal anomaly at surface levels of the terrestrial crust. For this purpose, representative samples of recent volcanic sequences will be taken, seeking to get information about the present, at surface levels, of a thermal anomaly (nature of the volcanic rocks, presence of a series of differentiation, etc.) and being so, the possibility of determining absolute ages. All of the hydrothermal areas, fossil as well as active, will be studied.

A detailed mapping of all the volcanic structures will be done (central volcanoes, domes, craters of phreatic explosion, extensions of fissured and pyroclastic lavas). Also a study of morphological characteristics will be carried out.

b) Identification of the cover formations and an evaluation of their efficiency. This includes the mapping and the collection of samples from all of the formations which offer adequate cover characteristics, from primary origin (clays, etc.) as well as due to self-sealing by processes of hydrothermal alternation. In volcanic zones a greater emphasis will be placed on searching for craters of phreatic explosion. Their presence indicates the existence of an effective cover.

c) To gather information about the existence of possible geothermal "reservoirs".

All of the existing evidence about the presence of a "reservoir" at an income-producing depth should be studied.

In the volcanic zones, the sampling and study of xenoliths produced by explosive eruptions, can provide information about the nature of the rocks located beneath the surface of the volcanic cover.

In those cases in which it is possible, this investigation of low cost will enable one to become familiar with the lithology of the reservoir and the temperature and the nature of the circulating fluids. In any case, these datum provide information about the lithology of the subsoil that are useful for other types of investigations: hydrogeology, geochemistry, etc.

Finally, the identification and mapping of recent faults is very important, since the actives faults frequently represent good objectives for exploration due to their permeability by fractures. The old faults, on the contrary, can be completely sealed by hydrothermal processes.

In tropical countries, where a rapid and strong weathering of rocks occurs and where there is a heavy covering of vegetation, the geological data, can be, at times, difficult to obtain with surface studies or indeed limited to small areas which are not easily correlated.

In such cases emphasis should be placed on the following types of studies:

1. Morphological observations carried out with the help of aerial photographs and analyses of satellite pictures. In many cases, simple morphological observations supply useful information about the tectonics of the area, volcanic structures, age of the volcanism, etc.

II. The identification of recent faults can be the one of greatest importance in these regions since the rapid weathering of the volcanic products can substantially reduce their primary permeability. Therefore, in these areas the fractured zones will be the objective of geothermal exploration.

III. Aerial geophysics with remote sensors (SLAR) can be productively used in these areas; the degree of application will depend upon economic considerations and local situations.

A-2) Geochemistry and Hydrogeology

The main objectives of the hydrogeological-geochemical programs during the prefeasibility studies, are the following:

1. To determine the regional geochemical conditions for the best understanding of the patterns of water circulation.

II. To try to determine the presence of a geothermal system in the subsoil, by using chemical and isotopic geothermometers or by detecting anomalies in the manifestation of existing leakages.

The hydrogeological-geochemical study is made up of three interdependent activities and they are:

a) Field operations

-Visit to all the sites of water discharge, such as cold or hot springs, wells, and drainages.

-Detailed description of each site, including an exact calculation of water flow and description of the altered zone adjacent to the source of the discharge

-Sampling of water, and if pertinent, of gases, always in suitable containers

-Field determination of: T°C, pH, Cl-, conductivity and possibly Fe^2, Ca^2, Mg^2, HCO_3, NH_4. A field analysis is required, or an adequate conditioning of the sample for future analysis, since with time important changes in the chemistry of the constituents can take place. The field analysis should be done at the same level of quality as the laboratory analysis.

-Sampling of the sublimates in the thermal springs.

-In accordance with the average geological make-up, an analysis of gases (He, Hg, CO_2) can directly indicate the presence of a thermal anomaly in the subsoil.

b) Laboratory analysis

-The laboratory analysis work depends on the nature of the average geological conditions, normally it requires the determination of 12 to 18 constituents. The determination of the sublimates can be done by a chemical analysis or by means of of x-rays.

c) Interpretation

-The processing of the analytic data will give as a result: the identification of the main chemical types of water and existing mixes; an interpretation of the source of the thermal waters; a map survey of the leakage anomalies and the calculation of the temperature of the reservoir. This processing of data and interpretation can be facilitated by doing the anlysis with a computer, when possible.

B. Geophysics and Shallow Wells

B-1) Geophysics

The use of mining techniques should be focused on three main objectives:

1. To determine the regional structural-geological conditions of the zone where the geothermal resources are found situated.

2. Mapping and demarcation of thermal anomalies.

In the first stage, a gravimetric study, and eventually one in magnetometry or aeromagnetometry provide the most accurate tool for determining the major geological structures in the zone. These techniques of geophysical exploration can be realized during the development of the studies in stage A, but being careful that they are begun at the time that the most relevant geological situation is known.

In the second stage, the traditional electronic methods, maps, and/or geoelectric profiles of resistivity, can be utilized in order to analyze the contrasts in resitivity associated with possible zones of anomalous temperatures. A semi-detailed study, regional or partially regional, can be planned upon having an adequate knowledge of the geological situation of the zone; on the basis of this study a more detailed survey will be scheduled.

The use of other techniques (electric, electromagnetic, seismic noise,etc.) should be considered for the moment as experimental techniques, but without rejecting their use in the future.

In the last stage, the geoelectric techniques (vertical electric soundings), active seismic (reflection or refraction), passive seismic (micro-earthquakes) and others, can be used to determine particular geological situations like: cover thickness, depth of particular geological layers, determination of active faults, etc. The planning for the use of any of these techniques should take into account the specific problem to be analyzed and the cost/accuracy that will result.

B-2) Multipurpose Shallow Drillings

The drilling program for surface wells will not be decided until a sufficient knowledge of the geological and hydrogeological conditions has been obtained. The number, location and depth of the test holes will be those needed in order to get the maximum information with the minimum investment. These holes will be decisive factors in the definition of the geothermal model of the zone.

The depth of these small diameter wells will be planned in accordance with the geohydrological conditions; they should reach, and even penetrate the impermeable stratum of the reservoir key horizons if the objective is to calculate the temperature of the reservoir. Nevertheless, it should be taken into account that the determination of geothermal gradients on the basis of the supposition that the process is purely conductive has caused numerous failures, because the interpretation of the slightly deep thermal gradients are frecuently erroneous.

The sampling of gas and water in undisturbed horizons; the structural correlations and, naturally, the temperature predictions at key horizon depths are examples of some of the objectives of these drillings.

In these circumstances, it is difficult to establish the most appropriate depths; the decision, depends on a correct evaluation of the data that one has tried to obtain against the total cost of the drilling.

Generally, the objectives of these wells are one or more of the following:

-To carry out a series of temperature measurements in order to calculate the thermal gradient and predict the temperature in depth

-To collect rock samples for measurements of conductivity (calculation of calorific flow)

-To collect samples of the fluids that are usually found, in order to determine possible convectors that would alter the previous objective, and to carry out chemical analyses in order to integrate them with the surface geochemical study

-Measurements of electric resistivity throughout the drilled section, in order to correlate the studies of surface electric resistivity

-Study of the stratographic succession

It should be emphasized that only a detailed knowledge of the surface geological, hydrogeological, and hydrochemical conditions will permit carrying out an estimate and extrapolation of the geothermal gradient, of the temperatures, and of the production possibilities.

2.3.3 Personnel requirements, time and costs

The number of technical personnel required for the execution of the phase depends on the local situation. Nevertheless, it is possible to give a general idea with regard to the organization and the time reouired, taking into consideration an area between 500 to 2000 km2 and the existence of basic data like detailed topographical maps, geological maps and aerial photographs.

A. Personnel

The following is a schematic summary of the personnel required to carry out a prefeasibility study of such magnitude in an area.

-Geology and Volcanology

Photogeological interpretation	1 photo/interpreter geologist 1 photo/interpreter technician
Field work	1 geologist 1 volcanologist
Laboratory analysis	1 petrographer
Preparationof data and reports	1 geologist 1 volcanologist
Supervision	1 geologist, expert in geothermal exploration

Hydrogeology and geochemistry

Field work	1 hydrogeologist 1 geochemist 1 chemical technician
Laboratory analysis	1 geochemist 1 chemical technician
Preparationof data and reports	1 geochemist 1 hydrogeologist 1 estimator
Supervision	1 geochemist, expert in geothermal exploration

-Geophysics

Independently of the geophysical studies that will be carried out by management or by means of contracts, the project should rely on a chief geophysicist, who will be responsible for the geophysical program to be carried out, as well as for its execution and interpretation.

-Shallow Wells

In this stage a contractor will be used for the drilling unless the proper equipment is available. When considering the use of a contractor, the project should have the personnel needed for the supervision of the drilling, the measurements, and the analysis of data; these personnel are:

At the wells	1 geologist 1 geochemist 1 geophysicist

-Preparationof the final prefeasibility report

This work should be done by all personnel that took part in the field work and preliminary reports, including a drilling engineer. The supervision of geothermal experts with proven experience in exploration are necessary in order to obtain a better analysis.

B. Time

The technical work, based on the averages attained up to now in the geothermal exploration of some Latin American countries, can be summarized in the following manner:

Geology-Volcanology (field work, laboratory analysis, report)	9-15 months
Geochemistry-Hydrogeochemistry (field work, laboratory analysis, report)	9-15 months
Geophysics (field work, interpretation, report)	9-15 months
Shallow drillings* (drilling, measurements, report)	7-16 months
Final report	4-6 months

The total amount of time for the production of a prefeasibility study, taking into account that some of the previously mentioned activities can be done simultaneously, varies between 20-30 months. Nevertheless, these periods, total and partial, can be reduced by an optimization of the methodology and the personnel employed. That is, in itself, one of the main intentions of this program.

C. Costs

The costs for an exploration program like the one described in the preceding chapters, can vary according to various factors:

-The volume of existing geological and hydrogeological information

-The existence of trained and expert local personnel

-The geographical and geological characteristicsof the region to be investigated

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*Average amount: 2000 m of drilling in multiple wells

-The local availability of laboratory and computation facilities

A cost estimate is, nevertheless, very difficult to make, due to the great variations in the above indicated factors. Nevertheless, we will attempt to describe the necessary investment scale. The philosophy that will be followed in order to estimate the needed investments is based on two principles:

a) Emphasis should be placed on the use of exploratory instruments, such as for vulcanology and geochemistry. These methods provide very important information and cut down on the use of more expensive techniques.

b) When a certain stage of exploration has been reached, major expenditures will not be necessary in order to have additional understanding of the geothermal system. It is in this stage that the decision to begin the deep drilling can be made.

In this estimate are also considered variables such as: availability of expert local personnel, number of members from local personnel, number of staff from external personnel, and to a certain degree, geographic conditions.

With these given considerations, the estimated cost, total, of the prefeasibility study, based on an area between 500 to 2000 km2, would be:

minimum of	$800,000 U.S.
maximum of	$1,600,000 U.S.

Once the prefeasibility phase is completed, and if the results point to continuing the work, one will precede to the last phase of the exploration stage: the feasibility study.

The feasibility phase can be defined as the study that establishes the physical site of a geothermal field, subsequent evaluation of extractable reserves and preliminary evaluation of the available resources; as well as the study of the fluid, possible plans for its utilization for power and/or other uses and the eventual installation of a pilot plant or industrial unit.

This study, as part of a geothermal project, includes the first exploration soundings, studies which allow determining the production characteristics and utilization of the fluid, economic studies, as well as the design of a power plant.

In this document only the first two stages of a geothermal type project will be analyzed, or in other words, the reconnaissance and prefeasibility studies. The analysis of the feasibility phase is the subject for another program.

3. DESCRIPTION OF THE PRINCIPAL METHODS OF EXPLORATION

3.1 Geological Exploration in Volcanic Areas

A geothermal field susceptible to exploitation, whether for production of gas for purposes of electric power, or of hot water (low heat content) for non-power purposes, should have the following as principal characteristics:

-A thermal anomaly

-A reservoir made up of permeable rocks within which geothermal fluid circulates. The reservoir should be at depths that make its exploitation economical.

-An impermeable cover on the reservoir that impedes the loss of heat by convection of fluids towards the surface.

3.1.1 Heat sources

In many volcanic regions, the heat required for the formation of a geothermal system, located near the terrestrial surface, can be supplied, essentially, by a mass of high temperature magma situated in the terrestrial crust, either as an intrusion in the process of cooling or as a magmatic chamber feeding a volcano. Theoretically, all the zones affected by recent volcanic phenomenon are probable geothermal sites; nevertheless, the areas of practical interest are only those where a large volume of magma is found at a relatively shallow depth (less than 10 km). So, areas in which the magma has directly and rapidly risen from the mantle through fissures, such as plateau basalts, are of less interest.

Also one should consider geothermal potential, those areas where there remain locally large volumes of magma within the upper part of the continental crust (acidic magmas originating within the crust itself) or areas with large central volcanoes related to magmatic chambers.

In the preliminary exploration of a geothermal region, the problem of locating a thermal anomaly, normally near the surface, should be dealt with by volcanological, structural and petrological methods.

These methods help to distinguish central volcanoes by assessing their significance in the regional structural scheme and by estimating their age by morphological criterion or by measurements of absolute age using radiometric methods. The presence of active fumaroles in the craters of central volcanoes is the best indication of the recent age of the volcano. Nevertheless, the crater of an active volcano cannot be considered, for the present, for geothermal exploitation.

Petrological studies of lavas and other volcanic products are helpful in defining the nature of the magma, in particular its degree of acidity and differentiation. These datum are essential for evaluating the possible existence of magmatic chambers near the surface, which feed the volcanism; besides, in order to estimate if the nature of the magma confirms the existence of a superficial thermal anomaly within the terrestrial crust. The latter includes the case of magmas formed by anatexis of the crust (partial fusion of the upper continental crust, which is a process that requires strong anomalies at a moderate depth).

The formation of magmatic chambers of sufficient thermal capacity, which allow increasing the heat of a large volume of rock, requires favorable tectonic conditions, like the crossing of different faults or the inclination of faulted blocks that make up appropriate tectonic traps, where the rising magma settles and creates its differentiation. Therefore, one should investigate the relation between volcanic structures and tectonic outlines in order to spot the occurrence, at a shallow depth, of hot magmatic bodies.

Favorable elements are: the persistence of volcanic activity through time and the frequent eruptions of strongly differentiated products, which for their formation require a long period of demurrage of the magma in the chamber. In the majority of cases, the magmatic chambers are reservoirs that feed the complex of central volcanoes; the volcanic structures are formed around a central chimney with various eruptions of products of different composition, genetically connected to each other by fractional crystallization.

In other cases, only the differentiated magmas, more evolved and lighter, are capable of getting to the surface through fissural eruptions of different intensities, forming volcanic fields with some monogenetic centers (Campi Flegrei, Italy) or, also, important pyroclastic eruptions.

Also, the magma can remain at a shallow depth without producing a volcanism; nevertheless, these upheavals in the upper crust affect the surface tectonics by the formation of "horst" generally interspersed with minor collapses (as in Larderello, Italy) or peculiar systems of radial or concentric faults.

3.1.2 The reservoir

The reservoir is formed by rocks of high permeability, with a sufficient volume to insure an extended exploitation. Besides, the reservoir should be located within a favorable hydrological system. The delineation of the reservoir is the most difficult problem in geological exploration. The principal reason, is the presence of extensive surface volcanic covers that often prevent the direct study of the deepest substratum. This, requires a knowledge of general geological standards; in particular, those of thicknesses, depth, lithology and permeability of various stratographic units that are found under surface volcanic cover. In many cases, the stratographic studies and the geological surveying can provide important information concerning the reservoir.

Also the identification of areas of greatest permeability by fractures due to tectonism and their pattern of distribution is very important.

From the study of the xenoliths in the volcanic rocks, important information can be obtained. This includes samples of the subsurface lithological horizons and their study can also provide evidence of manifestations of hydrothermal alteration caused by the circulation of high temperature fluids.

The xenoliths of rocks in the subsoil occur chiefly in products of volcanic explosions (tufa, tephrites or ibnimbrites)**. These xenoliths should be studied and sampled, the altered as well as the unaltered. Special attention should be given to observing the texture of the hydrothermal minerals (in veins or random distribution) and to the usual paragenetic changes, with which it is possible to identify changes in the physical-chemical conditions of the circulation of fluids.

Finally, the evaluation of the reservoir (lithology, depth, structure) requires the use of geophysical methods: one of theppřinciple objectives of geological exploration is to determine the best geophysical method and to use it in the exploration, always basing it on the local geological characteristics.

3.1.3 The cover

The cover should be made up of an impermeable formation. It can be sedimentary rock with primary impermeability (clay, lime, lacustrine deposits), as in Cerro Prieto, Mexico; Larderello, Italy, or in Wairakei, New Zealand; or rock impermeabilized by self-sealing due to the continuous effects of thermal activity, as isthe case of the Geysers, USA, or Otake, Japan. In order to determine this cover, it is necessary to know the stratigraphy and lithology of the subsurface horizons; this investigation can be done on a strictly geological basis, although geophysical studies are almost always necessary in order to determine the thickness of the impermeable layer. The presence of an impermeable formation near the surface is essential for determining the usefulness of shallow wells of geothermal gradient in the later stages of exploration. These wells are useful only when they penetrate the impermeable stratum where the temperature distribution is not altered by the circulation of meteoric or surface water. The drilling will be economical only if the impermeable beds are at a shallow depth.

3.1.4 Surface manifestations

In regions where the cover is fractured by faults, the fluids of the reservoir can rise directly to the surface, producing various thermal phenomenon (hot springs and fumaroles). The presence of such surface manifestations is an indication of the probable existence of a geothermal field. Nevertheless, such indications are not absolutely necessary; geothermal fields can exist without chemistry of the fluid in a dominant steam system doesnot generally have a direct relation with the underground "reservoir" due to the boiling of the fluid and the subsequent presence of two phases: liquid and steam. In this case, the presence of a high temperature fluid is already established.

In the prefeasibility stage, the geochemical studies are used for:

a) determining the variation in the average geochemical conditions, through the classification of the types and interactions (mixes) of the different waters and gases, according to their chemical composition. The result of this is a grouping of surface waters, underground waters and thermal springs according to their chemical composition and permits the identification or characterization of the possible reservoir(s) based on the type of water.

b) determining the origin of the fluid phase, as well as locating the recharging area through the use of isotopic analysis (hydrogen and oxygen) of the the waters

c) Identifying the distribution patterns of certain particular elements; these can result from the dispersion of said elements outside of the heat source or more generally, outside of the geothermal system.

d) estimating the minimum temperature of the reservoir by the use of various geothermometers and patterns of mix

e) becoming familiar with the chemical problems related to the production and removal of waste fluids, including waters as well as gases

3.2.1 Purpose of the program and methodlogy

The geochemical program consists of three activities: 1) field 2) laboratory and 3) processing and interpretation of data

The relations between these three activities is represented in a diagrammatic form in Figure 2.

a) Field activities

The field studies are necessary inoorder to collect water, gas and sublimate samples in order to analyze them in the laboratory and also in order to do measurements of variables such as T°C and volume of flow of fluid, which cannot be measured in the laboratory. It is advisable to take portable lab equipment to the field in order to do measurements of pH, NH_4, Fe 2, gas dissolved in the water, as well as for sampling and analysis of gases.

b) Laboratory activities

The laboratory studies involve the analysis of samples collected in the field. In the water samples, the following elements and constituents should be identified.

such geothermal manifestations (Los Humeros, Mexico). Also, there are hot emanations that do not have any relation to geothermal fields of high heat content, but instead are related to a rapid rise, along the faults, of water originating from depths in areas with normal geothermal gradient.

The study of the surface phenomena should be done taking into consideration the general hydrological organization. One the one hand it presupposes a knowledge of the hydrology of the region (meteoric water and underground water) as well as of the principle structures that control the hydrothermal systems and also of the structural characteristics of each source; on the other hand, it requires a detailed geochemical exploration. The purpose of the geochemical study is to provide data for the hydrogeological model and to detect theleakage phenomena of the deep geothermal reservoir. Valuable information can also be obtained from studies of the sublimates of the fumaroles.

3.1.5 Craters of phreatic explosion (hydrothermal)

A particularly important part of a geothermal field (not necessarily volcanic) is the frecuent presence of craters of phreatic explosion (hydrothermal). These structures are produced by the explosion of pockets of steam heated and kept under pressure by an impermeable cover. Their presence indicates that all the basic elements of a geothermal field (impermeable cover, fluids at depth, heat anomalies) are present in the zone affected by the explosion. Nevertheless, these structures should be carefully investigated, by estimating their age.

3.2 Geochemistry

A geothermal area can be considered as a chemical system of high temperature. The principle components of this sytem are: the fluid phase (water, gas, steam) and a complex heterogenous (rock) solid phase. Two classes of geothermal systems have been generally identified based on the physical state of the fluid phase that has the control of pressure: a) hot water systems in which the water is the fluid phase of control of the pressure gradient; and b) systems of dominant steam in which the water and the steam normally coexist in the "reservoir", with the steam being the continuous controlling phase of the pressure.

Systems of dominant steam are very good for the generation of electric energy; unfortunately, systems of dominant steam are more scarce than hot water systems.

In the hot water systems, the chemistry of the fluid phase maintains a direct relation with the underground "reservoir" of thermal water and with the rock. Due to the high temperature, the chemical reactions between the constituents reach an equilibrium in a relatively short time. The chemistry of the fluid in a hot water system shows a state of equilibrium between the fluid and the rock of the "reservoir" and can be determined in accordance with that. Nevertheless, the

cations: Ca, Mg, Na, K;
Li, Rb, Sr, Cs, B;

anions: Cl, SO_4, HCO_3
F, Br.

It is advisable that the gas samples be analyzed in regards to:

O_2, N_2, Ar, CO_2, H_2, He, CH_4 and other hydrocarbons.

Information about the source of the thermal waters can be obtained by measuring the isotopic distribution of oxygen ($^{18}O^{16}O$) and hydrogen (H/D)

c) Processing and interpretation of data
The purpose of automatic data processing is the organization of a great quantity of numerical and non-numerical information. By using computers one can carry out: the selection of a breakdown, statistical calculations, printing of lists and tables for reports, plotting curves of chemical relations.

Some of the objectives pursued in the interpretation of geochemical data include: the pattern of mix, the water/rock interaction, and in a more general way, becoming familiar with the process or processes responsible for the composition of the observed water. The analysis of these factors is generally carried out in order to identify processes or in order to deal with a great quantity of data. It is in this way that it is possible to calculate the temperature of the reservoir, to detect leakages in the reservoir, and on occassions, to determine the relative value of the geothermal gradient in the surrounding areas.

By employing a computer these calculations can be done more efficiently and rapidly, therefore minimizing costs.

3.2.2 Techniques

In this section a brief description of the different techniques used in a geochemical study are outlined. It is necessary to point out that the techniques for geochemical prospecting are constantly being developed, revised, and improved; nevertheless, the specific methods are not discussed in detail. The implementation of these methods depends on various factors, such as the location and access to the area; available personnel and equipment, as well as financial assets. Depending on meteorological factors such as annual variations in precipitation and the evapo-transpiration index, one can determine the necessity for doing the sampling more than once a year in order to get a correct understanding of the geothermal potential.

a) In the field

The field study should be done by a geochemist trained and familiarized with the problems and pitfalls of field measurments and samples. The following table summarizes the types of measurments that are necessary, the equipment and the approximate costs of the same:

Measurements	Equipment	Costs
1) temperature (+0.5°C)	Thermometer	US $20-100 each
2) pH (+0.1 pH unit)	pH meter	$300 each
3) conductance	Conductance meter	$3000 each
4) alkalinity	Alkalinity equipment	$200 each
5) flow estimate	visual estimate	
6) alkalai (Ca, Mg)	Field equipment	up to $1000 for each piece of equipment
7) NH_4, CO_2	Field equipment	$1500-3000 for each piece of equipment
8) collection of samples	Bottles, reagents	$1000

b) In the laboratory

The precise analysis of the collected waters and gases, and the identification of the sublimates, are perhaps the most important parts of the geochemical studies. The analysis should be done as soon as possible after collection (especially the gases) by laboratories specializing in the chemical analysis of waters and gases. Providing the analyses required by geothermal exploration presupposes a great amount of time and effort, even for highly qualified laboratories. The following lab equipment is the minimum amount needed inorder to do the required analyses: 1) atomic absorption, (AA); 2) chromatography of the gases; 3) normal chemical analyses; and 4) spectrophotometry.

When local facilities do not exist, it is recommended that the chemical anlyses be done on a contractual basis by a reliable and experienced laboratory. A system by which samples selected at random are analyzed by other laboratories, in order to verify the accuracy of the results, is recommended; this method of verification is a common practice in geochemical prospecting. In case that contractual arrangements are not made for the analyses, a chemist specialized in analysis of waters should be an integral part of the geochemical team, supervising the preparation and chemical analysis of the samples.

A complete chemical analysis can be done on the basis of a lump sum contract with a cost between 100.000 and 200.000 U.S. dollars per sample. The analysis of the oxygen and hydrogen isotopes could be done, where and when necessary, for approximately $150.00 U.S. per sample. When gases are examined, O_2, N_2, CO_2 H_2S, He, H_2 and methane should be analyzed. In special cases, it could be necessary to do an analysis of heavy hydrocarbons, CO and rare noble gases (Ne, Xe, Kr). The cost for the analysis of gases of this type varies between U.S. $50.00 and $200.00 per sample.

c) Processing and interpretation of data

Once the field and laboratory studies are completed, a large quantity of measurements of the different physical and chemical parameters of the geothermal system will have been obtained. The organization of this data will be facilitated by the use of a computer.

Data processing can include:

- Examination of the chemical analyses in order to verify their internal consistency
- Statistical calculations, such as: averages, standard deviations, measurements of correlation between the variables, etc.
- Graphs of correlations of two variables
- Analysis of multivariable regression, analysis of factors and subsequent studies and preparation of graphs

The processing and the representation of the data, as has already been indicated, helps with its interpretation. The distribution of water types and geochemical processes that take place in the system or systems being studied can be understood and varified in this manner. At this point the utilization of exploratory techniques like geochemical thermometry, detection of leakage phenomenon and the calculation of mix patterns are important.

On the basis of these studies, it will be possible to construct a thermal and hydrogeochemical model consistent with the geothermal system. This model should take into account all the geological, geophysical and geochemical data. The refinement of this model is an iterative process, in which one is constantly incorporating the results of the latest geochemical, geological and geophysical studies that are being carried out, including those from the development and exploitation stages of the geothermal program.

Some of the questions that these studies can help to resolve include:

- Identification of the chemical types of the waters
- Identification of aquifers and their role in the regional circulation of water
- Studies of leakage phenomemon
- Geothermometry
- Mix patterns

Leakage phenomenon

The identification of leakage phenomenon (emissions of geothermal steam towards the surface) and the detection of leakage anomalies (geochemical anomalies resulting from the emission of steam and/or geothermal gases in places where surface manifestations do not occur) are an important part of the geochemical studies, since small mixes of steam and/or gases from the geothermal "reservoir" can be detected. The best indicators of leakages are: ammonia (NH_4), boric acid (H_3BO_3), and reservoir gases (CH_4, H_2S, CO_2, H_2, He, Ar^{40}). The leakage studies, at the same time that they provide valuable information about the hot water systems, are particularly important for detecting the presence of systems of dominant steam.

Due to the presence of water and steam in the dominant steam system, the chemistry of the condensate of the steam cannot have a direct relation to the underground reservoir, but with its volatile constituents. Boric acid and ammonia are common in fumaroles and are concentrated in condensed water.

Due to the relatively low volatility of the boric acid and the high reagency of the ammonia with clayey material, near the surface, these constituents are not carried for long distances in the steam phase.. Where they are present, these constituents can show continous gradation within the prospecting area, which can indicate the zone with the most intense underground boiling The statistical analyses processed by computers can verify the accuracy of the data, as well as indicate the presence or absence of leakage anomalies in the area under study.

Geothermometry

An important goal of geochemical studies is the estimation of the temperature distribution in the reservoir. In hot water geothermal systems, the temperatures of the reservoir can be estimated by the chemistry of the springs. The two most populars geothermometers are the SiO_2 content and the atomic relations of K/Na/Ca. Both geothermometers have been empircally and experimentally calibrated; with them it is assumed that the chemical flow reflects equilibrium with the rock in the reservoir through chemical reactions depending on the temperature. Other geothermometers such as the Mg content, Cl content, Cl/F relation, Ca and HCO_3 contents have not been calibrated and only provide semiquantitative estimates of the temperature in the reservoir.

One problem for geothermometry is the necessity of having very pure samples of the fluids from the reservoir. The requisites that must be taken into account in geothermometry include: insignificant reaction of the fluid with the rock during the trajectory towards the surface in such a way that its composition remains balanced with that of the reservoir; absence of dilution or mix with other water at intermediate levels; and rapid flow of the water from the reservoir to the surface. Such requisites are not necessary for the study of the leakage phenomenon since they can be studied in terms of the mix patterns.

Mix Pattern

Where the surface manifestations of a geothermal system are a mixture of hot water originating in depth and cold phreatic water, the composition of the water of the thermal source and the flow characteristics can be suitable for the use of mix patterns, with the purpose of estimating the temper ture and salinity of the high temperature component of the mix. The estimated temperature is commonly more elevated and precise than the maximum temperature obtained from chemical geothermometers, when the mix isn't considered. In some places the mix patterns have indicated the existence of different reservoirs (permeable zones where the period of residence of the water in the rock is sufficiently long and the temperature is sufficiently high to reach a water/rock chemical equilibrium) with different tempperatures and compositions in different parts of the same hydrothermal system.

3.2.3 Costs, equipment and personnel

The geochemical studies are extremely economical compared with other methods of geothermal exploration such as geophysics and exploratory drilling. The following table is an estimate of costs, as well as the requirements for equipment and personnel needed for the study of an area (1) selected for the reconnaissance phase and studied in the prefeasibility phase

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(1) Area of 500 to 2000 km2

APPROXIMATE COSTS (1977)	EQUIPMENT	PERSONNEL/TIME
FIELD (excluding salaries of local personnel) US$3000 to $4000 for each piece of equipment US$7500/month for consultant	thermometer pH meter conductance meter alkalinity equipment equipment for Ca, Mg, NH_4 equipment for sample collection including bottles and chemical reagents	1 geochemical expert 1 field assistant (2 to 6 months)
LABORATORY US$100 to $200 per sample for elements and compounds	When local installations are not available, it is recommended that the chemical analyses be done on a contractual basis. The following equipment is the minimum necessary in order to do the required analyses: 1) Atomic absorption (AA) 2) Gas chromotagraphy 3) Systems for normal chemical analysis 4) Spectrofotometry	(2 to 4 months)
CALCULATION AND DATA PROCESSING US$1000 to $2000 for rental time on computer (Cost if the calculations are done by computer) US$7500 per month for consultant	Rental time on computer	1 geochemist (expert) 1 data processor (1 to 2 months)

FIGURE 2

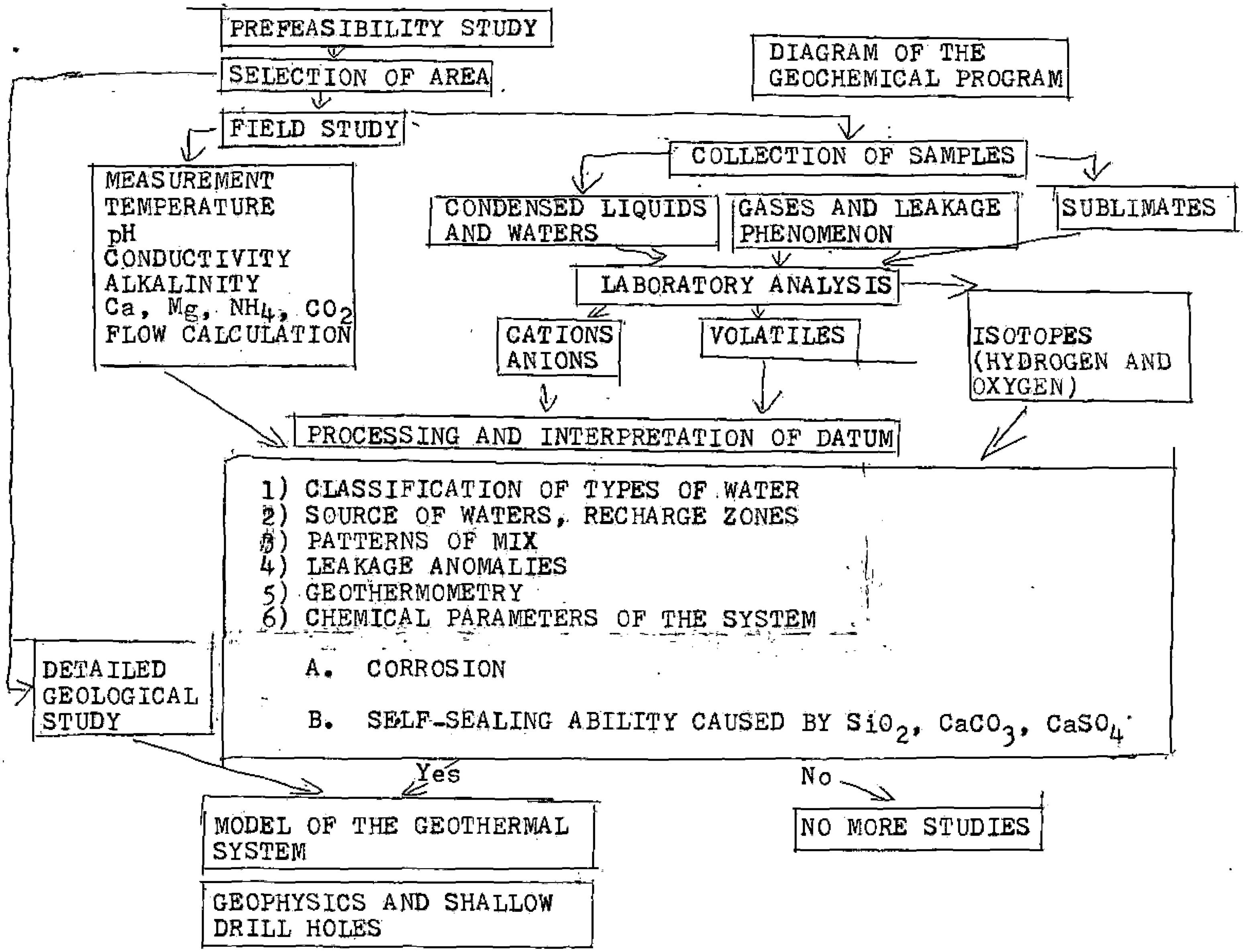
DIAGRAM OF THE GEOCHEMICAL PROGRAM

3.3 Geophysics

The main objective of the use of geophysical prospecting techniques in geothermal exploration is to contribute with the other exploration studies (geology, volcanology, geohydrology, and geochemistry) to the elaboration of the geothermal pattern in the area under study. It seeks to:

a) To determine the regional geological-structural conditions

b) Locate and describe geothermal anomalies in the area

c) To determine particular structural conditions

Geophysical prospecting methods are based on the measurement of variation, in time and space, of some of the physical properties of the rocks, the most common being: density, magnetic susceptibility, elasticity and electric and thermal conductivity.

The anlysis of these variants permits carrying out a qualitative and/or quantitative interpretation that, together with the geological, volcanological, geohydrological and geochemical preliminary data, is used for the elaboration of a tridimensional geothermal model.

3.3.1 Methods of geophysical exploration

a) Regional structural determinations

In the general framework of geothermal explorations, the geophysical techniques of magnetometry and gravimetry have been used principally to delineate the geological-structural situation of the regional area where the geothermal resources are found located. A qualitative interpretation of the gravimetric and magnetometric maps gives indications about the location of the major geological structures. The analysis of precise models, making use of computers and geological information, reduces the amount of data to be determined. The utilization of these techniques is contingent on having a previous knowledge of the area. A gravimetric study and, usually a magnetometric or aeromagnetometric one, will provide valuable information about the regional structural situation at a substantially reduced cost.

b) Delineation of thermal anomalies in the area

To date, in order to discover, describe and evaluate a geothermal field there has been extensive use made of electric and electromagnetic methods (resistivity, telluric, magnetotelluric, and other techniques).

Regional reconnaissances of geothermal anomalies have been carried out looking for contrasts in resistivity, produced by the existence of zones of anomalous temperatures. These contrasts in resistivity are produced, among other ways, as a result of the temperature. Nevertheless, it must be taken into consideration that the electric resistivity of the rocks is also affected by factors such as: porosity, salinity, pressure, mineral alteration, and that these must be taken into account for a correct analysis.

Other elctrical techniques like: telluric, magnetotelluric, audio-magnetotelluric, as well as other geophysical techniques like seismic noise, are used in the stage of experimentation in order to delineate the thermal anomalies of the subsoil; nevertheless, their possible utilization in the future should be considered.

c) Particular determinations

The use of geophysical techniques for the determination of particular situations, depends on the nature of the problem itself. On this point, gravimetric and magnetometric techniques have helped to obtain very specific information. In some cases the gravimetric anomalies are directly tied to the existence of hot bodies or fluids in the subsoil. An identical situation can be obtained from the magnetometric studies, where it is possible to have, in some cases, information about igneous bodies related to the calorific source of the geothermal field.

These gravimetric and magnetometric data, also have other specific applications: in certain areas and with quantitative models, getting specific information about problems in locating faults, fracture zones, alteration zones, anomalies of mass related to temperatures; also, detecting variations in density of a geothermal field caused by the transfer of mass during the exploitation itself.

The seismic methods (active or passive) can also provide valuable information about specific situations. With active seismic methods, a considerable amount of information can be obtained about the position of geological interphases by means of the precise analysis of the trajectories followed by the elastic waves generated at or near the surface.

In geothermal prospecting, these methods have been little used, principally due to their high costs. Nevertheless, reflection and refraction studies have been used in some geothermal fields in order to become familiar with very particular geological situations (depth and thickness of stratum, faults, etc.)

In recent years seismic activity has been used, within a geothermal zone (microquakes) in order to determine the zone of active faults. It is being considered as a possible tool for determining magmatic chambers, studying the attenuation of the velocity of the P and S waves, the lag time, and the relative spectrum of the waves produced by local earthquakes or microearthquakes.

They have been used with a lot of success considering their cost/efficiency ratio, techniques of resistivity (vertical electric soundings)in order to determine the depths of particular geological stratum; thickness of the cover, etc.

3.3.2 Final considerations

The realization of any geophysical study means counting on qualified personnel and suitable equipment. Normally, save exceptions, these geophysical studies are contracted to specialized companies.

Even when that is the case, it should include, at least one geophysicist trained in techniques of geothermal prospecting, so that it is he that plans, in conjunction with the geological, volcanological, geohydrological, and geochemical personnel, the geophysical studies to be carried out.

A quite delicate matter is setting up a program of geophysical explorations within geothermal exploration, given the great many geological situations that can be presented and the results obtained in the other reconnaissance studies (geology, volcanology, geohydrology, and geochemistry).

The use of these geophysical techniques should be a supporting tool for becoming familiar with the geothermal zone. The methods employed in regional exploratory prospecting, structural measurements, and the delineation of anomalies has given excellent results. Other techniques for delineating and evaluating a geothermal field are still in a stage of experimentation.

An important conclusion is the advantage of creating a geophysical staff dedicated to geothermal exploration, in spite of the fact that a majority of these studies are done under contract. If this is not done, it is essential, at least, to have a competent person that will plan and supervise the execution of these studies.

METHODOLOGY OF GEOTHERMAL EXPLORATION

Reconnaissance and prefeasibility phases

INDEX

1. Introduction

organización Latino de Energía

In keeping with the observations and recommendations listed by the VIII Reunion de Ministros de la OLADE, which took place in Quito, Ecuador, from the 5th to the 8th of last September, the Permanent Ministry is placing special emphasis on a new alternative source of energy which offers to satisfy energy requirements in a reasonable period of time: Geothermics.

The incorporation agreement, signed in Lima, Peru, the 2nd of November, 1973 for OLADE, considers as fundamental objectives of the Latin American Energy Organization, the promotion, coordination, and orientation of Member States with respect to new energy sources in accordance with the terms contained in Chapter II; in line with this Agreement, the Permanent Ministry believes that geothermal energy has wide prospects in Latin America in the area of development of non-traditional energy sources.

In accordance with the above, the Permanent Ministry of OLADE prepared a program of action that establishes as an objective the planned development of geothermics in the Latin American countries. In order to accomplish this, and as a first step in this plan, a general outline of methodology for geothermal exploration was completed, adaptable to the conditions and characteristics of each country, permitting OLADE to coordinate efforts in order to optimize technical, human and financial resources. These would be relied on in the area to set up a continuous interchange of experiences and multilateral support between the countries undertaking a search for or exploration of this resource.

Therefore, the Permanent Ministry assembled a group of experts that were requested to prepare a preliminary document about the methodology of geothermal exploration. That program was participated in by Dr. Thomas Casadevall, Geochemist, who was assistant professor in the National Polytechnical School of Ecuador, and presently Resident Geochemist for the U.S. Geological Survey in the vulcanology observatory of Hawaii; Engineer Salvador Garcia Duran, Geophysicist with the Comisión Federal de Electricidad de Mexico, current Superintendent of the Geothermal Project of the Smokejacks in the State of Puebla and the former Chief Geophysicist for the Cerro Prieto field; and Dr. Andrea Merla, Geologist, who presently is Director of AQUATER Geothermal Exploration, a subsidiary company of the Italian ENI Group. The geothermal program of OLADE and the work of the group of experts were coordinated by Engineer Elizarras from the Technical Department of OLADE.

The preliminary document was entitled: "Plan for a Methodology of Geothermal Exploration". This is the same one that was circulated among the Latin American countries and among some official institutions of other countries and international organizations interested in Geothermics.

Because of the interest shown by OLADE's iniative, a Seminar on Geothermal Exploration was organized that would allow revising and completing the issuance of the document. This seminar took place in Quito, Ecuador the 27 to 31 of March, 1978, with the attendance of 10 Latin American countries, the United States and Italy, as weel as Observers from institutions of higher education and companies in the business of geothermal exploration (see the attached list of participants).

The geothermal program of OLADE, from its beginning, relied on the valuable support of the Instituto Italo-Latino Americano (IILA) who provided the presence of Dr. Andrea Merla in the group of aforementioned experts and at the same time IILA cosponsored the Seminar. For these reasons, OLADE was very happy to have joined its efforts with the IILA for the start of the program and especially for the Cooperation Agreement signed between the two organizations, an act that would provide for joint action in common areas in the energy field.

Given the splendid possibilities that Geothermics offers the countries in the Andean area as an alternative energy source, the Corporation Andina de Fomento (CAF) was added as cosponsor to the Seminar.

Also, because of the experience that has been gained on the subject and as a further support for getting Latin American energy integration, the Comision Federal de Electricidad and Petroleos Mexicanos (PEMEX) contributed to the cosponsorship of the Seminar.

The main result of that meeting is this paper and in it is proposed:

-to outline the development of a geothermal type project
-to describe the methodology that could be used during the different phases of surface exploration
-to present a preliminary evaluation of the human and financial resources required for a geothermal type project in order to reach the stage of deep exploration and to place the different phases of the project in a schedule

Therefore, this paper tries to serve as a reference-guide for planning specific geothermal projects and directing their development during the first stages of activity, by making use of the best information available and the technical resources of the countries themselves.

It is important to point out that the attention given to geothermics by the Permanent Secretary of OLADE, is based on technical-economic plans that could be adapted for any country in the area; and that by carrying them out, following programs such as this one, they could help in the search for and acquisition of funds which managed by OLADE will insure the start of new geothermal projects or the enlargement and support for those already in progress.

Finally, OLADE wants to express its appreciation to the aforementioned experts that made up the OLADE Geothermal Group and extend its thanks in a special way to their respective institutions for their cooperation in agreeing to the temporary absence of their experts without any profit except the experienced gained by them in this work.

The Permanent Secretary acknowledges the effort put out by the administrative personnel who helped with this part of the program and especially those of Mrs. Elvia Ortega de Andrade who was in charge of proofreading and the final document.

Quito, April 1978

2. PROPOSED METHODOLOGY FOR EXPLORATION

The methodology for exploration that is proposed, gives a general idea of what a geothermal type project is, the exploratory methods to be made use of, and the necessary personnel; all of this for each one of the stages, and finally, the amount of required investment. The proposed methodology is the result of the revision of a certain quantity of geothermal exploration projects, completed or in progress, in the recent areas of volcanism in Mexico, Italy and various Latin American countries, and is in agreement with the most advanced scientific progress in techniques for geothermal exploration.

This work has as its principal objective directing those countries where geothermal exploration is in its first stages and for which a special emphasis is placed on low cost exploration tools; in addition, the importance of complete reconnaissance studies is pointed out. In determining the exploration sequence an effort has been made to minimize, in the first stages, the intensive use of methods that would require large investments.

With the lack of a 'universal method'.capable of resolving the problems related to the different exploration phases and automatically permitting the identification of a geothermal field, the preparation of a methodology has as it most wary feature the selection and combination of techniques that are suitable for the particular objectives of each project. In effect, the wide variety of possible local conditions can demand substantial changes in the sequence, and/or the manner os use of the proposed exploration techniques. In the computation of time and investment requirements, one has taken into account variables like: the size of the exploration area, the local availability of personnel, logistic support and the geographic conditions. In fact, the exploration philosophy proposed here focuses on the average geological conditions of Latin America and the Carribbean.

2.1 Development of a Geothermal Type Project

A first approach to the establishment of objectives of geothermal interest are the borders of the lithoferric slabs, characterized by tectonic and recent magmatic activity (e.g.: the Andean system, the Central American mountain range, the Carribbean area, etc.)

Nevertheless, the simple fact that a country or region belongs geographically to these parts of continents, does not guarantee finding 'a priori', geothermal fields with industrial value. As a result, in order to develop a geothermal project in little studied geological areas, it will be necessary to begin exploration activities with a Reconnaissance Study in areas that can vary between 10,000 and 100,000 square kilometers.

This initial study would allow one to set up the first work program as well as select choice areas, whose extension would be defined as being between 500 and 2,000 km2, thus more easily permitting the development of a geothermal project.

In general, a geothermal type project consists of two main parts (fig. No. 1): the first ahs a predominantly high risk, associated with the exploration of any mineral or energy source, and its objective is the identification of the field (geothermal field), including a study of possible applications; the second is a mixed type (exploratory, technological and energy risks) and is concerned with the development and exploration of the field. The first part has high levels of economic risk and should be met by progressively increasing investments; nevertheless, in all it makes up a small sum as will be seen later on in the estimates for required expenditures; the second part, on the contrary involves less risks but requires much greater outlays.

From the practical point of view, it is important to divide the geothermal type project into 5 different stages, of which the first three - 1) reconnaissance study, 2) prefeasibility study and, 3) feasibility study, refer to the exploratory part of the project; the other two - 4) development, and 5) working, are directed towards the systematic production of endogenous fluid, its industrial applications and the problems of managing the field.

The schematic drawing of the development of a geothermal type project is shown in the flow chart in Fig. No. 1.

STAGES IN A COMPLETE GEOTHERMAL PROJECT FIGURE 1

Reconnaissance study
Area: 10,000-100,000 km2

Prefeasibility study
Area: 500-2,000 km2

Exploration

Feasibility study
Area: 10-100 km2

Development

Working

Experience gained to date has shown that the average dimensions of a 'field' are found to be between 10 and 100 km2. If, as already stated, the geothermal project is located in a region of around 10,000-100,000 km2, the localization of the possible field will require intermediate stages of exploration that will allow: first, delineation of the 'area of interest' (500-2,000 km2) on the basis of the reconnaissance study, and later, the selection of one or more promising areas not greater than 100 km2 where the sites for the deep exploratory drill holes will be situated.

In keeping with the above, the prefeasibility study will have as its main objective the localization of the sites where the deep drilling will take place and should be subdivided into different phases, which should be carried out in reasonable periods of time since the expenditures grow proportionately with the progress of the progress. Therefore, it is necessary to begin with studies and explorations of a regional character whcih involve relatively low costs, leaving the more detailed study and exploration only for the areas of greater interest, and which, as already stated, normally are found between 500 and 2,000 km2.

These criterion facilitate the interpretation, systematically and in an integrated manner, of the results of the explorations and to disgard the unfavorable portions of territory, and also evaluate the expediency of going on to thenext stage of work.

2.2 Reconnaissance study

This would consist of the evaluation, for geothermal purposes, of all of the available information in conjunction with a series of preliminary investigations on a local scale. It would help to set up the first work conditions, to select the most promising areas, and to lay out in a concrete manner the courses of action for the following phases of the project (prefeasibility and feasibility)

2.2.1 Objectives

-Preliminary evaluation of the geothermal possibilities on a national or regional level

-Selection of the areas of interest

-Determination of a preliminary geothermal plan and subsequent detailed study of exploration in each area

These objectives represent the technical data that, together with socioeconomic and political considerations, will form the basis for making the following decisions:

a) What priority should be given, on a national or regional level, to geothermics commensurate with alternate energy sources (ex: hydroelectricity, fossil fuels, etc.)

b) Defining areas of maximum priority in planning future explorations, taking into consideration the technical factors (indications of geothermal potential resulting from the reconnaissance study) as well as the economic ans social factors. Some local factors could play an important role in this stage; such as is the case of the possible exploitation of geothermal energy in an area in which there isn't any other energy sources available for generating power in this area or other activities that need local availability of energy at a low price (example: mining or certain types of industries, etc.)

c) Determining the amount of investment and technical data necessary in order to evaluate the geothermic potential of the area that has been established as having the greatest priority

2.2.2 Methodology

Speaking in general terms, a reconnaissance study at a national or local level can be summed up in the following manner:

Phase 1 - Evaluation of all the relative existing information.

In this stage all the basic documentation would be collected. This documentation would include:

- Geological maps, detailed and on a local scale
- Local geological study , including stratigraphy, structural geology, volcanic history, etc.
- Satellite pictures and/or aerial photography
- Topographical maps, detailed as well as regional
- Information about the presence and characteristics of the thermal sources and hydrothermal conditions
- Data obtained from wells that have been drilled for other purposes (oil, water, etc.)
- All the available geophysical information

The evaluation of this information outlining geothermal areas (geologically homogenous areas) and selecting the areas where the following phase will take place (field exploration).

Phase II. -Field exploration and laboratory analysis

On the basis of the results in Phase I, a field reconnaissance study will be planned.

The main object of this study would be to collect specific information related to:

1) the possible presence of a thermal anomaly at surface levels of the terrestrial crust

2) the local hydrogeological conditions; and,

3) the nature of the thermal manifestations

In volcanic regions it would be very important to concentrate the geological observations on the following points:

-Identifying the areas in which there is a concentration of recent volcanic episodes. This concentration is clear evidence of the persistence of an important thermal anomaly in the subsoil

-Evaluating the relative quantity of acid volcanic products that are caused by differentiation of basic magmas or by anatexis.

-Explaining, at a local level, the relations existing between the volcanic structures and the regional tectonics.

-Investigating the possible presence of craters of phreatic explosion

-Collecting samples, of the greatest possible number, of lithological types for subsequent analytical work. At this stage, the petrographic work will be limited, in most of the samples, to studies of thin laminas.

-Collecting samples of xenoliths of the pyroclastics for studies in thin laminas

-Determining the absolute age in selected samples.

-Studying in a preliminary form all the possible formations, cover and reservoir

As far as the the geochemical and hydrogeological field work are concerned, it would be necessary to sample a representative number of the waters in the reconnaissance zone (cold or thermal springs, surface or well water).

The study to be done in this stage should be chosen based on the availability of: 1) personnel; 2) financing; 3) equipment; and 4) time. Depending upon the availability of the 4 previously mentioned factors, two plans can be set up: one that we will call mimimum and another that would be optimum, both trying to fulfill the objectives of the reconnaissance study. These are:

DATA REQUIRED:		MINIMUM	OPTIMUM
	Field	$T^{o}C$ pH	$T^{o}C$ pH Cl or conductivity
		visual estimate of flow	visual estimate of flow
		collection of samples	collection of samples
	Laboratory	K;Na;Ca;Mg;Cl; SO_4/ SiO_2	K;Na;Ca;Mg; Cl;SO_4; NH_4; SiO_2 (diluted)
	Personnel	Personnel not necessarily specialized in chemistry	Person(s) trained in field chemistry

	MINIMUM	OPTIMUM
Equipment	Thermometer	Thermometer
	pH paper	pH paper or pH meter
		Cl^- paper or conductivity meter
	Flasks for samples and collection system	Flasks for samples and collection system

The chemical analyses will allow the calculation of subsoil temperatures by means of the use of geothermometers such as SiO_2, K/NA/Ca, etc. Flow estimates (l/sec or l/min) will be required for the application of models in order to determine the possible rate of mix between thermal fluids and other waters of the soil and subsoil.

2.2.3 Results

The work in phases I and II, in combination with the subsequent evaluation of all the data, should give as a result the following:

a) Determination of the main geothermal areas. (examples: areas of geothermal interest related to recent volcanism or magmatic intrusions, areas of normal gradient)

b) Selection of areas of interest, indicating the probable existence of fluids with high heat contents in the subsoil, that is, areas in which the exploitation of geothermal energy would be feasible with presently used techniques.

Also the areas in which it would only be possible to find fluids with low heat content would be specified. Their exploitation could be: energy by binary systems or, non-energy in agricultural, industrial or residential situations.

The selected areas should have an area between 500 and 2000 km2.

c) Determination of the scale of priorities. Those areas which offer the most favorable geological conditions for the presence of a geothermal field at an economically exploitable depth should be of top priority. This scale of priotities should be determined on the basis of 'technical' considerations.

d) Determination in each area of a preliminary geothermal plan. This plan will take into consideration the features relative to the presence of a superficial thermal anomaly and the geological and hydrological conditions of the zone, and

e) Establishment of a detailed exploration program (Prefeasibility Study)

A plan for the in depth studies needed in order to better define the geothermal pattern of each area will be laid out. The objective of this plan will be to locate sites for drilling deep exploration holes in diameters suitable for production tests.

2.2.4 Personnel requirements, time and costs

The initial part of the geothermal exploration in any area requires highly experienced personnel, since it is during this stage that the guidelines for future exploration are established.

Date collection (Phase I) can be done by technical personnel not specially trained in geothermics.

The evaluation of the collected data should be, nevertheless, done by extremely qualified technical personnel with a lot of experience in geothermal exploration. This staff will be, therefore, responsible for the second phase of the work and will include a structural geologist, a volcanologist, a geochemist, and a geohydrologist.

The amount of time required to complete Phase I and Phase II can vary according to the size of the area to be explored and the amount of available information

On the average, for the reconnaissance of an area of 10,000 to 100,000 km2, it shouldn't exceed a 9 to 16 month interval, estimating 2 to 4 months time for the collection and evaluation of data; 2 to 3 months for field reconnaissance; 1 to 3 months for laboratory analyses and 4 to 6 months for the evaluation of the results and preparation of the final reconnaissance report.

The cost of the reconnaissance study, assuming the aforementioned areas, could be between a minimum of 100,000.00 U.S. dollars and a maximum of 250,000.00 U.S. dollars. These estimates are dependent on many factors that will explained in more detail in the chapter on the costs of prefeasibility studies.

2.3 Prefeasibility Study

It has as its main object identifying the most promising areas, in which the costs would be sufficiently low to advise moving from superficial exploration to deep exploration. This phase carries out the preliminary evaluation of possible resources.

2.3.1 Objectives

a) To determine the preliminary geothermal plan of the selected area.

The 'geothermal plan' of an area will be determined when there is available detailed information regarding: 1) the presence and origin of thermal anomalies; 2) the characteristics of the cover formation or seal rock; 3) the pattern of general water circulation; and 4) the type and characteristics of the "reservoir".

b) Laying out the sites for deep exploratory drilling with diameters suitable for production tests.

A three dimensional model of a selected area would allow planning an adequate drilling program, directed towards testing the validity of the model.

2.3.2 Methodology

The detailed exploration plan for each given area, whose principal geothermal characteristics were already outlined during the Reconnaissance Study, will generally consist of investigations of varying costs. The emphasis given to low cost exploration seeks, as a result, maximum efficiency in the investment for higher costing investigations.

A. Geology-Hydrogeology-Geochemistry

A-1) Geology and Volcanology

The work will generally start off with an interpretation of a geological aerial photographs working towards the determination of faults, mapping of volcanic structures, definition of volcanic-tectonic relations and fault systems related to buried intrusions, and towards the integration of existing geological maps.

The second step will be a geological and vulcanological survey. Its principal objectives will be:

a) to investigate the presence of a thermal anomaly at surface levels of the terrestrial crust. For this purpose, representative samples of recent volcanic sequences will be taken, seeking to get information about the present, at surface levels, of a thermal anomaly (nature of the volcanic rocks, presence of a series of differentiation, etc.) and being so, the possibility of determining absolute ages. All of the hydrothermal areas, fossil as well as active, will be studied.

A detailed mapping of all the volcanic structures will be done (central volcanoes, domes, craters of phreatic explosion, extensions of fissured and pyroclastic lavas). Also a study of morphological characteristics will be carried out.

b) Identification of the cover formations and an evaluation of their efficiency. This includes the mapping and the collection of samples from all of the formations which offer adequate cover characteristics, from primary origin (clays, etc.) as well as due to self-sealing by processes of hydrothermal alternation. In volcanic zones a greater emphasis will be placed on searching for craters of phreatic explosion. Their presence indicates the existence of an effective cover.

c) To gather information about the existence of possible geothermal "reservoirs".

All of the existing evidence about the presence of a "reservoir" at an income-producing depth should be studied.

In the volcanic zones, the sampling and study of xenoliths produced by explosive eruptions, can provide information about the nature of the rocks located beneath the surface of the volcanic cover.

In those cases in which it is possible, this investigation of low cost will enable one to become familiar with the lithology of the reservoir and the temperature and the nature of the circulating fluids. In any case, these datum provide information about the lithology of the subsoil that are useful for other types of investigations: hydrogeology, geochemistry, etc.

Finally, the identification and mapping of recent faults is very important, since the actives faults frequently represent good objectives for exploration due to their permeability by fractures. The old faults, on the contrary, can be completely sealed by hydrothermal processes.

In tropical countries, where a rapid and strong weathering of rocks occurs and where there is a heavy covering of vegetation, the geological data, can be, at times, difficult to obtain with surface studies or indeed limited to small areas which are not easily correlated.

In such cases emphasis should be placed on the following types of studies:

1. Morphological observations carried out with the help of aerial photographs and analyses of satellite pictures. In many cases, simple morphological observations supply useful information about the tectonics of the area, volcanic structures, age of the volcanism, etc.

II. The identification of recent faults can be the one of greatest importance in these regions since the rapid weathering of the volcanic products can substantially reduce their primary permeability. Therefore, in these areas the fractured zones will be the objective of geothermal exploration.

III. Aerial geophysics with remote sensors (SLAR) can be productively used in these areas; the degree of application will depend upon economic considerations and local situations.

A-2) Geochemistry and Hydrogeology

The main objectives of the hydrogeological-geochemical programs during the prefeasibility studies, are the following:

1. To determine the regional geochemical conditions for the best understanding of the patterns of water circulation.

II. To try to determine the presence of a geothermal system in the subsoil, by using chemical and isotopic geothermometers or by detecting anomalies in the manifestation of existing leakages.

The hydrogeological-geochemical study is made up of three interdependent activities and they are:

a) Field operations

-Visit to all the sites of water discharge, such as cold or hot springs, wells, and drainages.

-Detailed description of each site, including an exact calculation of water flow and description of the altered zone adjacent to the source of the discharge

-Sampling of water, and if pertinent, of gases, always in suitable containers

-Field determination of: T°C, pH, Cl-, conductivity and possibly Fe^2, Ca^2, Mg^2, HCO_3, NH_4. A field analysis is required, or an adequate conditioning of the sample for future analysis, since with time important changes in the chemistry of the constituents can take place. The field analysis should be done at the same level of quality as the laboratory analysis.

-Sampling of the sublimates in the thermal springs.

-In accordance with the average geological make-up, an analysis of gases (He, Hg, CO_2) can directly indicate the presence of a thermal anomaly in the subsoil.

b) Laboratory analysis

-The laboratory analysis work depends on the nature of the average geological conditions, normally it requires the determination of 12 to 18 constituents. The determination of the sublimates can be done by a chemical analysis or by means of of x-rays.

c) Interpretation

-The processing of the analytic data will give as a result: the identification of the main chemical types of water and existing mixes; an interpretation of the source of the thermal waters; a map survey of the leakage anomalies and the calculation of the temperature of the reservoir. This processing of data and interpretation can be facilitated by doing the anlysis with a computer, when possible.

B. Geophysics and Shallow Wells

B-1) Geophysics

The use of mining techniques should be focused on three main objectives:

1. To determine the regional structural-geological conditions of the zone where the geothermal resources are found situated.

2. Mapping and demarcation of thermal anomalies.

In the first stage, a gravimetric study, and eventually one in magnetometry or aeromagnetometry provide the most accurate tool for determining the major geological structures in the zone. These techniques of geophysical exploration can be realized during the development of the studies in stage A, but being careful that they are begun at the time that the most relevant geological situation is known.

In the second stage, the traditional electronic methods, maps, and/or geoelectric profiles of resistivity, can be utilized in order to analyze the contrasts in resitivity associated with possible zones of anomalous temperatures. A semi-detailed study, regional or partially regional, can be planned upon having an adequate knowledge of the geological situation of the zone; on the basis of this study a more detailed survey will be scheduled.

The use of other techniques (electric, electromagnetic, seismic noise, etc.) should be considered for the moment as experimental techniques, but without rejecting their use in the future.

In the last stage, the geoelectric techniques (vertical electric soundings), active seismic (reflection or refraction), passive seismic (micro-earthquakes) and others, can be used to determine particular geological situations like: cover thickness, depth of particular geological layers, determination of active faults, etc. The planning for the use of any of these techniques should take into account the specific problem to be analyzed and the cost/accuracy that will result.

B-2) Multipurpose Shallow Drillings

The drilling program for surface wells will not be decided until a sufficient knowledge of the geological and hydrogeological conditions has been obtained. The number, location and depth of the test holes will be those needed in order to get the maximum information with the minimum investment. These holes will be decisive factors in the definition of the geothermal model of the zone.

The depth of these small diameter wells will be planned in accordance with the geohydrological conditions; they should reach, and even penetrate the impermeable stratum of the reservoir key horizons if the objective is to calculate the temperature of the reservoir. Nevertheless, it should be taken into account that the determination of geothermal gradients on the basis of the supposition that the process is purely conductive has caused numerous failures, because the interpretation of the slightly deep thermal gradients are frecuently erroneous.

The sampling of gas and water in undisturbed horizons; the structural correlations and; naturally, the temperature predictions at key horizon depths are examples of some of the objectives of these drillings.

In these circumstances, it is difficult to establish the most appropriate depths; the decision, depends on a correct evaluation of the data that one has tried to obtain against the total cost of the drilling.

Generally, the objectives of these wells are one or more of the following:

-To carry out a series of temperature measurements in order to calculate the thermal gradient and predict the temperature in depth

-To collect rock samples for measurements of conductivity (calculation of calorific flow)

-To collect samples of the fluids that are usually found, in order to determine possible convectors that would alter the previous objective, and to carry out chemical analyses in order to integrate them with the surface geochemical study

-Measurements of electric resistivity throughout the drilled section, in order to correlate the studies of surface electric resistivity

-Study of the stratographic succession

It should be emphasized that only a detailed knowledge of the surface geological, hydrogeological, and hydrochemical conditions will permit carrying out an estimate and extrapolation of the geothermal gradient, of the temperatures, and of the production possibilities.

2.3.3 Personnel requirements, time and costs

The number of technical personnel required for the execution of the phase depends on the local situation. Nevertheless, it is possible to give a general idea with regard to the organization and the time required, taking into consideration an area between 500 to 2000 km2 and the existence of basic data like detailed topographical maps, geological maps and aerial photographs.

A. Personnel

The following is a schematic summary of the personnel required to carry out a prefeasibility study of such magnitude in an area.

-Geology and Volcanology

Photogeological interpretation	1 photointerpreter geologist 1 photointerpreter technician
Field work	1 geologist 1 volcanologist
Laboratory analysis	1 petrographer
Preparationof data and reports	1 geologist 1 volcanologist
Supervision	1 geologist, expert in geothermal exploration

Hydrogeology and geochemistry

Field work	1 hydrogeologist 1 geochemist 1 chemical technician
Laboratory analysis	1 geochemist 1 chemical technician
Preparationof data and reports	1 geochemist 1 hydrogeologist 1 estimator
Supervision	1 geochemist, expert in geothermal exploration

-Geophysics

Independently of the geophysical studies that will be carried out by management or by means of contracts, the project should rely on a chief geophysicist, who will be responsible for the geophysical program to be carried out, as well as for its execution and interpretation.

-Shallow Wells

In this stage a contractor will be used for the drilling unless the proper equipment is available. When considering the use of a contractor, the project should have the personnel needed for the supervision of the drilling, the measurements, and the analysis of data; these personnel are:

At the wells	1 geologist 1 geochemist 1 geophysicist

-Preparationof the final prefeasibility report

This work should be done by all personnel that took part in the field work and preliminary reports, including a drilling engineer. The supervision of geothermal experts with proven experience in exploration are necessary in order to obtain a better analysis.

B. Time

The technical work, based on the averages attained up to now in the geothermal exploration of some Latin American countries, can be summarized in the following manner:

Geology-Volcanology (field work, laboratory analysis, report)	9-15 months
Geochemistry-Hydrogeochemistry (field work, laboratory analysis, report)	9-15 months
Geophysics (field work, interpretation, report)	9-15 months
Shallow drillings* (drilling, measurements, report)	7-16 months
Final report	4-6 months

The total amount of time for the production of a prefeasibility study, taking into account that some of the previously mentioned activities can be done simultaneously, varies between 20-30 months. Nevertheless, these periods, total and partial, can be reduced by an optimization of the methodology and the personnel employed. That is, in itself, one of the main intentions of this program.

C. Costs

The costs for an exploration program like the one described in the preceding chapters, can vary according to various factors:

-The volume of existing geological and hydrogeological information

-The existence of trained and expert local personnel

-The geographical and geological characteristicsof the region to be investigated

*Average amount: 2000 m of drilling in multiple wells

-The local availability of laboratory and computation facilities

A cost estimate is, nevertheless, very difficult to make, due to the great variations in the above indicated factors. Nevertheless, we will attempt to describe the necessary investment scale. The philosophy that will be followed in order to estimate the needed investments is based on two principles:

a) Emphasis should be placed on the use of exploratory instruments, such as for vulcanology and geochemistry. These methods provide very important information and cut down on the use of more expensive techniques.

b) When a certain stage of exploration has been reached, major expenditures will not be necessary in order to have additional understanding of the geothermal system. It is in this stage that the decision to begin the deep drilling can be made.

In this estimate are also considered variables such as: availability of expert local personnel, number of members from local personnel, number of staff from external personnel, and to a certain degree, geographic conditions.

With these given considerations, the estimated cost, total, of the prefeasibility study, based on an area between 500 to 2000 km2, would be:

minimum of	$800,000 U.S.
maximum of	$1,600,000 U.S.

Once the prefeasibility phase is completed, and if the results point to continuing the work, one will precede to the last phase of the exploration stage: the feasibility study.

The feasibility phase can be defined as the study that establishes the physical site of a geothermal field, subsequent evaluation of extractable reserves and preliminary evaluation of the available resources; as well as the study of the fluid, possible plans for its utilization for power and/or other uses and the eventual installation of a pilot plant or industrial unit.

This study, as part of a geothermal project, includes the first exploration soundings, studies which allow determining the production characteristics and utilization of the fluid, economic studies, as well as the design of a power plant.

In this document only the first two stages of a geothermal type project will be analyzed, or in other words, the reconnaissance and prefeasibility studies. The analysis of the feasibility phase is the subject for another program.

3. DESCRIPTION OF THE PRINCIPAL METHODS OF EXPLORATION

3.1 Geological Exploration in Volcanic Areas

A geothermal field susceptible to exploitation, whether for production of gas for purposes of electric power, or of hot water (low heat content) for non-power purposes, should have the following as principal characteristics:

-A thermal anomaly

-A reservoir made up of permeable rocks within which geothermal fluid circulates. The reservoir should be at depths that make its exploitation economical.

-An impermeable cover on the reservoir that impedes the loss of heat by convection of fluids towards the surface.

3.1.1 Heat sources

In many volcanic regions, the heat required for the formation of a geothermal system, located near the terrestrial surface, can be supplied, essentially, by a mass of high temperature magma situated in the terrestrial crust, either as an intrusion in the process of cooling or as a magmatic chamber feeding a volcano . Theoretically, all the zones affected by recent volcanic phenomenon are probable geothermal sites; nevertheless, the areas of practical interest are only those where a large volume of magma is found at a relatively shallow depth (less than 10 km). So, areas in which the magma has directly and rapidly risen from the mantle through fissures, such as plateau basalts, are of less interest.

Also one should consider geothermal potential, those areas where there remain locally large volumes of magma within the upper part of the continental crust (acidic magmas originating within the crust itself) or areas with large central volcanoes related to magmatic chambers.

In the preliminary exploration of a geothermal region, the problem of locating a thermal anomaly, normally near the surface, should be dealt with by volcanological, structural and petrological methods.

These methods help to distinguish central volcanoes by assessing their significance in the regional structural scheme and by estimating their age by morphological criterion or by measurements of absolute age using radiometric methods. The presence of active fumaroles in the craters of central volcanoes is the best indication of the recent age of the volcano. Nevertheless, the crater of an active volcano cannot be considered, for the present, for geothermal exploitation.

Petrological studies of lavas and other volcanic products are helpful in defining the nature of the magma, in particular its degree of acidity and differentiation. These datum are essential for evaluating the possible existence of magmatic chambers near the surface, which feed the volcanism; besides, in order to estimate if the nature of the magma confirms the existence of a superficial thermal anomaly within the terrestrial crust. The latter includes the case of magmas formed by anatexis of the crust (partial fusion of the upper continental crust, which is a process that requires strong anomalies at a moderate depth).

The formation of magmatic chambers of sufficient thermal capacity, which allow increasing the heat of a large volume of rock, requires favorable tectonic conditions, like the crossing of different faults or the inclination of faulted blocks that make up appropriate tectonic traps, where the rising magma settles and creates its differentiation. Therefore, one should investigate the relation between volcanic structures and tectonic outlines in order to spot the occurrence, at a shallow depth, of hot magmatic bodies.

Favorable elements are: the persistence of volcanic activity through time and the frequent eruptions of strongly differentiated products, which for their formation require a long period of demurrage of the magma in the chamber. In the majority of cases, the magmatic chambers are reservoirs that feed the complex of central volcanoes; the volcanic structures are formed around a central chimney with various eruptions of products of different composition, genetically connected to each other by fractional crystallization.

In other cases, only the differentiated magmas, more evolved and lighter, are capable of getting to the surface through fissural eruptions of different intensities, forming volcanic fields with some monogenetic centers (Campi Flegrei, Italy) or, also, important pyroclastic eruptions.

Also, the magma can remain at a shallow depth without producing a volcanism; nevertheless, these upheavals in the upper crust affect the surface tectonics by the formation of "horst" generally interspersed with minor collapses (as in Larderello, Italy) or peculiar systems of radial or concentric faults.

3.1.2 The reservoir

The reservoir is formed by rocks of high permeability, with a sufficient volume to insure an extended exploitation. Besides, the reservoir should be located within a favorable hydrological system. The delineation of the reservoir is the most difficult problem in geological exploration. The principal reason, is the presence of extensive surface volcanic covers that often prevent the direct study of the deepest substratum. This, requires a knowledge of general geological standards; in particular, those of thicknesses, depth, lithology and permeability of various stratographic units that are found under surface volcanic cover. In many cases, the stratographic studies and the geological surveying can provide important information concerning the reservoir.

Also the identification of areas of greatest permeability by fractures due to tectonism and their pattern of distribution is very important.

From the study of the xenoliths in the volcanic rocks, important information can be obtained. This includes samples of the subsurface lithological horizons and their study can also provide evidence of manifestations of hydrothermal alteration caused by the circulation of high temperature fluids.

The xenoliths of rocks in the subsoil occur chiefly in products of volcanic explosions (tufa, tephrites or ibnimbrites)**. These xenoliths should be studied and sampled, the altered as well as the unaltered. Special attention should be given to observing the texture of the hydrothermal minerals (in veins or random distribution) and to the usual paragenetic changes, with which it is possible to identify changes in the physical-chemical conditions of the circulation of fluids.

Finally, the evaluation of the reservoir (lithology, depth, structure) requires the use of geophysical methods: one of the principle objectives of geological exploration is to determine the best geophysical method and to use it in the exploration, always basing it on the local geological characteristics.

3.1.3 The cover

The cover should be made up of an impermeable formation. It can be sedimentary rock with primary impermeability (clay, lime, lacustrine deposits), as in Cerro Prieto, Mexico; Larderello, Italy, or in Wairakei, New Zealand; or rock impermeabilized by self-sealing due to the continuous effects of thermal activity, as isthe case of the Geysers, USA, or Otake, Japan. In order to determine this cover, it is necessary to know the stratigraphy and lithology of the subsurface horizons; this investigation can be done on a strictly geological basis, although geophysical studies are almost always necessary in order to determine the thickness of the impermeable layer. The presence of an impermeable formation near the surface is essential for determining the usefulness of shallow wells of geothermal gradient in the later stages of exploration. These wells are useful only when they penetrate the impermeable stratum where the temperature distribution is not altered by the circulation of meteoric or surface water. The drilling will be ecoromical only if the impermeable beds are at a shallow depth.

3.1.4 Surface manifestations

In regions where the cover is fractured by faults, the fluids of the reservoir can rise directly to the surface, producing various thermal phenomenon (hot springs and fumaroles). The presence of such surface manifestations is an indication of the probable existence of a geothermal field. Nevertheless, such indications are not absolutely necessary; geothermal fields can exist without

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chemistry of the fluid in a dominant steam system does not generally have a direct relation with the underground "reservoir" due to the boiling of the fluid and the subsequent presence of two phases: liquid and steam. In this case, the presence of a high temperature fluid is already established.

In the prefeasibility stage, the geochemical studies are used for:

a) determining the variation in the average geochemical conditions, through the classification of the types and interactions (mixes) of the different waters and gases, according to their chemical composition. The result of this is a grouping of surface waters, underground waters and thermal springs according to their chemical composition and permits the identification or characterization of the possible reservoir(s) based on the type of water.

b) determining the origin of the fluid phase, as well as locating the recharging area through the use of isotopic analysis (hydrogen and oxygen) of the the waters

c) identifying the distribution patterns of certain particular elements; these can result from the dispersion of said elements outside of the heat source or more generally, outside of the geothermal system.

d) estimating the minimum temperature of the reservoir by the use of various geothermometers and patterns of mix

e) becoming familiar with the chemical problems related to the production and removal of waste fluids, including waters as well as gases

3.2.1 Purpose of the program and methodlogy

The geochemical program consists of three activities: 1) field 2) laboratory and 3) processing and interpretation of data

The relations between these three activities is represented in a diagrammatic form in Figure 2.

a) Field activities

The field studies are necessary in order to collect water, gas and sublimate samples in order to analyze them in the laboratory and also in order to do measurements of variables such as T°C and volume of flow of fluid, which cannot be measured in the laboratory. It is advisable to take portable lab equipment to the field in order to do measurements of pH, NH_4, Fe 2, gas dissolved in the water, as well as for sampling and analysis of gases.

b) Laboratory activities

The laboratory studies involve the analysis of samples collected in the field. In the water samples, the following elements and constituents should be identified.

such geothermal manifestations (Los Humeros, Mexico). Also, there are hot emanations that do not have any relation to geothermal fields of high heat content, but instead are related to a rapid rise, along the faults, of water originating from depths in areas with normal geothermal gradient.

The study of the surface phenomena should be done taking into consideration the general hydrological organization. One the one hand it presupposes a knowledge of the hydrology of the region (meteoric water and underground water) as well as of the principle structures that control the hydrothermal systems and also of the structural characteristics of each source; on the other hand, it requires a detailed geochemical exploration. The purpose of the geochemical study is to provide data for the hydrogeological model and to detect theleakage phenomena of the deep geothermal reservoir. Valuable information can also be obtained from studies of the sublimates of the fumaroles.

3.1.5 Craters of phreatic explosion (hydrothermal)

A particularly important part of a geothermal field (not necessarily volcanic) is the frecuent presence of craters of phreatic explosion (hydrothermal). These structures are produced by the explosion of pockets of steam heated and kept under pressure by an impermeable cover. Their presence indicates that all the basic elements of a geothermal field (impermeable cover, fluids at depth, heat anomalies) are present in the zone affected by the explosion. Nevertheless, these structures should be carefully investigated, by estimating their age.

3.2 Geochemistry

A geothermal area can be considered as a chemical system of high temperature. The principle components of this sytem are: the fluid phase (water, gas, steam) and a complex heterogenous (rock) solid phase. Two classes of geothermal systems have been generally identified based on the physical state of the fluid phase that has the control of pressure: a) hot water systems in which the water is the fluid phase of control of the pressure gradient; and b) systems of dominant steam in which the water and the steam normally coexist in the "reservoir", with the steam being the continuous controlling phase of the pressure.

Systems of dominant steam are very good for the generation of electric energy; unfortunately, systems of dominant steam are more scarce than hot water systems.

In the hot water systems, the chemistry of the fluid phase maintains a direct relation with the underground "reservoir" of thermal water and with the rock. Due to the high temperature, the chemical reactions between the constituents reach an equilibrium in a relatively short time. The chemistry of the fluid in a hot water system shows a state of equilibrium between the fluid and the rock of the "reservoir" and can be determined in accordance with that. Nevertheless, the

cations: Ca, Mg, Na, K;
Li, Rb, Sr, Cs, B;

anions: Cl, SO_4, HCO_3
F, Br.

It is advisable that the gas samples be analyzed in regards to:

O_2, N_2, Ar, CO_2, H_2, He, CH_4 and other hydrocarbons.

Information about the source of the thermal waters can be obtained by measuring the isotopic distribution of oxygen ($^{18}O^{16}O$) and hydrogen (H/D)

c) Processing and interpretation of data
The purpose of automatic data processing is the organization of a great quantity of numerical and non-numerical information.
By using computers one can carry out: the selection of a breakdown, statistical calculations, printing of lists and tables for reports, plotting curves of chemical relations.

Some of the objectives pursued in the interpretation of geochemical data include: the pattern of mix, the water/rock interaction, and in a more general way, becoming familiar with the process or processes responsible for the composition of the observed water. The analysis of these factors is generally carried out in order to identify processes or in order to deal with a great quantity of data. It is in this way that it is possible to calculate the temperature of the reservoir, to detect leakages in the reservoir, and on occassions, to determine the relative value of the geothermal gradient in the surrounding areas.

By employing a computer these calculations can be done more efficiently and rapidly, therefore minimizing costs.

3.2.2 Techniques

In this section a brief description of the different techniques used in a geochemical study are outlined. It is necessary to point out that the techniques for geochemical prospecting are constantly being developed, revised, and improved; nevertheless, the specific methods are not discussed in detail. The implementation of these methods depends on various factors, such as the location and access to the area; available personnel and equipment, as well as financial assets. Depending on meteorological factors such as annual variations in precipitation and the evapo-transpiration index, one can determine the necessity for doing the sampling more than once a year in order to get a correct understanding of the geothermal potential.

a) In the field

The field study should be done by a geochemist trained and familiarized with the problems and pitfalls of field measurments and samples.
The following table summarizes the

types of measurments that are necessary, the equipment and the approximate costs of the same:

Measurements	Equipment	Costs
1) temperature (± 0.5°C)	Thermometer	US $20-100 each
2) pH (± 0.1 pH unit)	pH meter	$300 each
3) conductance	Conductance meter	$3000 each
4) alkalinity	Alkalinity equipment	$200 each
5) flow estimate	visual estimate	
6) alkalai (Ca, Mg)	Field equipment	up to $1000 for eac piece of equipment
7) NH_4, CO_2	Field equipment	$1500-3000 for each piece of equipment
8) collection of samples	Bottles, reagents	$1000

b) In the laboratory

The precise analysis of the collected waters and gases, and the identification of the sublimates, are perhaps the most important parts of the geochemical studies. The analysis should be done as soon as possible after collection (especially the gases) by laboratories specializing in the chemical analysis of waters and gases. Providing the analyses required by geothermal exploration presupposes a great amount of time and effort, even for highly qualified laboratories. The following lab equipment is the minimum amount needed in order to do the required analyses: 1) atomic absorption, (AA); 2) chromatography of the gases; 3) normal chemical analyses; and 4) spectrophotometry.

When local facilities do not exist, it is recommended that the chemical anlyses be done on a contractual basis by a reliable and experienced laboratory. A system by which samples selected at random are analyzed by other laboratories, in order to verify the accuracy of the results, is recommended; this method of verification is a common practice in geochemical prospecting. In case that contractual arrangements are not made for the analyses, a chemist specialized in analysis of waters should be an integral part of the geochemical team, supervising the preparation and chemical analysis of the samples.

A complete chemical analysis can be done on the basis of a lump sum contract with a cost between 100.00 and 200.00 U.S. dollars per sample. The analysis of the oxygen and hydrogen isotopes could be done, where and when necessary, for approximately $150.00 U.S. per sample. When gases are examined, O_2, N_2, CO_2 H_2S, He, H_2 and methane should be analyzed. In special cases, it could be necessary to do an analysis of heavy hydrocarbons, CO and rare noble gases (Ne, Xe, Kr). The cost for the analysis of gases of this type varies between U.S. $50.00 and $200.00 per sample.

c) Processing and interpretation of data

Once the field and laboratory studies are completed, a large quantity of measurements of the different physical and chemical parameters of the geothermal system will have been obtained. The organization of this data will be facilitated by the use of a computer.

Data processing can include:

-Examination of the chemical analyses in order to verify their internal consistency

-Statistical calculations, such as: averages, standard deviations, measurements of correlation between the variables, etc.

-Graphs of correlations of two variables

-Analysis of multivariable regression, analysis of factors and subsequent studies and preparation of graphs

The processing and the representation of the data, as has already been indicated, helps with its interpretation. The distribution of water types and geochemical processes that take place in the system or systems being studied can be understood and varified in this manner. At this point the utilization of exploratory techniques like geochemical thermometry, detection of leakage phenomenon and the calculation of mix patterns are important.

On the basis of these studies, it will be possible to construct a thermal and hydrogeochemical model consistent with the geothermal system. This model should take into account all the geological, geophysical and geochemical data. The refinement of this model is an iterative process, in which one is constantly incorporating the results of the latest geochemical, geological and geophysical studies that are being carried out, including those from the development and exploitation stages of the geothermal program.

Some of the questions that these studies can help to esolve include:

-Identification of the chemical types of the waters

-Identification of aquifers and their role in the regional circulation of water

-Studies of leakage phenomemon

-Geothermometry

-Mix patterns

Leakage phenomenon

The identification of leakage phenomenom (emissions of geothermal steam towards the surface) and the detection of leakage anomalies (geochemical anomalies resulting from the emission of steam and/or geothermal gases in places where surface manifestations do not occur) are an important part of the geochemical studies, since small mixes of steam and/or gases from the geothermal "reservoir" can be detected. The best indicators of leakages are: ammonia (NH_4), boric acid (H_3BO_3), and reservoir gases (CH_4, H_2S, CO_2, H_2, He, Ar^{40}). The leakage studies, at the same time that they provide valuable information about the hot water systems, are particularly important for detecting the presence of systems of dominant steam.

Due to the presence of water and steam in the dominant steam system, the chemistry of the condensate of the steam cannot have a direct relation to the underground reservoir, but with its volatile constituents. Boric acid and ammonia are common in fumaroles and are concentrated in condensed water.

Due to the relatively low volatility of the boric acid and the high reagency of the ammonia with clayey material, near the surface, these constituents are not carried for long distances in the steam phase,. Where they are present, these constituents can show continous gradation within the prospecting area, which can indicate the zone with the most intense underground boiling The statistical analyses processed by computers can verify the accuracy of the data, as well as indicate the presence or absence of leakage anomalies in the area under study.

Geothermometry

An important goal of geochemical studies is the estimation of the temperature distribution in the reservoir. In hot water geothermal systems, the temperatures of the reservoir can be estimated by the chemistry of the springs. The two most populars geothermometers are the SiO_2 content and the atomic relations of K/Na/Ca. Both geothermometers have been empircally and experimentally calibrated; with them it is assumed that the chemical flow reflects equilibrium with the rock in the reservoir through chemical reactions depending on the temperature. Other geothermometers such as the Mg content, Cl content, Cl/F relation, Ca and HCO_3 contents have not been calibrated and only provide semiquantitative estimates of the temperature in the reservoir.

One problem for geothermometry is the necessity of having very pure samples of the fluids from the reservoir. The requisites that must be taken into account in geothermometry include: insignificant reaction of the fluid with the rock during the trajectory towards the surface in such a way that its composition remains balanced with that of the reservoir; absence of dilution or mix with other water at intermediate levels; and rapid flow of the water from the reservoir to the surface. Such requisites are not necessary for the study of the leakage phenomenon since they can be studied in terms of the mix patterns.

Mix Pattern

Where the surface manifestations of a geothermal system are a mixture of hot water originating in depth and cold phreatic water, the composition of the water of the thermal source and the flow characteristics can be suitable for the use of mix patterns, with the purpose of estimating the temperature and salinity of the high temperature component of the mix. The estimated temperature is commonly more elevated and precise than the maximum temperature obtained from chemical geothermometers, when the mix isn't considered. In some places the mix patterns have indicated the existence of different reservoirs (permeable zones where the period of residence of the water in the rock is sufficiently long and the temperature is sufficiently high to reach a water/rock chemical equilibrium) with different tempperatures and compositions in different parts of the same hydrothermal system.

3.2.3 Costs, equipment and personnel

The geochemical studies are extremely economical compared with other methods of geothermal exploration such as geophysics and exploratory drilling. The following table is an estimate of costs, as well as the requirements for equipment and personnel needed for the study of an area (1) selected for the reconnaissance phase and studied in the prefeasibility phase

(1) Area of 500 to 2000 km2

APPROXIMATE COSTS (1977)	EQUIPMENT	PERSONNEL/TIME
FIELD (excluding salaries of local personnel) US$3000 to $4000 for each piece of equipment US$7500/month for consultant	thermometer pH meter conductance meter alkalinity equipment equipment for Ca, Mg, NH_4 equipment for sample collection including bottles and chemical reagents	1 geochemical expert 1 field assistant (2 to 6 months)
LABORATORY US$100 to $200 per sample for elements and compounds	When local installations are not available, it is recommended that the chemical analyses be done on a contractual basis. The following equipment is the minimum necessary in order to do the required analyses: 1) Atomic absorption (AA) 2) Gas chromotagraphy 3) Systems for normal chemical analysis 4) Spectrofotometry	(2 to 4 months)
CALCULATION AND DATA PROCESSING US$1000 to $2000 for rental time on computer (Cost if the calculations are done by computer) US$7500 per month for consultant	Rental time on computer	1 geochemist (expert) 1 data processor (1 to 2 months)

FIGURE 2

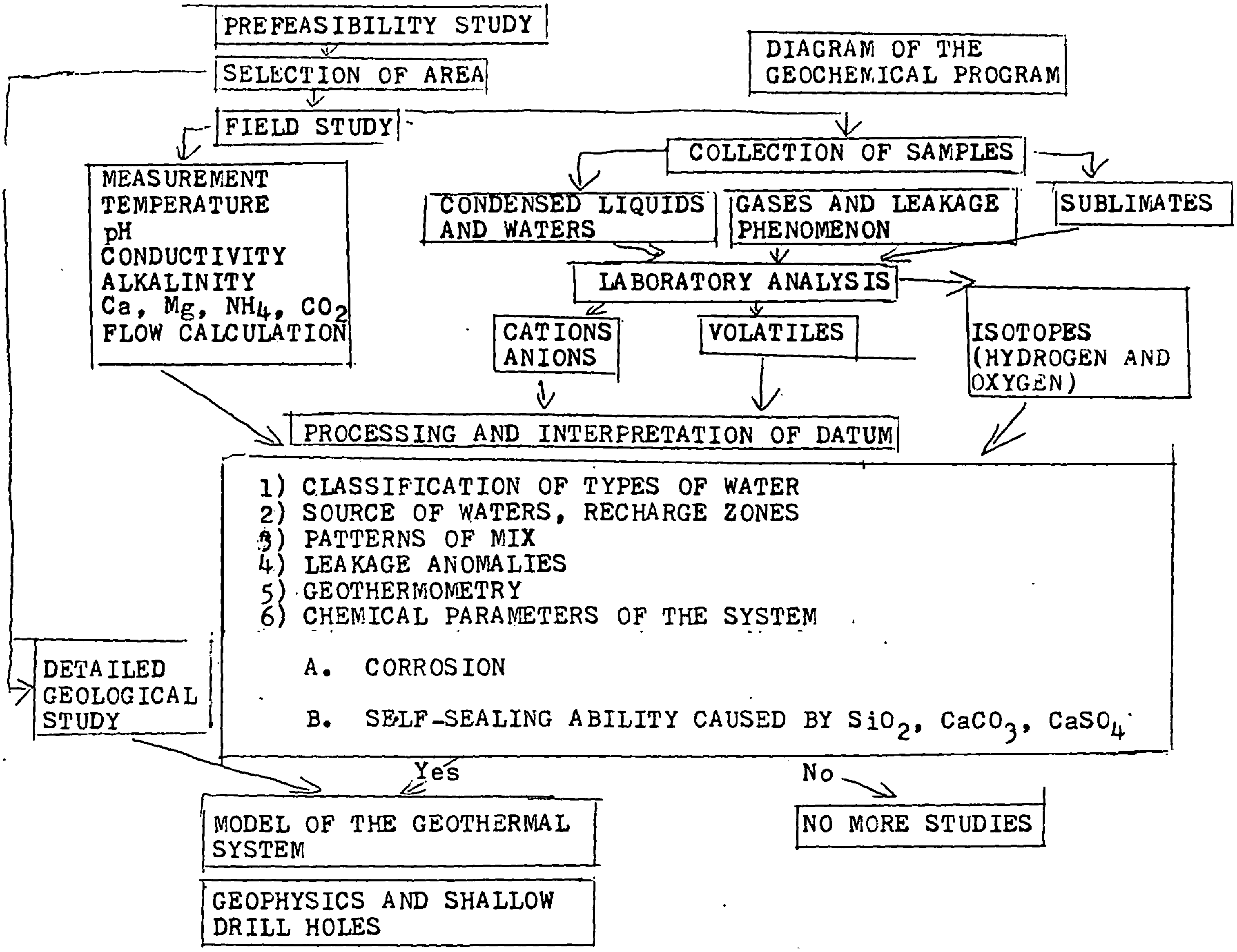

DIAGRAM OF THE GEOCHEMICAL PROGRAM

3.3 Geophysics

The main objective of the use of geophysical prospecting techniques in geothermal exploration is to contribute with the other exploration studies (geology, volcanology, geohydrology, and geochemistry) to the elaboration of the geothermal pattern in the area under study. It seeks to:

a) To determine the regional geological-structural conditions

b) Locate and describe geothermal anomalies in the area

c) To determine particular structural conditions

Geophsical prospecting methods are based on the measurement of variation, in time and space, of some of the physical properties of the rocks, the most common being: density, magnetic susceptibility, elasticity and electric and thermal conductivity.

The anlysis of these variants permits carrying out a qualitative and/or quantitative interpretation that, together with the geological, volcanological, geohydrological and geochemical preliminary data, is used for the elaboration of a tridimensional geothermal model.

3.3.1 Methods of geophysical exploration

a) Regional structural determinations

In the general framework of geothermal explorations, the geophysical techniques of magnetometry and gravimetry have been used principally to delineate the geological-structural situation of the regional area where the geothermal resources are found located. A qualitative interpretation of the gravimetric and magnetometric maps gives indications about the location of the major geological structures. The analysis of precise models, making use of computers and geological information, reduces the amount of data to be determined. The utilization of these techniques is contingent on having a previous knowledge of the area. A gravimetric study and, usually a magnetometric or aeromagnetometric one, will provide valuable information about the regional structural situation at a substantially reduced cost.

b) Delineation of thermal anomalies in the area

To date, in order to discover, describe and evaluate a geothermal field there has been extensive use made of electric and electromagnetic methods (resistivity, telluric, magnetotelluric, and other techniques).

Regional reconnaissances of geothermal anomalies have been carried out looking for contrasts in resistivity, produced by the existence of zones of anomalous temperatures. These contrasts in resistivity are produced, among other ways, as a result of the temperature. Nevertheless, it must be taken into consideration that the electric resistivity of the rocks is also affected by factors such as: porosity, salinity, pressure, mineral alteration, and that these must be taken into account for a correct analysis.

Other elctrical techniques like: telluric, magnetotelluric, audio-magnetotelluric, as well as other geophysical techniques like seismic noise, are used in the stage of experimentation in order to delineate the thermal anomalies of the subsoil; nevertheless, their possible utilization in the future should be considered.

c) Particular determinations

The use of geophysical techniques for the determination of particular situations, depends on the nature of the problem itself. On this point, gravimetric and magnetometric techniques have helped to obtain very specific information. In some cases the gravimetric anomalies are directly tied to the existence of hot bodies or fluids in the subsoil. An identical situation can be obtained from the magnetometric studies, where it is possible to have, in some cases, information about igneous bodies related to the calorific source of the geothermal field.

These gravimetric and magnetometric data, also have other specific applications: in certain areas and with quantitative models, getting specific information about problems in locating faults, fracture zones, alteration zones, anomalies of mass related to temperatures; also, detecting variations in density of a geothermal field caused by the transfer of mass during the exploitation itself.

The seismic methods (active or passive) can also provide valuable information about specific situations. With active seismic methods, a considerable amount of information can be obtained about the position of geological interphases by means of the precise analysis of the trajectories followed by the elastic waves generated at or near the surface.

In geothermal prospecting, these methods have been little used, principally due to their high costs. Nevertheless, reflection and refraction studies have been used in some geothermal fields in order to become familiar with very particular geological situations (depth and thickness of stratum, faults, etc.)

In recent years seismic activity has been used, within a geothermal zone (microquakes) in order to determine the zone of active faults. It is being considered as a possible tool for determining magmatic chambers, studying the attenuation of the velocity of the P and S waves, the lag time, and the relative spectrum of the waves produced by local earthquakes or microearthquakes.

They have been used with a lot of success considering their cost/efficiency ratio, techniques of resistivity (vertical electric soundings)in order to determine the depths of particular geological stratum; thickness of the cover, etc.

3.3.2 Final considerations

The realization of any geophysical study means counting on qualified personnel and suitable equipment. Normally, save exceptions, these geophysical studies are contracted to specialized companies.

Even when that is the case, it should include, at least one geophysicist trained in techniques of geothermal prospecting, so that it is he that plans, in conjunction with the geological, volcanological, geohydrological, and geochemical personnel, the geophysical studies to be carried out.

A quite delicate matter is setting up a program of geophysical explorations within geothermal exploration, given the great many geological situations that can be presented and the results obtained in the other reconnaissance studies (geology, volcanology, geohydrology, and geochemistry).

The use of these geophysical techniques should be a supporting tool for becoming familiar with the geothermal zone. The methods employed in regional exploratory prospecting, structural measurements, and the delineation of anomalies has given excellent results. Other techniques for delineating and evaluating a geothermal field are still in a stage of experimentation.

An important conclusion is the advantage of creating a geophysical staff dedicated to geothermal exploration, in spite of the fact that a majority of these studies are done under contract. If this is not done, it is essential, at least, to have a competent person that will plan and supervise the execution of these studies.

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A closely-spaced magnetotelluric study of the Ahuachapán-Chipilapa geothermal field, El Salvador

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Introduction

The Ahuachapán geothermal field is one of several geothermal areas in El Salvador under different stages of exploration and development (Campos, 1988). These areas are associated with a volcanic chain associated with the subduction of the Cocos Plate under the Caribbean Plate. The exploration of the Ahuachapán field began in the 1960s. Today, more than 30 productive wells have been drilled supplying geothermal fluids to generate about 60 MW of electrical power, an important contribution to the country's electricity needs. The Comisión Ejecutiva Hidroeléctrica del Río Lempa (CEL), the government agency in charge of the geothermal program in El Salvador, has carried out exploratory work toward the area of the Chipilapa hot springs, a zone located 3 km east of the Ahuachapán field.

Because of the large contrast in electrical resistivity between cold ground water and hot saline geothermal fluids, dc-resistivity and electromagnetic (EM) methods have been effective tools in geothermal exploration (e.g. Berktold, 1983; Wright et al., 1985, Thanassoulas, 1991; Martínez-García, 1992). The magnetotelluric (MT) method is a natural-source EM technique that measures the surface time-varying electric and magnetic fields. During the spring of 1990, the Centro de Investigación Científica y Educación Superior de Ensenada (CICESE), México, carried out a MT survey at the Ahuachapán-Chipilapa field (Fig. 1). The work was part of a feasibility study conducted by the Instituto de Investigaciones Eléctricas (IIE) which comprised geological, geochemical, hydrogeological and reservoir engineering investigations.

The about 80 km^2 study area (Fig. 1), has been the subject of intense exploration during the last 20 years. Some results have been published and others are given in internal reports owned by CEL. The geology of the zone has been studied by a number of authors (Jonsson,1970; Jiménez, 1971; Jiménez and Campos, 1976; Electroconsult, 1982; Ortíz, 1984), the more recent being the work by González-Partida et al. (1991; this issue). Other studies include geochemistry (Truesdell et al., 1989; Nieva et al., 1992; this issue), alteration mineralogy (Aumento et al.,1982), and geohydrology (Jiménez, 1971; Ortíz, 1984; Laky et al., 1989). The volcanic evolution of the zone can be briefly summarized as follows (González-Partida et al., 1991): an earlier magmatic event (~1 My ago) produced the Empalizada and Cuyanausul volcanoes; a large explosive event originated the Concepción de Ataco caldera, (~0.3 My ago), followed by less extensive calderic collapses; finally a new period of volcanism (less than 0.1 My ago) created the Laguna Verde and Las Ninfas volcanos and injection of andesitic dikes took place.

The geology exposed at the surface is the product of the latest volcanic events, and is affected by four structural systems (González-Partida et al., this issue). The older is an extensional NE-SW system called Mesas del Llano system. The system known as El Molino, oriented NW-SE, affects the local basement and the former structures. There is a younger N-S system which is related to more regional structures. The calderic events have produced semicircular features which are also evident on the surface.

Results of previous geophysical work include gravity (Rodríguez and Rivas, 1986; CGF, 1992; Flores, 1991), dc-resistivity (Rodríguez, 1985; Rodríguez, 1988; Quijano, 1989; Fink et al., 1989; Fink, 1990; Flores et al., 1991), magnetotellurics (Geosystem, 1984; Flores et al., 1992), and passive seismic monitoring (Fabriol et al., 1990, 1992; Fabriol and Beauce, this issue).

Two types of dc-resistivity surveys have been carried out in the area : 135 Schlumberger soundings (Díaz, 1983; Rodríguez, 1985) and four long-offset dipole-dipole profiles (Rodríguez, 1988). The Schlumberger vertical electric soundings (VES) were acquired in a regular grid covering a 35 km^2 area (Fig. 2). They are distributed along nine profiles, with a typical separation between individual soundings of 500 m. The current-electrode separation (AB/2) ranges from 15 to 1500 m. Due to the high ground conductivities and the particular repetition rate used in the bipolar source current, most of the apparent resistivity data are distorted by EM induction effects at electrode-separations greater than 750 m (Rodríguez, 1985). After eliminating these distorted data, Flores et al. (1991) interpreted 115 VES in terms of layered models using a linearized inversion algorithm (Jupp and Vozoff, 1975). Most of the resulting models can be represented by a K-type three-layered sequence ($\rho_1 < \rho_2 > \rho_3$) characterized by a thin (less than 30 m thick) conductive layer with resistivities less than 30 Ω-*m*, underlain by an about 150-200 m thick resistive (50 to 300 Ω-*m*) layer. These two layers rest on a conductive half-space with a resistivity less than 10 Ω-*m*. This general sequence was also suggested by Fink (1990), who independently interpreted the VES data and performed a statistical analysis of the models.

In order to summarize the spatial variation of the modeling results, Flores et al. (1991) presented maps of the longitudinal conductance S (thickness x conductivity) of the shallow layer and of the transverse resistance T (thickness x resistivity) of the resistive layer. Figure 2 shows a map of the horizontal variation of T, where low values indicate that either the second layer is thin or it has a low resistivity. The zones with values of T below 10^4 Ω-m^2 were interpreted as evidence of hydrothermal alteration, hydrothermal fluids at low pressure and temperature, or a combination of both. These zones are spatially correlated with the surface hydrothermal manifestations.

The dipole-dipole resistivity survey was carried out as a joint project between CEL and Los Alamos National Laboratory (Rodríguez, 1988). It consisted of four 10 to 14 km long lines (L-1, L-2, L-4 and L-5 on Fig. 2), using dipole lengths of 500 and 1000 m (*a*=500 and 1000 m in standard notation). For the short dipole length, measurements were taken at 14 source-receiver separations ranging from 500 to 7000 m with integer multiples of *a*. For the long dipole length, 12 source-receiver distances were used ranging from 500 to

6000 m with integer multiples of *a/2*. This field operation produced more than 1200 apparent resistivity measurements with unusual redundancy and with offsets designed to reach greater depths than conventional surveys. Two-dimensional (2-D) modeling of these profiles has been done by different workers, applying a finite-difference algorithm (Dey and Morrison, 1979) and a trial-and-error approach. Quijano (1989) obtained simple models accounting for the coarse conductivity features, while Fink et al.(1989), Fink (1990) and Flores et al.(1991) arrived to gradually more complicated models attempting to improve the fit to the data. Pérez-Flores and Gómez-Treviño (this issue) utilize an innovative technique consisting of a one-step approximate inverse method, which avoids the inconvenience of the intensive forward computations inherent in the trial-and-error approach. They obtain images of the subsurface which reproduce the main features of the forward models but also include subtle variations difficult to recognize on the former models. The images correlate reasonably well with surface hydrothermal manifestations and with the information available from the deep wells.

Magnetotelluric data

The MT data were obtained in the spring of 1990 during an eight week period. The natural electric and magnetic fields in the 0.01 to 100 Hz band were recorded at 126 sites, using the MT-1 equipment from Electromagnetic Instruments Inc. (EMI) and a digital telemetry system developed and constructed by CICESE. The field set up was designed to measure two sites (500 m apart) at a time. Nine fields were recorded simultaneously in each set up: the horizontal components of the electric field at both sites, the three components of the magnetic field close to one of the sites, and the horizontal components of the magnetic field at a remote site (3 or 4 km away). The fields were processed and the impedance tensor was estimated using the remote reference technique (Gamble, 1978; Gamble et al., 1979a). The main problem during the measurements was the occurrence of high levels of EM noise in the proximity of power lines and close to the northern edge of the Ahuachapán geothermal plant, where four sites rendered useless impedance estimates. Toward the end of the field work the worsening electric storms caused an increase in the estimate variances. The field data were edited to preserve reliable estimates, based on the predicted coherencies of the EM fields as well as on the size of the error of the measurements (Gamble et al., 1979b).

The impedance tensor was first estimated in the principal direction coordinate system (Swift, 1967; 1986), then rotating it to a frequency-independent coordinate system selected by visual inspection at the low-frequency band. The resulting rotation angle is in the range of N15°W to N30°W for most of the sites. The tipper strike at low frequencies was estimated as N70°E and is consistent throughout the entire area. This agrees with the ENE trend of the volcanic chain, the strike of the Central Graben, and the trend of the gravity anomaly (Rodríguez and Rivas, 1986; Flores, 1991). Conversely, at the intermediate period range (i.e., 0.4 to 4.0 s) the visual correlation between the different apparent resistivity pseudosections delineates N-S trends, suggesting that at these periods the younger faults are the main controlling factor for the apparent resistivity variations. It is known that this pattern allows the flow of geothermal fluid through the area toward the discharge zone in the north (Torres et al., 1992).

After both apparent resistivity curves (ρ_{xy} , ρ_{yx}) were corrected for static effects (discussed below), practically all sounding sites show nearly coincident ρ_{xy} and ρ_{yx} curves, along with the corresponding phase curves, for periods from 0.01 to 2 s, followed by a growth of the ρ_{yx} mode over the ρ_{xy} mode for longer periods. Figure 3 shows typical sounding curves for three of the sites. They are representative of the general behavior of the data and serve also to illustrate the typical data scatter (the size of the error bars represent 68% confidence limits). Site 79 displays good quality estimates, suggesting a shallow homogeneous 12 Ω-*m* medium underlain by a resistive layer at depth. At site 69 the estimates exhibit larger uncertainties, mainly in the *yx* mode; the observed apparent resistivities at short periods are around 500 Ω-*m* and a pronounced minimum affects both polarization modes at intermediate periods, suggesting a resistive medium at the surface with a strong conductor at depth. Site 23 has adequate estimates for the *yx* mode in the whole period range, while the uncertainties increase after 1 s for the *xy* polarization mode. The curves are similar to those of site 79 regarding the absence of a pronounced minimum, but here the short-period apparent resistivity is much lower (~ 3 Ω-*m*), suggesting the presence of a conductor extending to shallow depths.

The general trend of the data is easier to visualize in a pseudosection format. Figure 4 shows the apparent resistivity and phase pseudosections for Line E4. This line is parallel to the volcanic chain and covers the southern margins of the Ahuachapán and Chipilapa zones (Fig. 1). Both polarization modes look similar for periods shorter than 10 s. At longer periods the increase of ρ_{yx} over ρ_{xy} is evident. The occurrence of three minima at periods of the order of 1 s, in the western, central and eastern portions of the line are indicative of conductive zones at depth. The short period behavior of the contours suggests that in some zones these conductors reach near-surface depths, while in other sites they are overlain by shallow resistive zones. The spatial correlation of the low apparent resistivity zones between lines, confirmed by the pseudosections of Lines E1, E2, E3, E6, E7, and E8, is an important property of these data which supports the N-S strike for the conductive structure.

Static correction

The static shift effect in MT apparent resistivity curves may lead to erroneous interpretations of the data (Pellerin and Hohmann, 1990). This effect is produced by distortions of the measured electric field caused by boundary charges of galvanic type built-up on shallow inhomogeneities. The galvanic response of such small, shallow bodies, is manifested in the data as a vertical shift of the log-log apparent resistivity curves leaving the phase curves unaffected (Jones, 1988). There are several methods to correct the static shift of MT data (Jiracek, 1990). A common approach is to use an independent geophysical method close to the MT site in order to determine an undistorted 1-D shallow model. The observed MT apparent resistivity curves can then be corrected to the undistorted values calculated from this model. Sternberg et al. (1988) have proposed the use of a controlled-source transient electromagnetic sounding to perform this correction. Their method, based on the measurement of magnetic fields, circumvents the problem of galvanic effects as the boundary charges mainly affect the electric field. In this work we use the available Schlumberger VES data as the auxiliary technique to correct the MT data. Even though in a purely galvanic technique such as the VES there are also boundary charges affecting the measurements, the mobility of the source and receiver electrodic-arrays during the VES data acquisition could contribute to reduce the effects, so that they are not as harmful as for MT. Recent experience at the Tres Vírgenes geothermal zone, México (Romo et al., 1994) shows that, while the models obtained from transient electromagnetic soundings are less affected by shallow inhomogeneities, those derived from VES data can adequately perform the task of correcting the static shift-distorted MT data.

The Schlumberger data set used in the present work cover 85% of the MT sites (Fig. 2). In most of the MT sites we selected a nearby (within 1 km radius) VES, and the corresponding layered model (Flores et al., 1991) was then used to calculate a short-period (usually 0.02 s) magnetotelluric response. The MT observed apparent resistivity curves were shifted to fit the calculated MT response. In eighteen MT sites located in the southern end of the area where there is no VES coverage, the MT resistivity curves were shifted to fit a value of 50 Ω-*m* at 0.02 s, based on the evidence of a shallow resistive cover similar to the one present in the eastern edge of the area covered by the Schlumberger survey. Such evidence is supported by the dipole-dipole data and by the absence of surface manifestations.

After this VES-derived static correction was applied, apparent resistivity pseudosections were constructed. Based on these pseudosections, 14 isolated sites were identified where there was evidence of an incomplete static correction, as suggested by a vertical pattern of the apparent resistivity contours surrounding these sites over the whole frequency range. The apparent resistivity curves for these sites were shifted again to values resulting from the interpolation of the short-period MT responses from the surrounding sites. This second static shift correction was performed in order to prevent an erroneous interpretation of false deep conductors, and was applied only if there was no evidence of shallow conductors from the VES survey.

Modeling

As a first step in the quantitative interpretation of the magnetotelluric data, we constructed 1-D continuous models using the Niblett-Bostick transformation (Bostick, 1977) and the Occam inversion method (Constable et al., 1987). Figure 5 displays the inverted resistivities derived from these techniques using the *yx* -mode data from Line E4. One significant difference between them is evident in the shallow portion of the sections. In most sites, the Niblett-Bostick transformation is not able to estimate the subsurface resistivity at depths shallower than 150 m,. while the Occam inversion produces a resistive zone in the 50-150 m depth range, in agreement with the VES results. This condition is due to the particular depth estimation used in each of these methods. The Niblett-Bostick transformation estimates the depth (D) using the apparent resistivity of each particular period, i.e., $D=\left(\rho_a T / 2\pi\mu\right)^{1/2}$. At the shortest period (i.e.. 0.02 s), apparent resistivities larger than 10 Ω-*m* give depth values larger than 150 m. Therefore, this transformation is blind to thin shallow resistive layers. On the other hand, the Occam 1-D inversion uses an initial model with a user-defined depth range (i.e., 50 to 7000 m) and produces the smoothest model with minimum misfit, in a predefined number of iterations.

In the 200 m to 2 km depth range, both sections of Line E4 (Fig. 5) display four localized conductive zones where the resistivity is lower than 10 Ω-*m*. . Below 2 km both sections display resistivities that increase with depth.

The data were further modeled using the 2-D finite element algorithm of Wannamaker et al. (1987), implemented into the Geotools MT data interpretational package of WSE Associates. The subsurface resistivity distribution in any real situation is three-dimensional (3-D), and the interpretation in terms of 2-D models has inherent limitations. Nevertheless, these models are currently the best way to simulate seemingly complicated geological situations. Considering the number and spatial distribution of the collected data, it can be expected that the 2-D models obtained along several properly selected profiles should produce a useful picture of the geoelectrical structure of the studied area. The final models are constrained by independent geophysical and geological information.

The MT survey at Ahuachapán-Chipilapa was designed to provide information along profiles parallel and perpendicular to the known structural systems. We constructed 2-D models along eight ENE-WSW lines with the aim of simulating the apparent resistivity variation in the 0.01 to 10 s range, assumed to be associated with the structure within the upper 2 km of depth. We also constructed models along four lines oriented NNW-SSE to constrain the ENE-WSW models, although the 2-D assumption is not fully supported by these four lines. Regarding the longer periods (10 to 100 s), we propose that they respond mainly to the regional strike N70°E suggested by the tipper and the gravity data, which could be produced by the more resistive rocks associated with the volcanic chain, as compared to more conductive sediments filling the Central Graben depression.

We arrive at the final models by a trial-and-error approach, ending the process when an acceptable visual fit between model response and observed data is achieved. The response of the 2-D models is obtained for the two independent field polarization modes: the *TM*-mode with the magnetic field parallel to strike, and the *TE*-mode with the electric field parallel to strike. The *TM* -mode model response was compared with ρ_{yx} while the *TE* -mode model response was compared with ρ_{xy} . The principal objective was to obtain the best fit in the ρ_{yx} apparent resistivity, as the *TM* -mode is less distorted by 3-D effects (Wannamaker et al., 1984). In each model we tried to preserve in the resistivity structure the maximum lateral smoothness as much as possible. In some cases we looked for a compromise between these smoothing and fitting criteria when they differed. Furthermore, care was taken in obtaining qualitative agreements between the models of crossing lines. In most of the lines the modeling of the data in the 0.02 to 10 s period range resulted in a detailed electrical structure defined down to a depth of 1 km. In three lines (E5, N2, and N3) it was necessary to include lateral resistivity variations down to 2 km. Below this depth the structure modeled is 1-D, consisting of a 150 Ω-*m* homogeneous layer over a 10 Ω-*m* half-space at 150 km depth, simulating an hypothetical conductive asthenosphere. We did not incorporate the topography into the models because tests showed that the topographic effect falls within the observed data dispersion.

It is usually difficult to assess the nonuniqueness inherent to forward models. When looking at finished interpretations or final results, even those with experience find it hard to judge whether a particular feature included in a model is actually constrained by the data. This is especially true in geothermal and volcanic environments because of their complicated geological characteristics and corresponding complex resistivity distributions. One way of approaching the problem is to construct different models based on the same data set, but using widely different methods. In the Appendix we contrast the results of forward modeling with resistivity images obtained using an automatic interpretation technique. This type of comparison is very illustrative because in the first case there is a considerable amount of human intervention and judgment; in the second, they are kept to a minimum. Assumptions such as minimum and maximum values of resistivity, shape of conductive bodies or maximum depth of penetration, all are critically challenged with this approach.

Line E3

The 2-D model for Line E3 is given in Fig. 6*a*. Based on this model we sketch a representation of the subsurface resistivity variation and show other relevant information (Fig. 6*b*). In addition to the zones with different resistivity, the surface structural information as well as some temperature data and selected lithology information from five drillholes are also included. On the upper part of Fig. 6*b* we indicate the zones where seismicity and radon emissions have been registered (Fabriol, et al., 1990; Nieva, et al., 1992). The locations of El Playón and El Tortuguero hydrothermal manifestations are also indicated as well as the intersections with Lines N1, N2, N3 and N4.

In the central and eastern shallow portions of the model the electrical structure is characterized by 15 to 25 Ω-*m* resistivities within the upper 50 m, followed by a resistive (65 to 100 Ω-*m*) zone down to 150 to 400 m. At these depths, a conductor of variable resistivity occurs. This shallow sequence of low-high-low resistivity agrees with that interpreted from the VES survey (Fink, 1990; Flores et al., 1991). This sequence is interrupted in two areas, i.e., in the central part of the line (sites 73,74 and 79) where the resistive zone is missing, and under the El Playón manifestation where a deep conductor reaches shallow depths. The most important geothermal features of this model is the presence of three separate conductors with resistivities equal or lower than 2.5 Ω-*m* , located within the 0.4 to 1 km depth interval, hereafter referred as the *A, B,* and *C* conductors. The *A* conductor, defined by the data from sites 82 and 81, is associated with the Ahuachapán geothermal reservoir. The *B* conductor, under sites 75 and 76, is about 100 m below conductor *A*. Finally conductor *C*, in the eastern part of the model, is especially important because of its relatively larger dimensions and lower resistivities. Its eastern edge is not properly defined as it lies outside the area covered by the line.

The ρ_{yx} and ϕ_{yx} pseudosections comparing the model's response and the observed data, are shown in Fig. 7. The agreement in the ρ_{yx} pseudosection is good both in geometry and intensities. The calculated response behaves as a smoothed version of the observed data. The closed minima at about 1 s periods are obviously produced by the conductors discussed above. However, in the observed response they show resistivities lower than those calculated from the model. We could not reproduce these low apparent resistivities by decreasing the resistivities of the conductors, probably because the 2-D model is not able to reproduce 3-D effects.

Another interesting feature of these observed closed minima is that they extend to slightly longer periods than those of the calculated response. This would suggest that the base of the conductors shown in Fig. 6*a* do not end at 1 km depth, but extend further down. The high well temperatures measured below 1 km seem to support a larger depth extent of these conductors. This possibility was tested by 1-D and 2-D perturbation analysis (Romo and Flores, 1992) showing that the base to the conductors could extend up to 1.5 km, but not deeper. This possibility should, however, be considered with caution because in the 2 to 10 s period range the responses start to be affected by the ENE-WSW regional trend and it might not be appropriate to use a 2-D interpretation tool to analyze the 3-D effects on the data. Consequently the model at 1 km is a conservative estimate.

Line N2

The profile has a NW-SE orientation, starting 1 km north of the Ahuachapán power plant. It crosses the wellfield, goes through the volcanic chain near the eastern edge of the Hoyo del Cuajuste crater, and ends on the volcanic highlands 3 km NE of the town of Apaneca. The corresponding models (Figs. 8*a* and 8*b*) show the conductor *A* to be associated with the Ahuachapán reservoir. As in Line E3, there is some correlation between the Pyroclastic Flows horizon (González-Partida et al., 1991; labeled PF in Fig. 8*b*) and the base of the shallow resistive cover, as well as between the Volcanic Breccia (González-Partida et al., 1991; labeled VB in Fig. 8*b*) and the intermediate (6.5 Ω-*m*) resistivities at the top of the conductive zone. The highest temperatures reported in the displayed drillholes also coincide with the conductive zone.

On the southern end of this profile another conductive zone is evident. There the distribution of the 6.5 Ω-*m* zone suggests an interesting connection between the deep conductor and the Cerro Blanco hydrothermal manifestation at the northern flank of the volcanic chain. There is also evidence of seismic hypocenters below this area between 1.5 and 4.5 km depth (Fabriol, et al., this issue).

Spatial distribution of conductive zones

In order to have a better understanding of the spatial distribution of the interpreted conductors we constructed maps by correlating the low-resistivity zones defined in the 2-D models of all the lines (Figs. 9 to 11). Three depth intervals were chosen based on the behavior of these models: shallow (0-200 m), intermediate (200-500 m), and deep (500-1000 m, or 500-2000 m). To facilitate the discussion, we are attaching the subscripts *s, i,* or *d* (shallow, intermediate or deep) to the corresponding conductors. Figure 9 displays the zones with resistivities lower than 4 Ω-m, within the depth range from 500 m to 1000, or 2000 m. Five distinct conductors can be observed (A_d , B_d , C_d , D_d , and E_d). We will limit the discussion to conductors A_d , B_d and C_d located north of the volcanic chain.

The conductors A_d and B_d interconnect between the 309 and 310 north-coordinates, suggesting a common source for the El Playón and Chipilapa hydrothermal manifestations. The spatial distribution of conductor B_d is well constrained by the interpreted resistivities of six different lines. Although its southern boundary is not well defined, it might be located in the vicinity of the coordinates (415, 308.5), because sites 29 and 30 detect resistive zones at these depths. This suggests that the source for B_d originates under the Laguna Verde volcano. Starting from its southern boundary B_d displays a wandering pattern. It follows first a NW trend, then changing to a NE direction between Lines E2 and E1, presumably controlled by the NE-SW structural system, particularly by the Escalante fault, and finally shows an apparent north direction. This latter trend suggests that this conductor supplies fluids to the low-temperature Turin hot springs, about 4 km north of the studied area. The conductor C_d , located in the eastern margin of the area, is constrained by 23 sites of six different lines. Its western boundary is well defined and can be related to the El Tortuguero Graben structure.

The map in Fig. 10 displays the low-resistivity zones with values smaller than or equal to 6.5 Ω-*m* within the 200 to 500 m depth range. In some of the lines the 6.5 Ω-*m* value was obtained by averaging the interpreted resistivities within this depth range. The areal distribution of these intermediate-resistivity zones resembles a blurred image of the conductivity anomalies better defined on the deeper depth interval discussed earlier. The connection zone between the *A* and *B* conductors is spread over a larger area, only interrupted by local higher resistivities below sites 9 and 75. The conductor C_i has a NW trend and is connected with conductor B_i in the vicinity of the Chipilapa hot springs. This suggests that this discharge zone could be supplied by two separate sources of hot fluids, one coming from the east and one from the south or southwest. On the northern segment of Line N3 the conductivity anomaly has been labeled $(B\text{-}C)_i$ and it seems to follow a N-S trend, although this geometry is only constrained by the three northern sites of this profile.

The shaded areas in Fig. 11 indicate the region where the interpreted resistivity is less than or equal to 10 Ω-*m* within the 0 to 200 m depth interval. The hydrothermal alteration zones mapped by González-Partida et al. (1991) are also shown in the figure. Clearly, the conductor A_s is the electrical expression of the Cerro Blanco, Agua Shuca and El Playón hydrothermal manifestations. An important feature is that only the southern portion of El Playón alteration zone is covered by A_s . It is interesting to note that the northern portion of this alteration zone has a shallow resistive structure, and that this area is where the higher density of producing wells in the Ahuachapán field occurs. This point will be discussed later.

The conductor B_s shows a particularly conductive zone which is surrounded by a more resistive halo on its north, east and southern sides. The association of B_s with the Chipilapa and La Labor hydrothermal alteration zones is evident. The deep (B_d) and intermediate (B_i) levels of conductor *B* are characterized by their elongated shape (Figs. 9 and 10). The conductor loses this pattern at shallow depths and occurs only in the northern portion of the studied area, highlighting the more resistive shallow structure prevailing south of the 310.5 north-coordinate.

A third shallow conductive zone, defined by three sites on Line E4, seems to be associated with the Cuyanausul hydrothermal manifestation. The El Tortuguero-Termópilas hydrothermal alteration zones do not seem to have an associated shallow conductive zone, nevertheless the deeper occurrence of conductor *C* increases the possibility of shallow high conductivities south of the area covered by this study.

Discussion

The relationship between the shallow conductors and the hydrothermal alteration zones is quite evident. Moreover, the extension of these conductors to the area surrounding the mapped alteration zones suggests that argillitization of the near-surface rocks contributes significantly to the high conductivities found, as should be expected (Ward and Fraser, 1967; Orellana, 1972).

The conductivity anomalies at depth seem to be controlled by the younger N-S, NNW-SSE, and NW-SE fault trends (González-Partida et al., 1991). The association of El Tortuguero Graben with the western boundary of C_d is an example of this relationship, as well as the correlation between the trend of conductor B_d and the Escalante Fault.

A straightforward relationship between lithology and electrical conductivity is difficult to establish. However the large number of drillholes provides some evidence of a correlation between the Pyroclastic Flows penetrated by many of the wells and the inferred bottom of the shallow resistive cover in the eastern portion of Ahuachapán production zone. Furthermore, the Volcanic Breccia occurs in many of the wells at a depth where a 6.5 Ω-

m resistivity was interpreted, agreeing with the top of the deep high-conductivity anomalies.

Some interesting correlations can be derived from the temperature data from 16 Ahuachapán wells located along the MT interpreted profiles. Ten of these wells (Ah1, 4, 14, 17, 19, 22, 23, 26, 29 and 31) cut through the deep conductive (2.5 Ω-*m*) anomaly and present temperatures above 200° C . Two other wells (Ah8 and 18) are drilled through the 4 Ω-*m* zone and also show temperatures higher than 200° C (Fig. 6*b*). The exception is well Ah3, which has a temperatures of 230° C, and is located in a 6.5 Ω-*m* zone, 700 m from the conductivity anomaly. Temperatures below 200° C are reported in wells Ah15, 10, and 12, located in higher resistivity zones. These facts lead us to propose for the Ahuachapán exploitation area a relationship between high temperatures and high conductivities. This would suggest that the influence of clay minerals resulting from hydrothermal alteration processes is not the main contributing factor to the enhanced deep conductivities.

The spatial distribution of the deep conductivity anomalies and of the productive wells (Fig. 12), also suggests an interesting relationship. There are 36 wells located in the Ahuachapán-Chipilapa area. According to Laky et al. (1989), 24 are productive, and 12 non-productive. Only two of the productive wells (Ah8 and Ah2) are located where the deep conductor is absent, while the other 22 cut through the inferred deep conductor.

Moreover, only three (Ah25, Ah14 and Ch-1) out of 12 non-productive wells are located where the existence of a deep conductor was inferred, while 9 are drilled into resistive zones. Therefore, in 86% of the cases there is a positive correlation between the presence of a deep conductor and the occurrence of a productive well, implying the existence of enhanced permeabilities possibly the result of faulting and fracturing. This correlation together with the temperature-conductivity relationship discussed above, suggest that the low resistivities found can be explained by the combined effect of high temperature and high permeability. Even though this is not a new concept, it is seldomly supported by the results of a geophysical field study. In this case the large number of drillholes and the dense MT site coverage allow us to propose such relationship.

Figure 12 shows also the distribution of shallow conductive zones. Two conditions are fulfilled by half of the productive wells: they were drilled into the deep conductor and are located in a region where the shallow conductor is absent. This fact does not suggest that these conditions by themselves should be used in the selection of new drilling sites.. However, as mentioned before, in these areas the bottom of the shallow resistive cover may be related to the Pyroclastic Flows, an impermeable layer that prevents the upward flow of hot water. In fact, this unit separates the shallow and saturated aquifers proposed by Laky et al. (1989). We consider that the presence of this layer creates better conditions for the existence of a high-pressure and temperature hydrothermal system in the subsurface. By contrast, we interpret the presence of the shallow conductor as evidence of hydrothermal clay alteration produced by the circulation of thermal fluids through a impermeable, but fractured, layer.

In summary, we propose that the presence of a deep conductor overlain by a shallow resistive layer is a feature favorable for the existence of an exploitable geothermal reservoir. This hypothesis has three components. The first two are the high temperature-deep conductor association, and the deep conductor - productive well - high permeability correlation, which seem to be statistically well supported. The third component, the required existence of the resistive cover, although statistically weaker, is based on the conceptual model of a geothermal reservoir consisting of a permeable rock formation capped by a impermeable seal. In the case of Ahuachapán-Chipilapa the Pyroclastic Flows act as the seal.

Based on this hypothesis two alternate areas for future exploratory drilling were proposed (Fig. 13). The first one is the southern portion of conductor *B* which is apparently controlled by the NNW-SSE fault system and is probably related to the Laguna Verde volcano. Even though there are no mapped faults on the surface, the existence of active faults at depth is very likely, as suggested by a cluster of seismic hypocenters between 1.5 and 4.5 km depth, in close vicinity to the Laguna Verde crater (Fabriol and Beauce, this issue). The second proposed zone is the conductor C_d, whose western limit seems to be controlled by El Tortuguero Graben. According with its behavior on the modeled cross-sections it could be the source of fluids for both, the Chipilapa and El Tortuguero - Termópilas hydrothermal zones.

Conclusions

The large number and the high spatial density of the observations were a determining factor to achieve a useful image of the subsurface conductivity distribution in the Ahuachapán-Chipilapa area. The existing Schlumberger data and the dipole-dipole profiles rendered valuable information for correcting the static effect and constraining the 2-D MT models. The observed magnetotelluric response in the intermediate period range (i.e., 0.4 to 4.0 s) delineates a NNW-SSE pattern, suggesting that the younger structural systems are the main controlling factor for the apparent resistivity variation in this period band. The regional structural trend imposed by the volcanic chain and the southern limit of the Central Graben gives rise to the long-period MT response as revealed by the consistent impedance rotation angle and the tipper strike. The lateral resistivity variations in the 2-D models were confined to the upper 2 km simulating the MT response in the 0.02 to 10 s range.

The results indicate the existence of three deep conductors (A_d , B_d , C_d) north of the volcanic chain, whose trend agrees with the NNW-SSE structural system. The conductor A_d representing the Ahuachapán field, conductor B_d apparently associated with the

Laguna Verde volcano, and conductor C_d possibly being controlled by El Tortuguero Graben. In the intermediate (200-500 m) depth interval the geometry of these conductivity anomalies supports the thesis that the fluids for the Chipilapa and La Labor hot springs are recharged not only from the south or southwest but also from the east. The shallow expression of the conductive anomalies agrees with the hydrothermal alteration zones mapped at the surface, suggesting that the hydrothermal argillitization process contributes significantly to the low resistivities observed at this shallow level.

The diverse geological and geophysical information available was very helpful to define important correlations between high temperatures and high conductivities, as well as between the deep conductivity anomaly and productive wells. The proposed new drilling sites were selected on the basis of 2-D models and existing drillhole information. The areas where the deep conductor is covered by a shallow resistive layer seem to provide better conditions for the existence of an exploitable geothermal system at depth.

The application of the imaging technique indicates that the models obtained by forward modeling are in general well constrained. In the poorly constrained cases, the resistivity images represent alternative models that enrich our understanding of the subsurface. The correlation between low resistivities and high temperatures are quite remarkable given the complex geology of the field, and the fact that the resistivity images were generated without any external assumptions besides the magnetotelluric data.

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Appendix

Magnetotelluric imaging of Lines N2 and N3

The imaging technique that we used is an approximate inverse method designed to be a two-dimensional version of the well-known Niblett-Bostick transformation for magnetotelluric soundings (Esparza, 1991; Esparza et al., 1993; Gómez-Treviño et al., 1994). The approximation is based on the exact nonlinear integral equations described in Gómez-Treviño (1987). It preserves the nonlinear character of the inverse problem and reduces it to a system of linear equations. The algorithm is fast and runs on personal computers. It handles differently the TE from the TM modes and, if desired, it can invert the determinant of the impedance tensor. In contrast to conventional iterative inverse methods, the resistivity images are obtained directly from the data in a single iteration. It does not need a reference model and requires minimum human intervention in the sense that there is very little that the interpreter can do to incorporate his views into the model. The approach is very similar to that applied by Pérez-Flores and Gómez-Treviño (this issue) to dipole-dipole resistivity data from the same area.

Lines N2 and N3 will be considered. The resistivity images were computed using apparent conductivity values derived from the determinant of the impedance tensor. In two dimensions this corresponds to the geometrical average of the apparent conductivity for the TE and TM modes. Initial tests using both modes separately and then using their average resulted in very similar images. We have chosen the images derived from the determinant because it is rotation invariant. The resulting images are then independent of the identification of modes. We used eleven periods per sounding in the 0.01 to 100 s range.

The comparison for Line N2 is presented in Fig. A-1. This line runs almost N-S and crosses the Ahuachapán field and the volcanic belt between the Laguna Verde and Hoyo del Cuajuste volcanoes. Fig. A-1(a) shows the resistivity image obtained with our automatic method and Fig. A-1(b) the resistivity model using forward modeling. The resistivity model presents two large, deep conductors in the 500-1500 m depth interval. The conductor to the North, between soundings 5 and 9, corresponds to the Ahuachapán field. This conductor is also in the resistivity image, between the same soundings and in the same depth range. Regarding the deep conductor to the South, it is clear that its mean depth is not very well constrained by the data, particularly below the last three soundings of the line. However, apart from these differences the shape of the conductor and its outcropping character are well determined. It can also be observed that except for small scale discrepancies, the resistive barrier below soundings 12 to 13 that separates the two large conductors is well determined by the data.

The most significant difference between Figs. A-1(a) and A-1(b) is the deep conductor shown in the resistivity image below soundings 6 and 5 in the northern part of the line. This conductor is not present in the forward model. It is of interest to ask whether this conductor actually exists because it would indicate a possible deep source of hot fluids for the Ahuachapán field. In this respect, it is worth mentioning that in the dipole-dipole resistivity image for Line L-1, the Ahuachapán field shows up as a conductive zone that extends in this area below 1 km depth. The numbers in kilometers along the horizontal axes in the resistivity image of Fig. A-1(a) correspond to Line L-1 of Pérez-Flores and Gómez-Treviño (this issue).

Although magnetotelluric and dc-resistivity methods are both sensitive to the same physical property, they respond differently and emphasize different aspects of a resistivity distribution. Comparing results and understanding their differences, require a physical insight that is best dealt with by inverting jointly both types of data. This type of analysis falls beyond the scope of the present paper. Here, we limit ourselves to the comparison of magnetotelluric images with magnetotelluric forward models. However, we will refer to the dc-resistivity images in Pérez-Flores and Gómez-Treviño (this issue) when, as in this line, there are features in the images that are not in the forward models.

The comparison of the resistivity image for Line N3 with its corresponding forward model is shown in Fig. A-2. In this case it is convenient to divide the section into two halves separated by sounding 28. The northern part of the section, from sounding 19 to 28, is clearly very well constrained by the data. For this half, the resistivity image of Fig. A-2(a) confirms the resistivity structure of the forward model shown in Fig. A-2(b). Even small details as the dipping character of the conductor between soundings 25 and 28 are common to both interpretations. The other half of the section, south of sounding 28, is less well constrained by the data than the first half. The main discrepancy between the resistivity image and the forward model for this half concerns the mean depth of the conductive zone below soundings 29 and 30. In the resistivity image the conductor occupies the 700 m to 1.5 km depth range, while in the forward model this range is between 1 and 2 km. If we assume that both interpretations are correct, in the sense that both reproduce the data reasonably well, we are then in the presence of complex equivalence effects. This would mean that the data supports the presence of a deep conductor, but contains relatively little information about the depths to its top and bottom. Following with the analysis of the rest of the line, we notice a deep conductive layer toward the south end of the resistivity forward model. This conductor is also present in the resistivity image, thus indicating that it is a well-constrained feature required by the data. Notice that the thickness of the deep layer decreases to the north suggesting a poor connection with the deep conductor below soundings 29 and 30. This poor connection is also a well-determined feature in the model, because the resistivity image also suggests a discontinuity there.

The classical association of high electrical conductivity (low resistivity) with the presence of high-temperature geothermal fluids is only an approximation in complex geological environments. However, perhaps because of its simplicity it is still the most often recurrent working hypothesis in the application of electrical methods to geothermal exploration. Pérez-Flores and Gómez-Treviño (this issue) present a comparative analysis of dipole-dipole resistivity images with temperature distributions obtained from deep wells. These authors found a reasonable good correlation in spite of the complex geology of the area. Here we attempt to do the same but using the resistivity images obtained from the magnetotelluric data.

The comparison of the resistivity image for Line N2 with the temperature distribution at depth is shown in Fig. A-3. The overall picture is a clear correlation between low resistivity and high temperature. The temperature in a given well increases with depth and reaches its maximum value around the point of lowest resistivity, and it decreases at depths where the resistivity increases again. Notice also the near-surface low resistivity associated with the Cerro Blanco hydrothermal manifestation.

The comparison of the resistivity image for Line N3 with the temperature distribution at depth is shown in Fig. A-4. In this case we can observe very much the same pattern in the conductive zone centered at 500 m depth. The temperature increases with depth until it reaches a local maximum and then decreases. The depth of maximum temperature correlates very well with the resistivity minimum. The temperature increases again at greater depths but there is no longer a correlation with the resistivity image. In this respect it is worth mentioning that the dipole-dipole resistivity image correlates very well with the temperature distribution in both shallow and deeper regions.

Figuras.doc

Figure captions

Fig. 1. Location of the MT sites (triangles) and interpreted lines. Also shown are the topographic relief (contours every 200 m), main faults, eruptive centers, and hydrothermal manifestations (ELP: El Playón, CRB: Cerro Blanco, LLB: La Labor, ASH: Agua Shuca, ELT: El Tortuguero, CUY: Cuyanáusul, CHP: Chipilapa, TER: Termópilas).

Fig. 2. Transverse resistance (in 10^3 Ω-m^2) derived from the VES models. Areas with values less than 10^4 Ω-m^2 have been shaded. The open dots represent the location of the VES soundings. Also shown are the four dipole-dipole dc-resistivity Lines L-1, L-2, L-4, and L-5.

Fig. 3. Apparent resistivity (after static shift correction) and phase data of three representative sites. The error bars represent one standard deviation.

Fig. 4. Apparent resistivity and impedance phase pseudosections for Line E4. The isolines are in Ω-*m* and degrees, respectively. Areas with apparent resistivity values greater than 10 Ω-*m* have been shaded to emphasize the conductive zones. The small dots under each sounding site indicate the data points used for contouring.

Fig. 5. 1-D inversions of the *yx*-mode for Line E4 using the Niblett-Bostick transformation (Bostick, 1977) and the Occam algorithm (Constable et al., 1987). The iso-resistivity lines are in Ω-*m*. The small dots in the Bostick section indicate the data points used for contouring.

Fig. 6. Two-dimensional model for Line E3: *a)* Interpreted model with block resistivities in Ω-*m*. *b)* Schematic model incorporating the topographic relief, the mapped faults (fault dips are not true dips), drillholes with reported temperatures in °C and depth intervals cutting the Pyroclastic Flows (PF) and Volcanic Breccia (VB) horizons (a dashed arrow indicates an off-section hole). Also shown at the top: zones of radon emission, seismic clusterings with indicated hypocenter depth range, hydrothermal alteration zones (dashed lines indicate an off-section location), and the crossover location of the other MT lines.

Fig. 7. Observed and calculated apparent resistivity and impedance phase for Line E3 (*yx*-mode).

Fig. 8. Two-dimensional model for Line N2: *a)* Interpreted model with block resistivities in Ω-*m*. *b)* Schematic model incorporating the topographic relief, the mapped faults (fault dips are not true dips), drillholes with reported temperatures in °C and depth intervals cutting the Pyroclasitic Flows (PF) and Volcanic Breccia (VB) horizons (a dashed arrow indicates an off-section hole). Also shown at the top: zones of radon emission, seismic clusterings with indicated hypocenter depth range, hydrothermal alteration zones (dashed lines indicate an off-section location), and the crossover location of the other MT lines.

Fig. 9. Deep conductors.

Fig. 10. Intermediate depth conductors.

Fig. 11. Shallow conductors and hydrothermal alteration zones.

Fig. 12. Deep conductors and drillholes.

Fig. 13. Proposed drilling zones.

Fig. A-1 (a) Resistivity image for Line N2 constructed from magnetotelluric data. The numbers in the horizontal scale (in km) are the same as that in Pérez-Flores and Gómez-Treviño (this issue) for the dipole-dipole resistivity image of Line L-1. (b) Resistivity forward model for the Line N2.

Fig. A-2 (a) Resistivity image for Line N3 constructed from magnetotelluric data. The numbers in the horizontal scale (in km) are the same as that in Pérez-Flores and Gómez-Treviño (this issue) for the dipole-dipole resistivity image of Line L-4. (b) Resistivity forward model for the Line N3.

Fig. A-3 Correlation of the resistivity image for Line N2 with temperatures (in °C) measured in deep wells.

Fig. A-4 Correlation of the resistivity image for Line N3 with temperature (in °C) measured in deep wells.

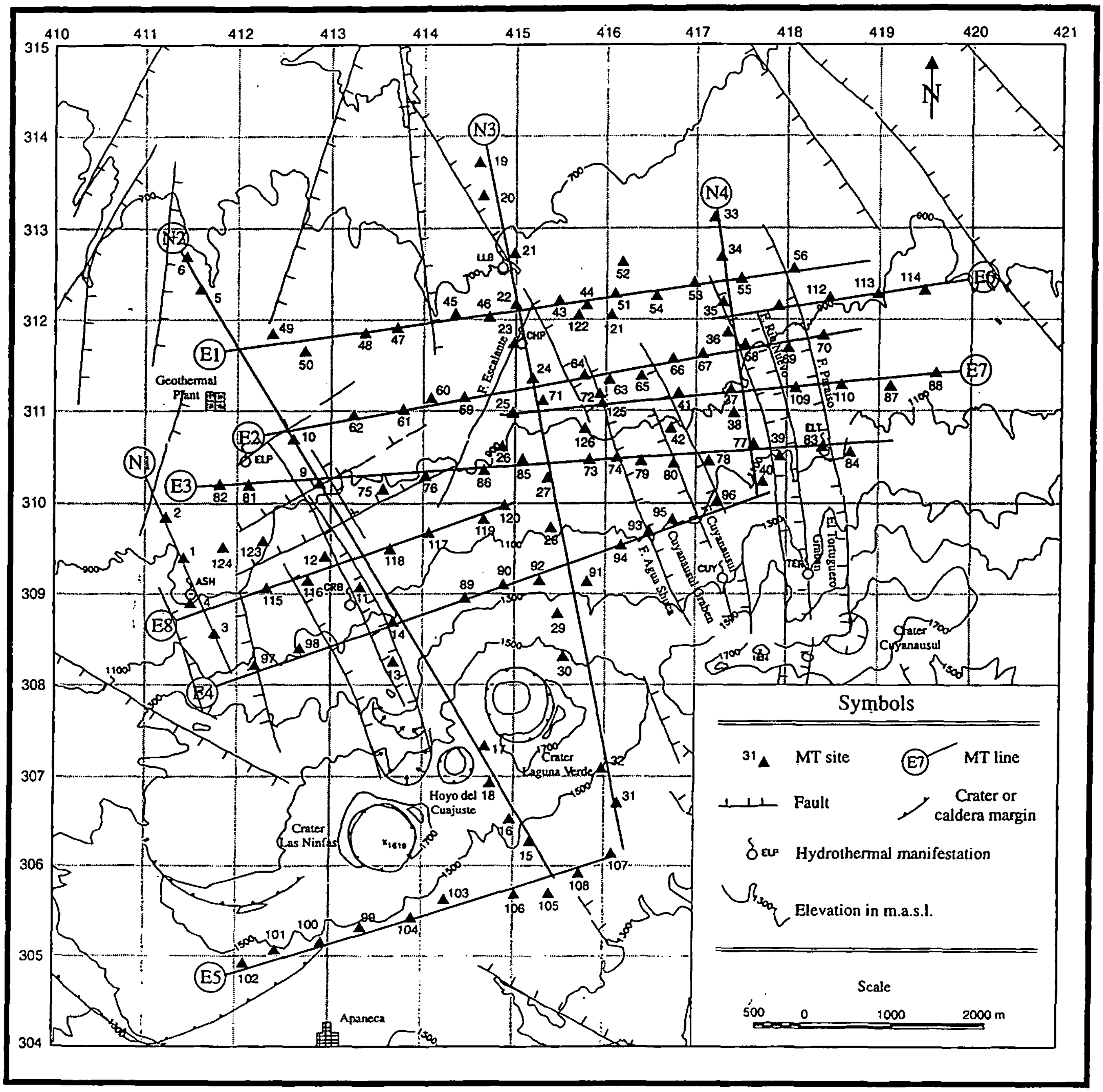
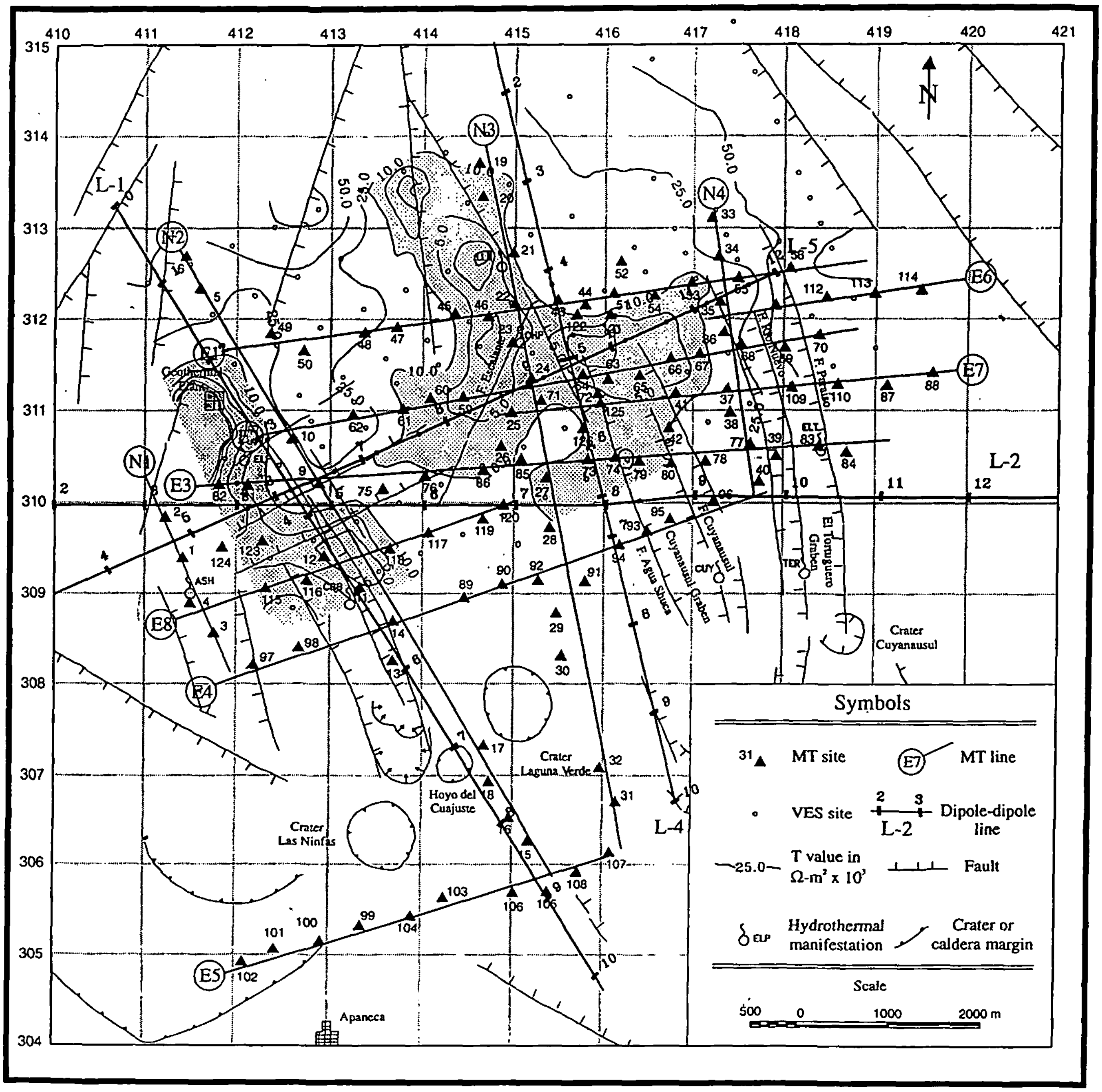


Fig. 1
Location of MT sites
C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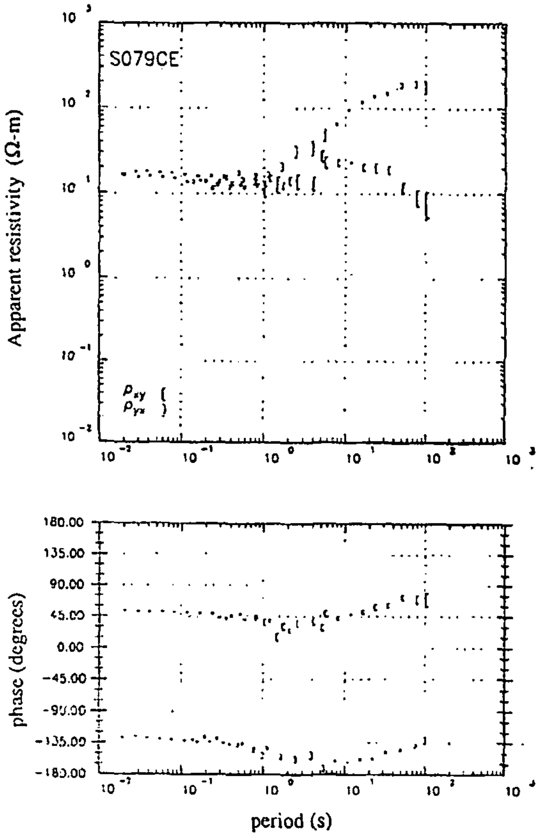
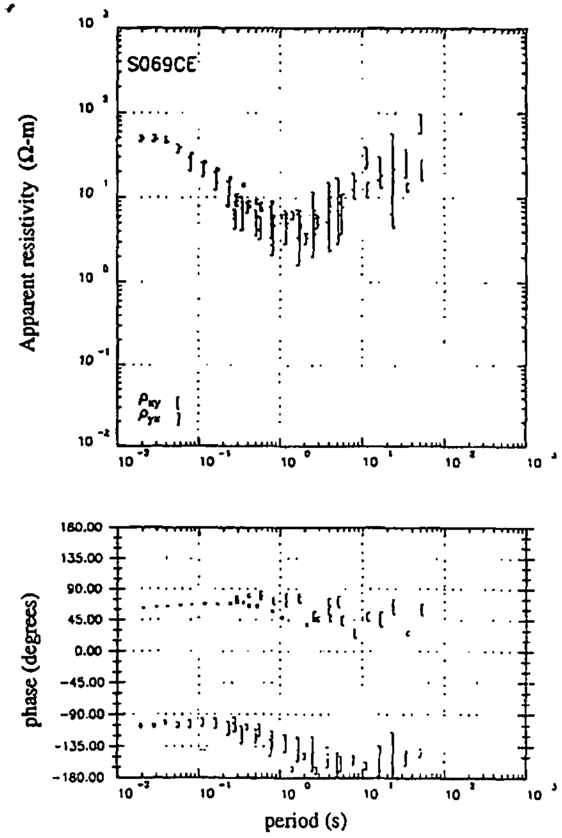
L-5
N1
N2
N3
N4
E1
E3
E4
E5
E6
E7
E8
Geothermal Plant
F. Escalante
F. Agua Shuca
F. Cuyanausul
F. Rodríguez
F. Paraíso
Cuyanausul Graben
El Tortuguero Graben
Crater Cuyanausul
Crater Laguna Verde
Hoyo del Cuajuste
Crater Las Ninfas
Apaneca
ASH
CUY
TER
ELT
CHP
ELP
50.0
25.0
10.0
5.0
Symbols
MT site
MT line
VES site
Dipole-dipole line
T value in Ω-m² x 10³
Fault
Hydrothermal manifestation
Crater or caldera margin
Scale
500
0
1000
2000 m

Fig 2.


S079CE
Apparent resistivity (Ω-m)
ρxy
ρyx
phase (degrees)
180.00
135.00
90.00
45.00
0.00
-45.00
-90.00
-135.00
-180.00
10⁻² 10⁻¹ 10⁰ 10¹ 10² 10³
period (s)


S069CE
Apparent resistivity (Ω-m)
ρxy
ρyx
phase (degrees)
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135.00
90.00
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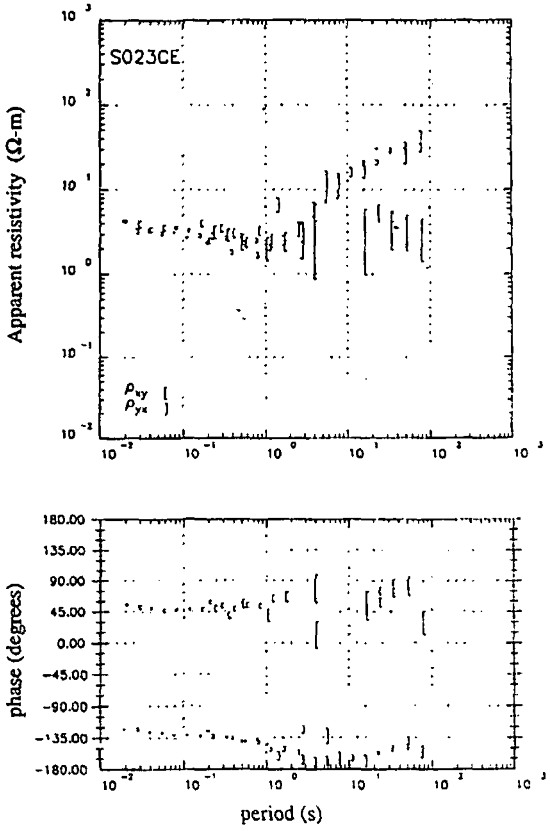
period (s)


S023CE
Apparent resistivity (Ω-m)
ρxy
ρyx
phase (degrees)
180.00
135.00
90.00
45.00
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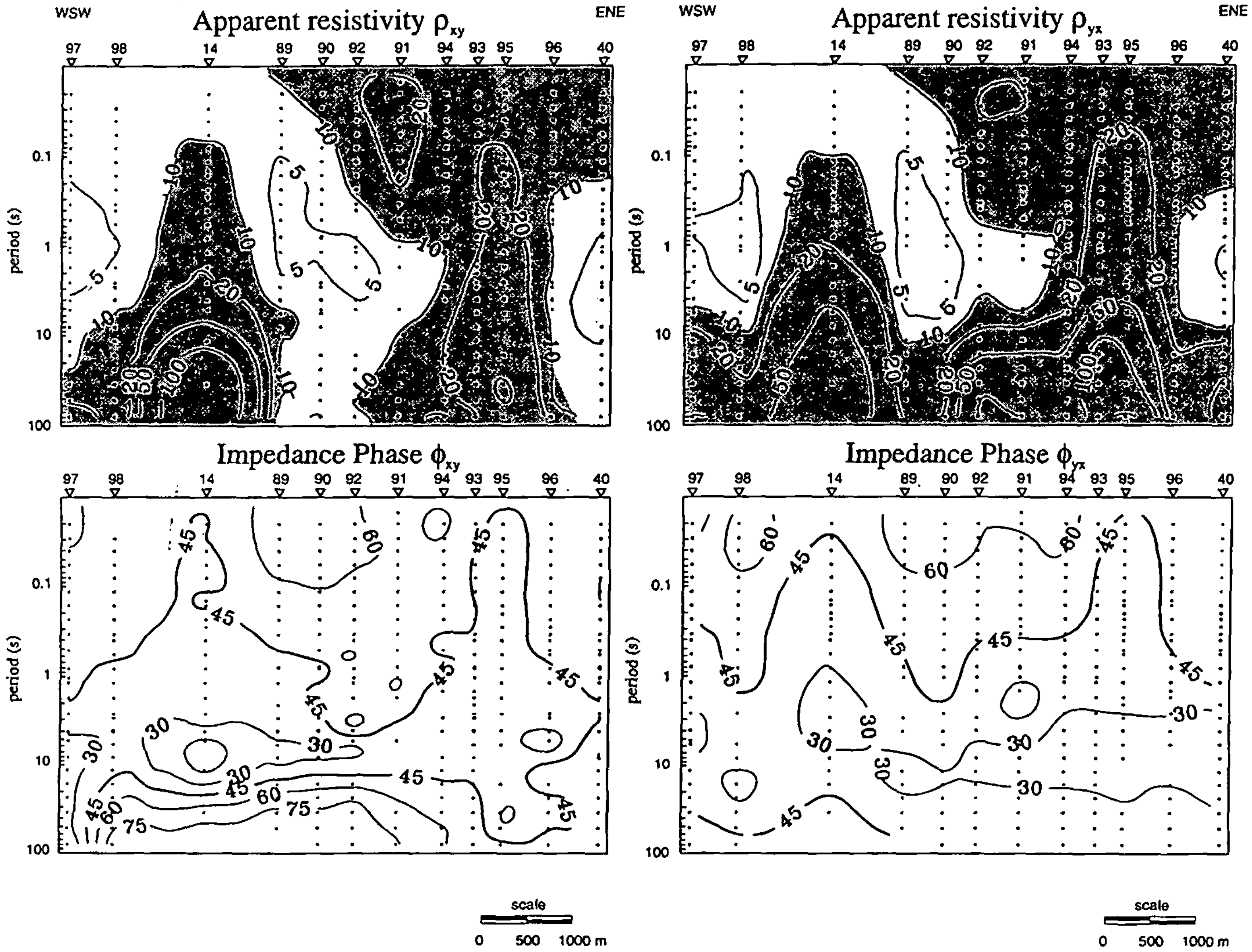
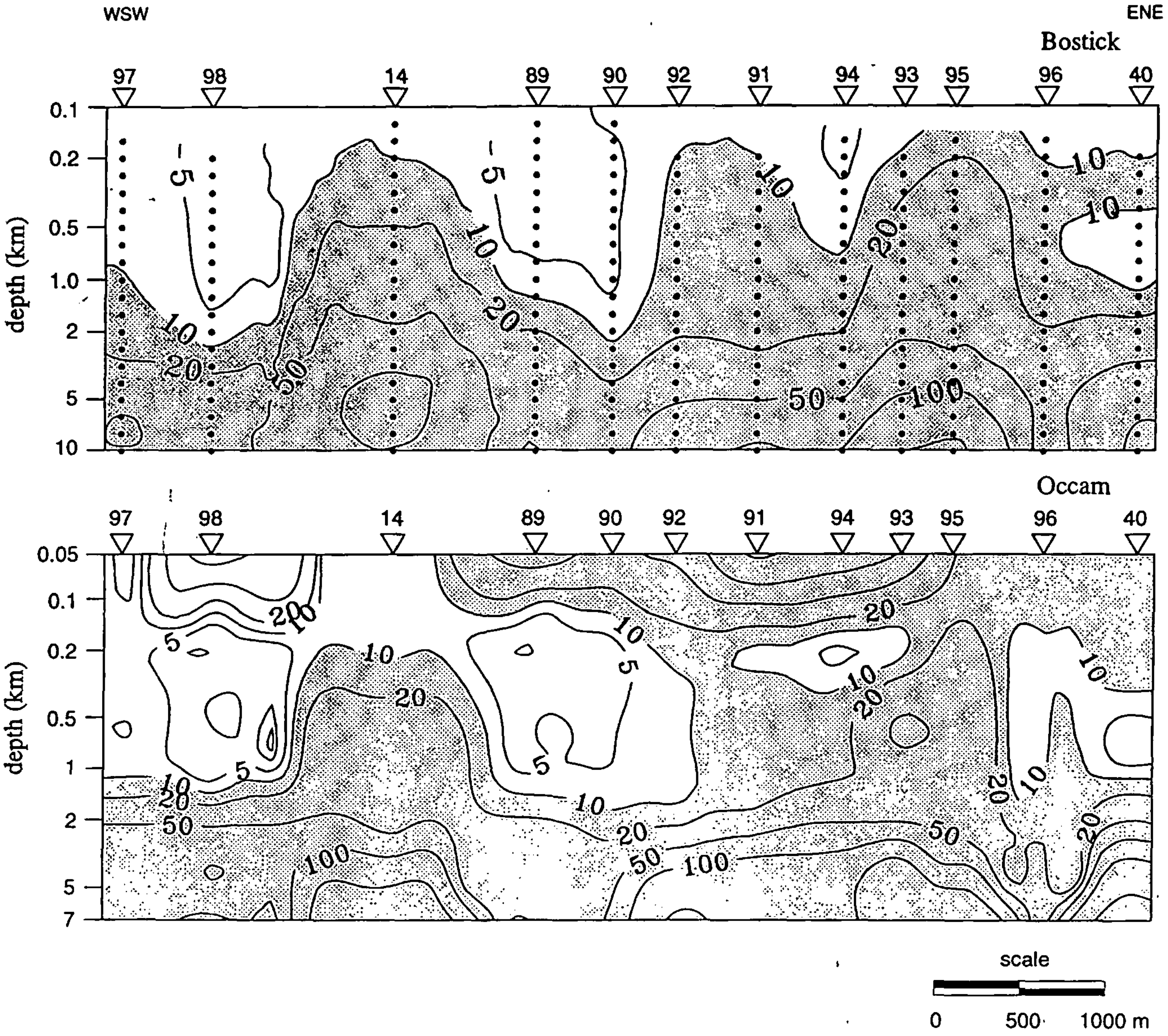
-135.00
-180.00
10⁻² 10⁻¹ 10⁰ 10¹ 10² 10³
period (s)

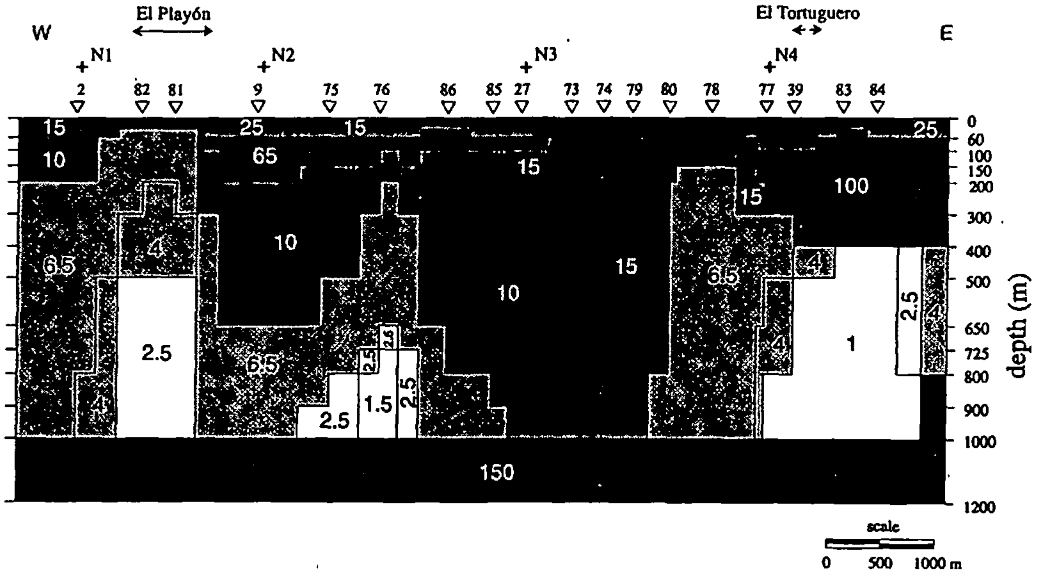
Line E4


WSW
Apparent resistivity ρ_{xy}
ENE
WSW
Apparent resistivity ρ_{yx}
ENE
97
98
14
89
90
92
91
94
93
95
96
40
period (s)
0.1
1
10
100
5
10
20
50
100
Impedance Phase ϕ_{xy}
Impedance Phase ϕ_{yx}
30
45
60
75
scale
0
500
1000 m

Line E4 (yx mode)



2D-model Line E3



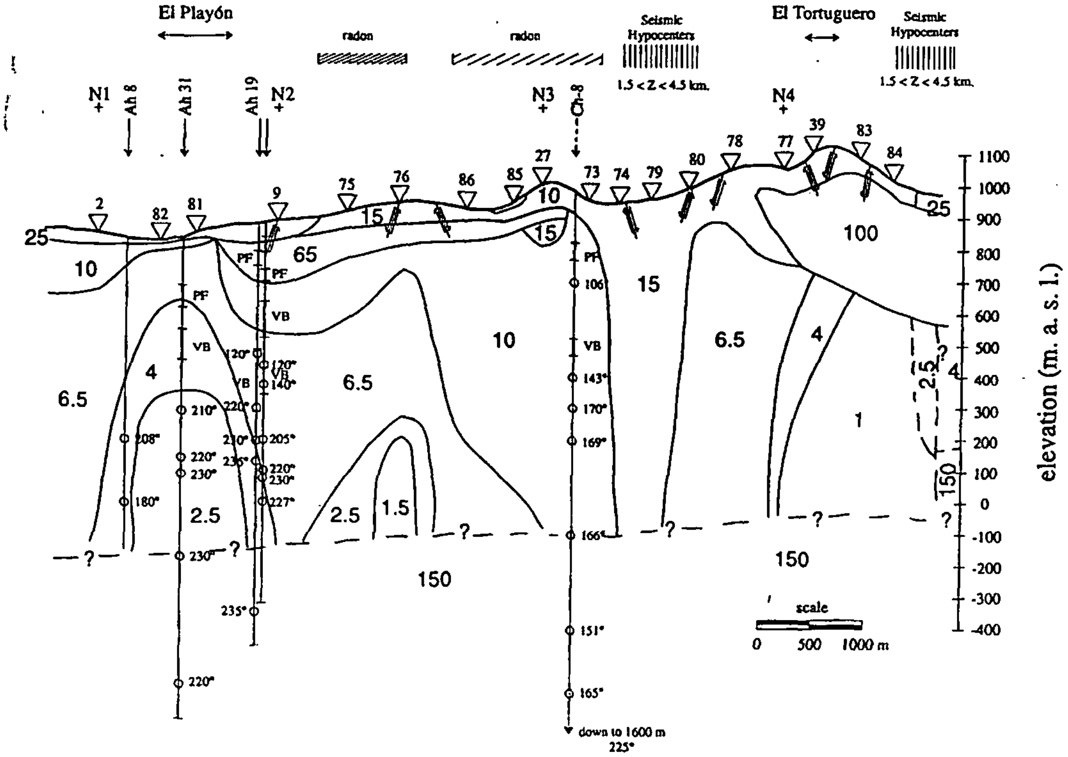
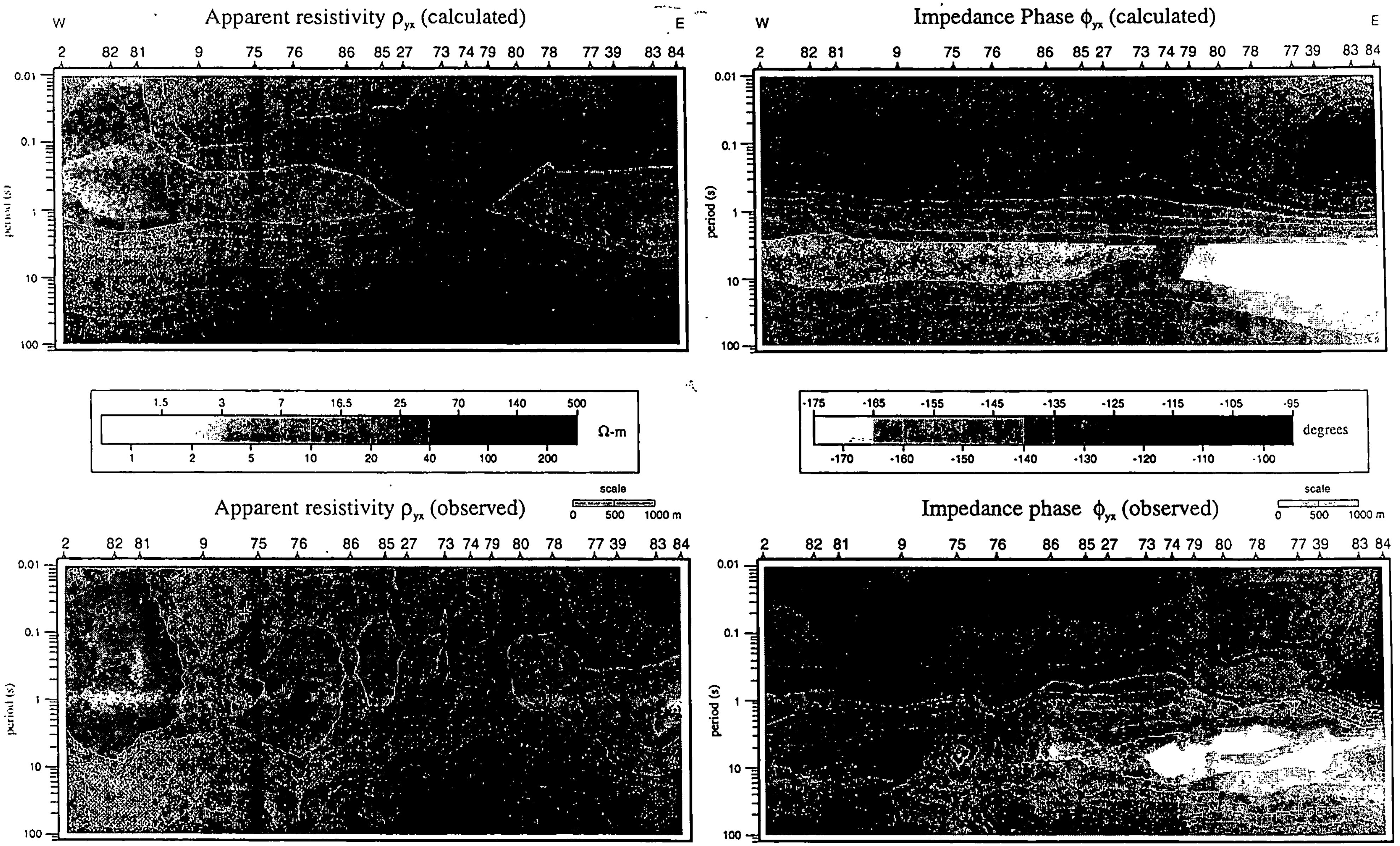


Fig 6

Line E3



Apparent resistivity ρ_{yx} (calculated)

Impedance Phase ϕ_{yx} (calculated)

Apparent resistivity ρ_{yx} (observed)

Impedance phase ϕ_{yx} (observed)

2D-model Line N2

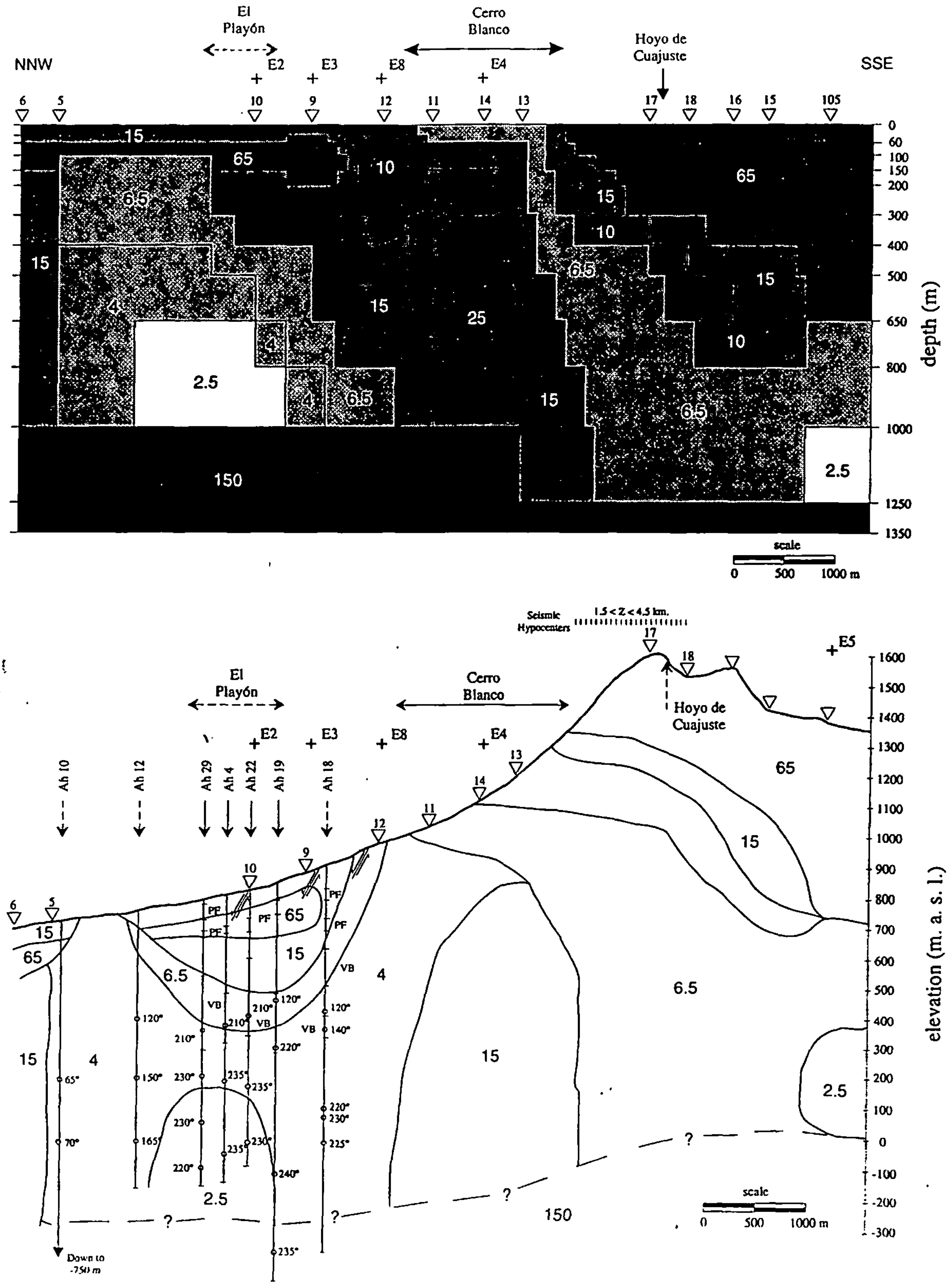


Fig. 8

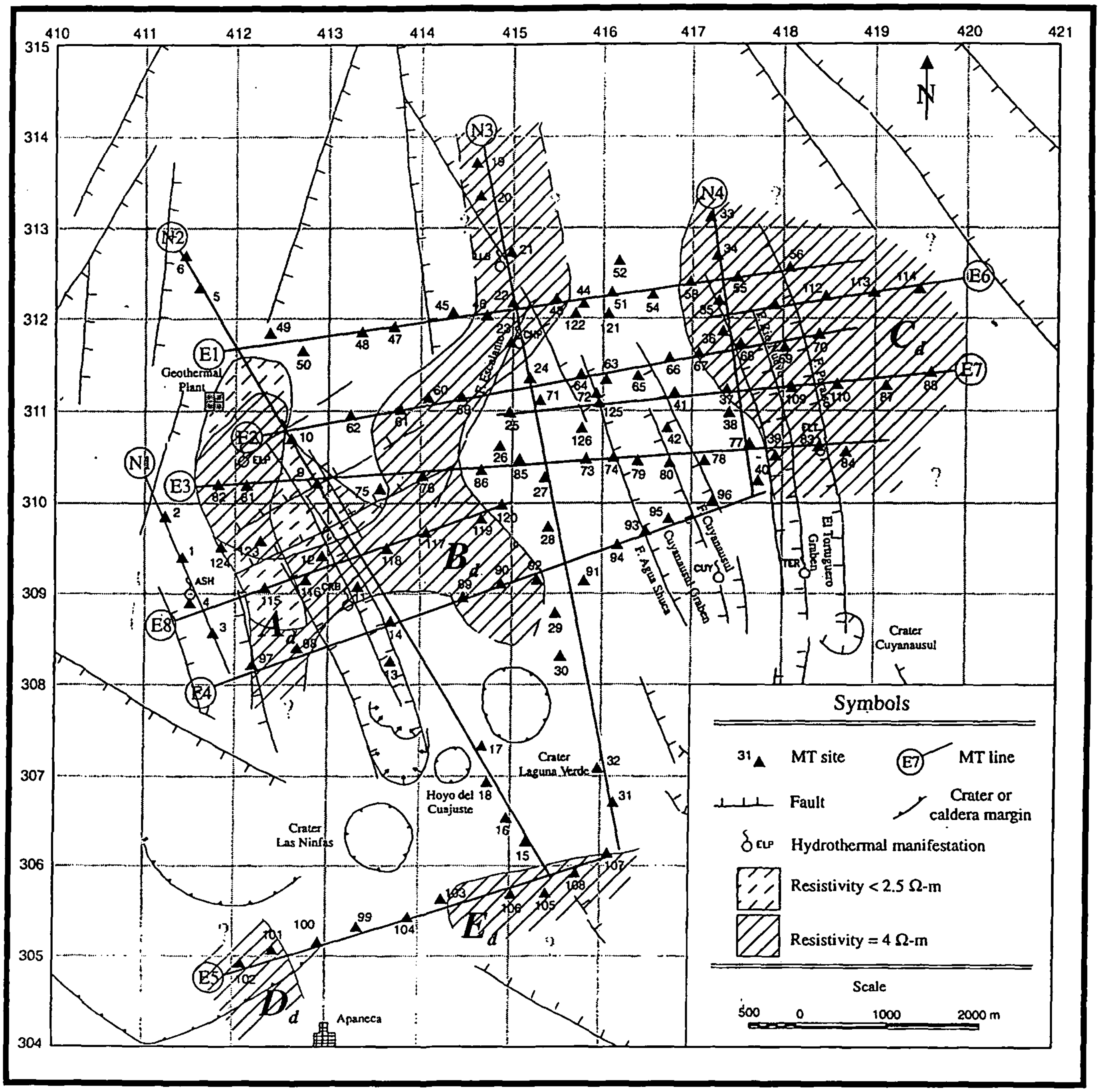


Fig. 9

Deep conductors

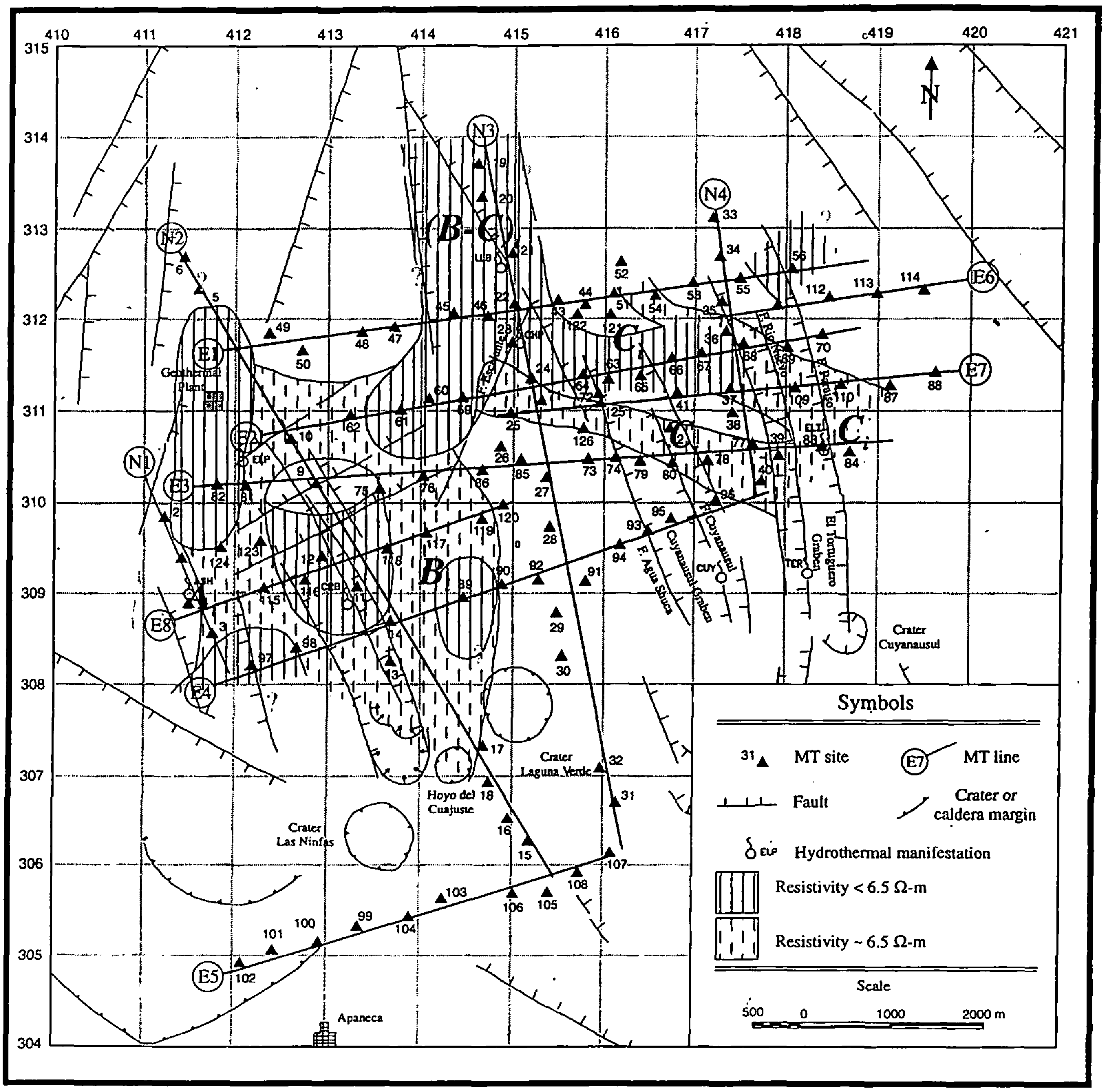
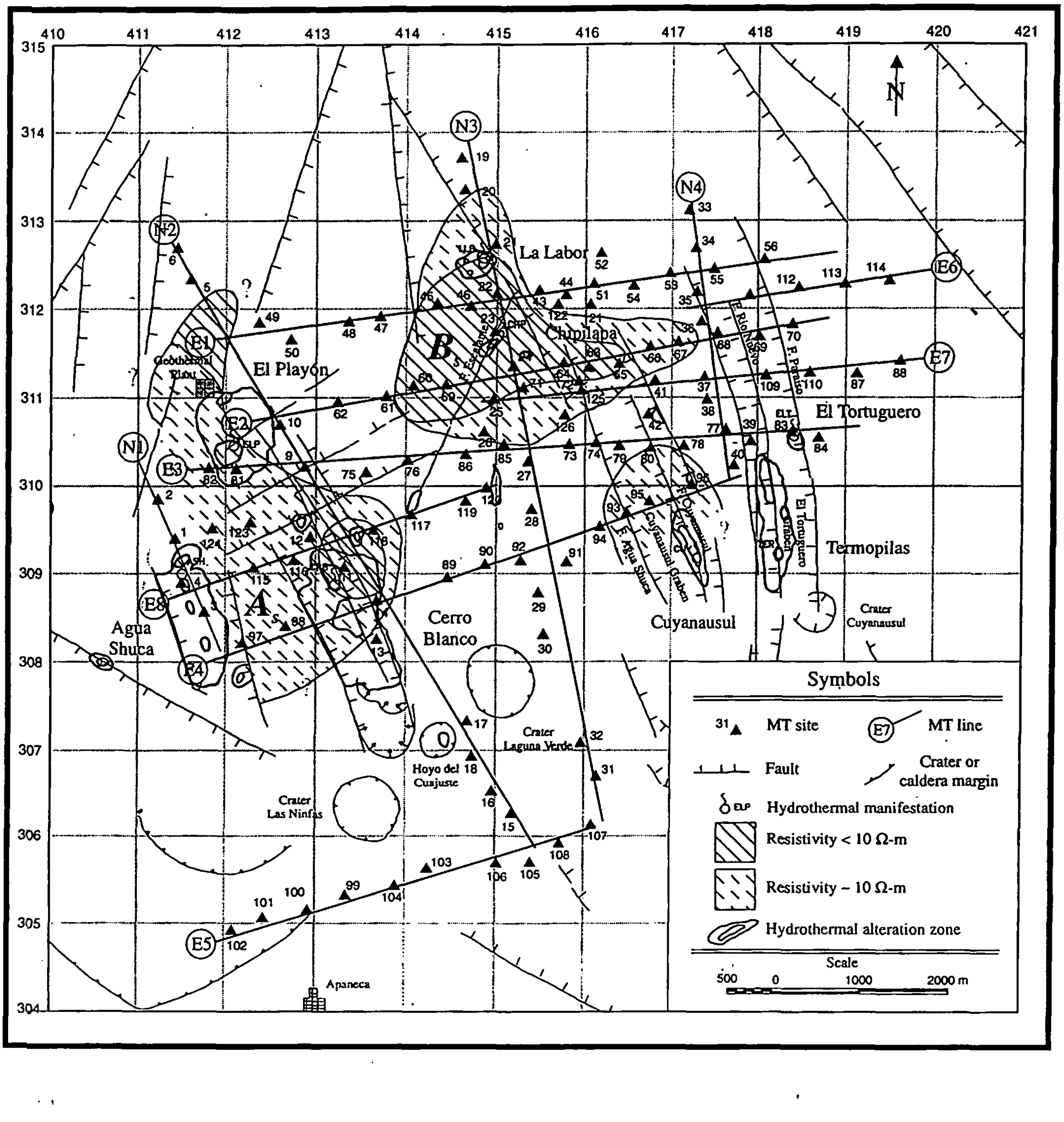


Fig. 10
Intermediate



S

Fig. 11
Shallow conductors

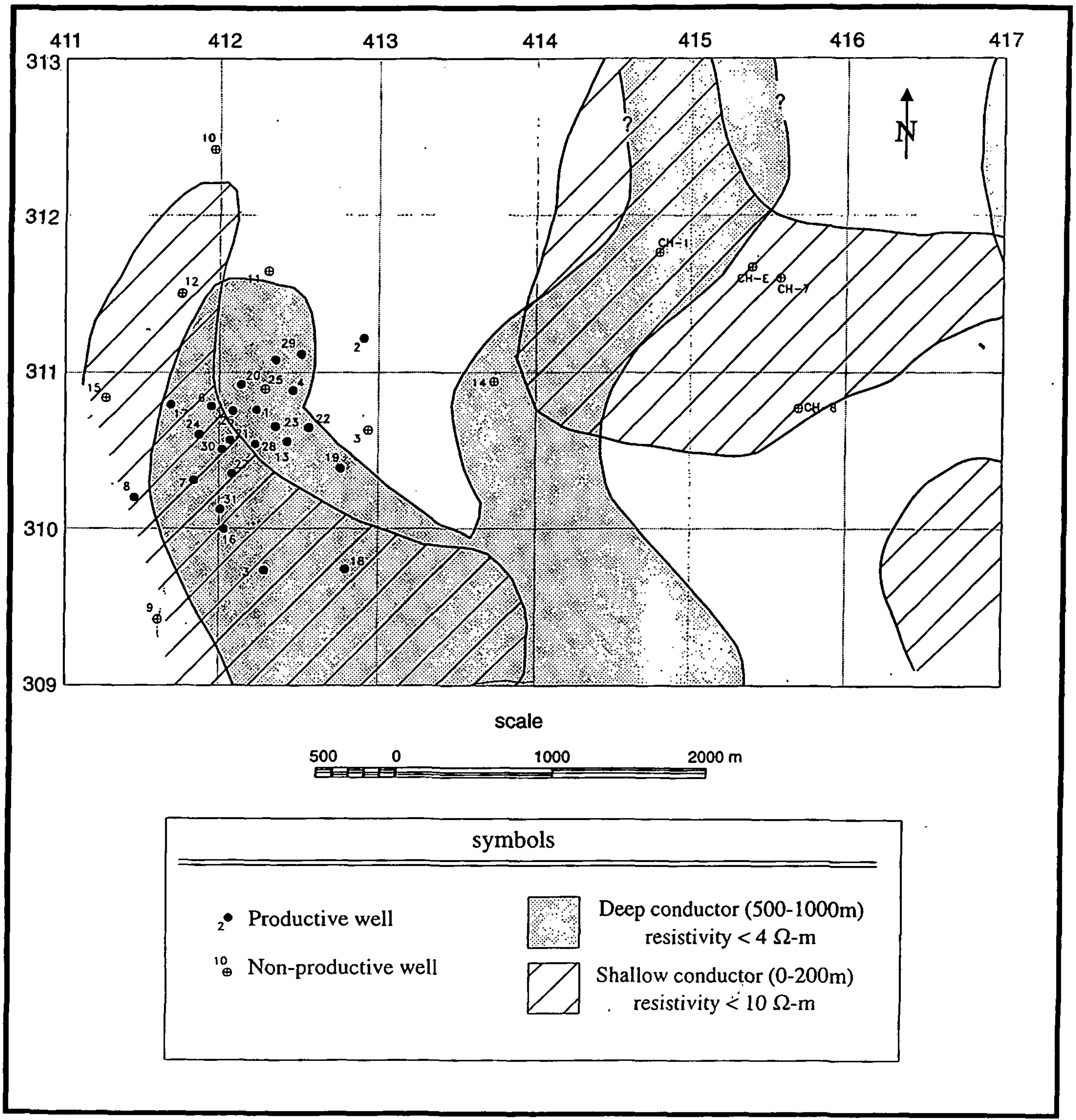


Fig. 12
Deep conductors & drillholes

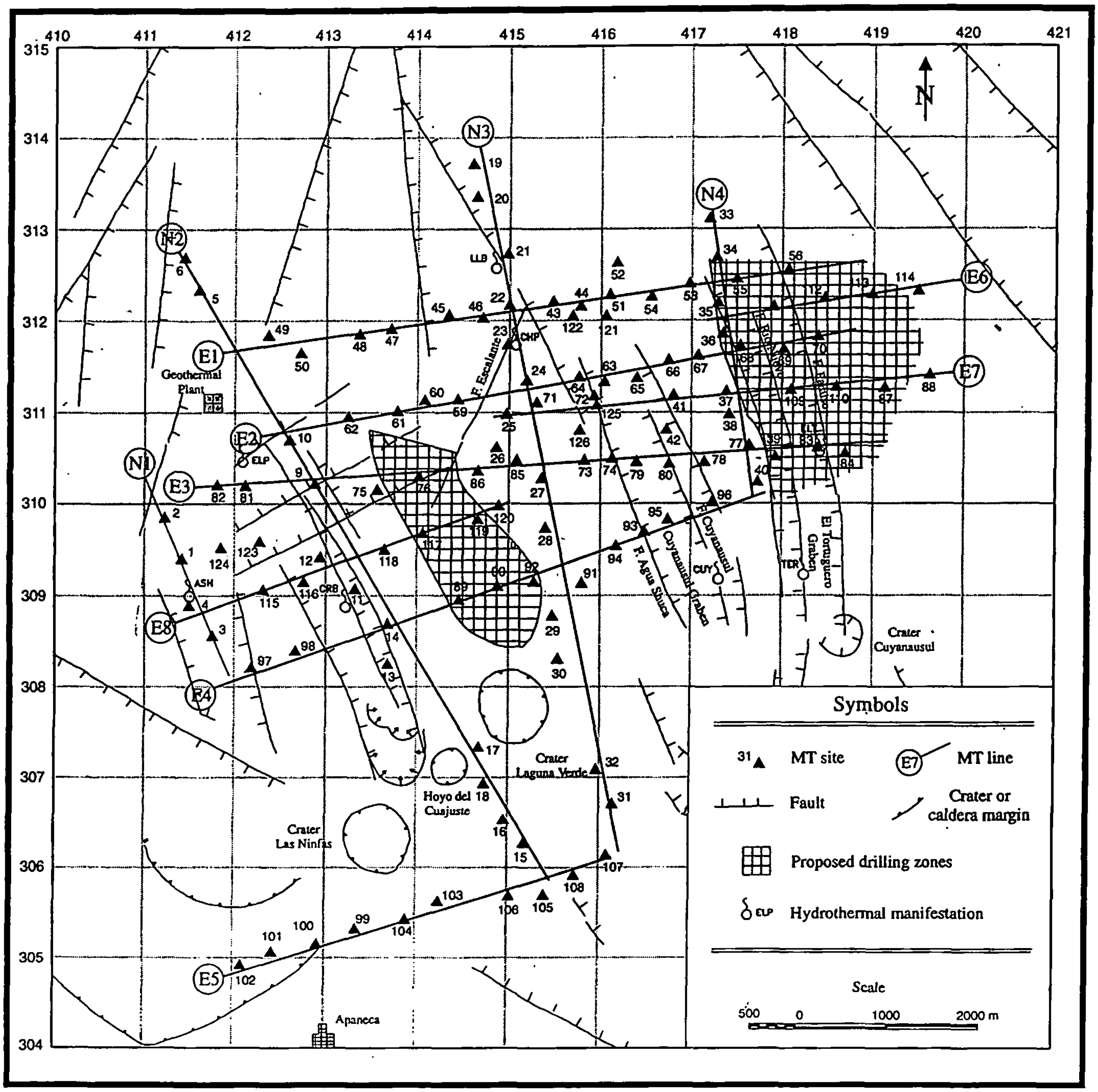
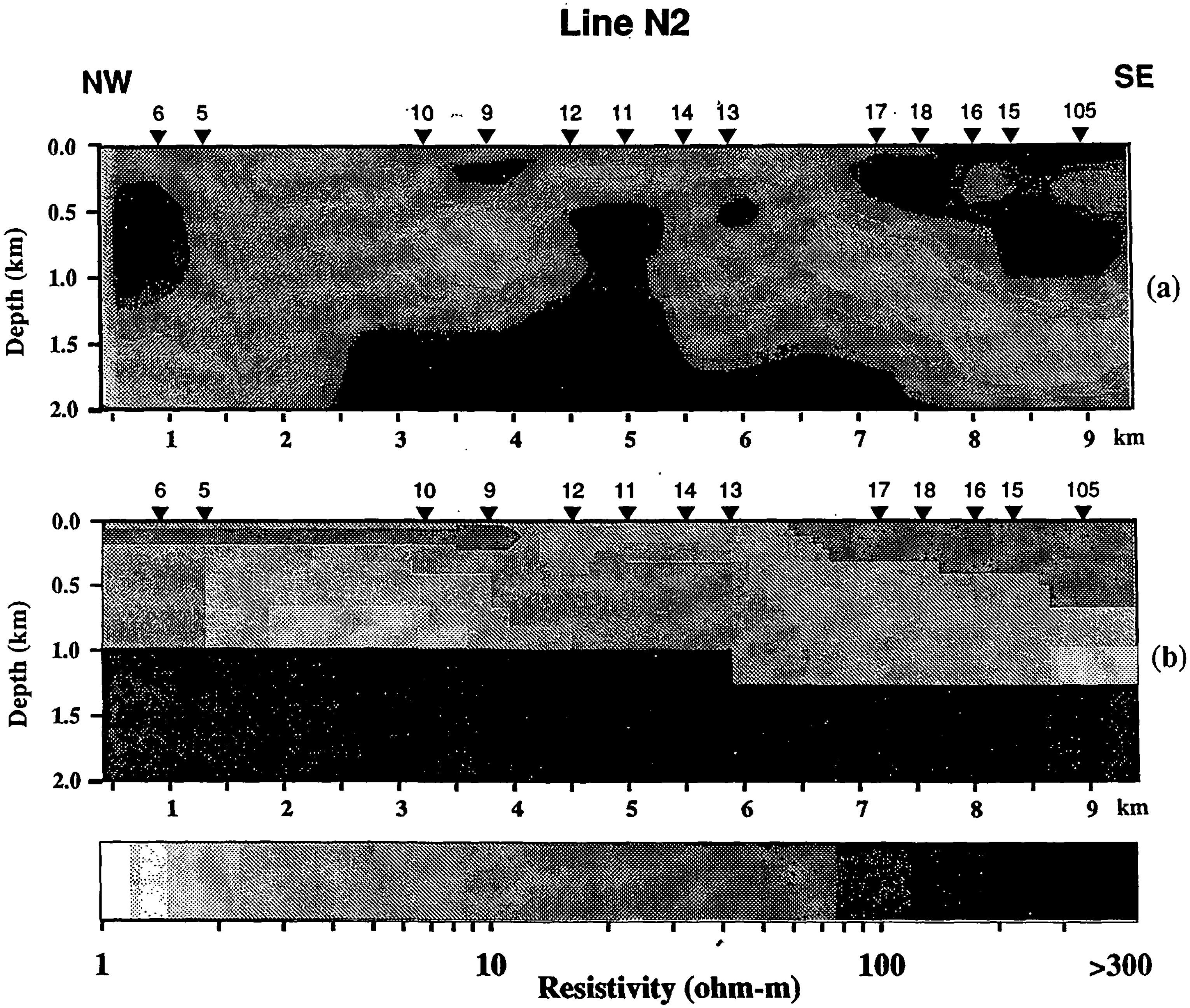
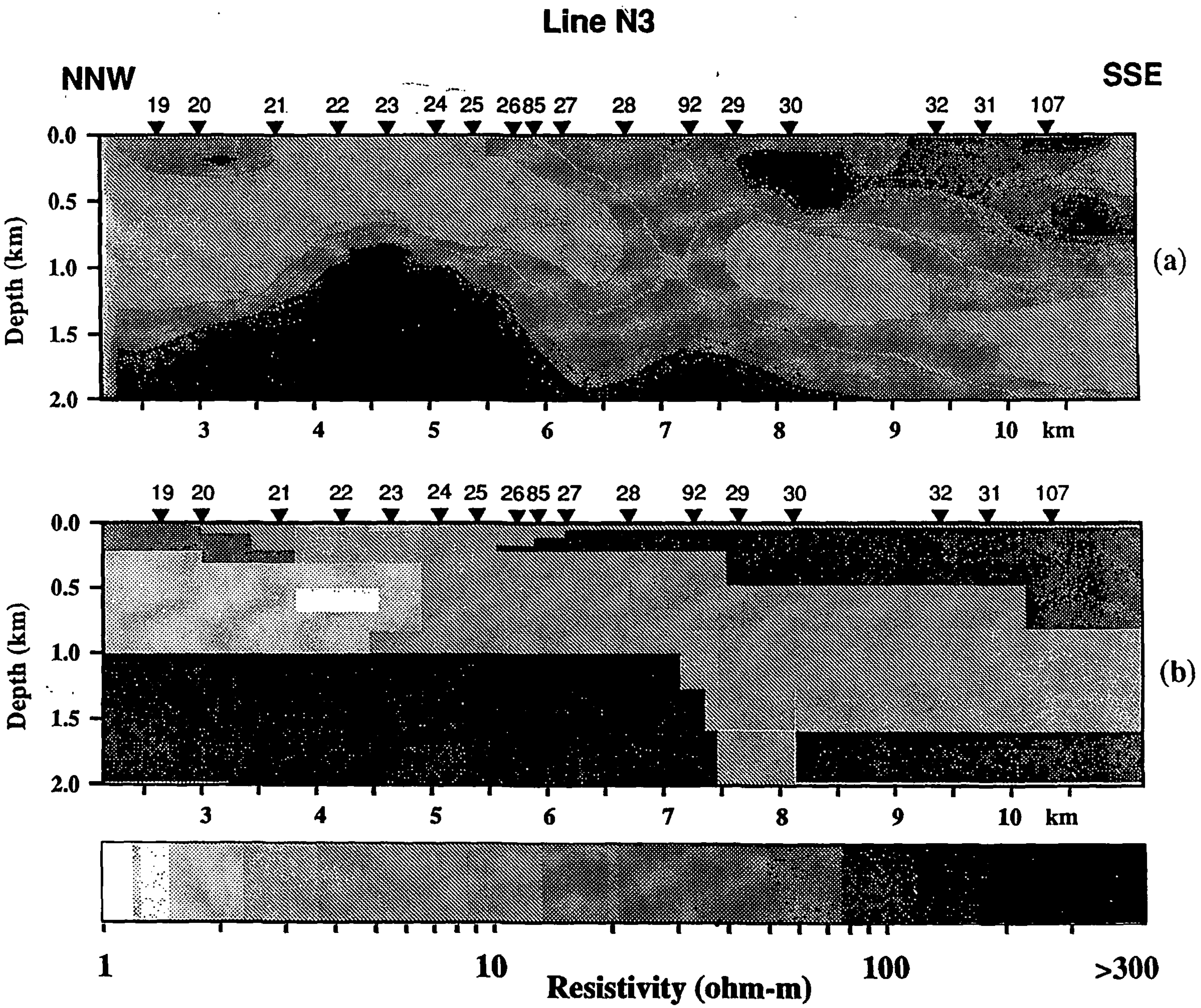
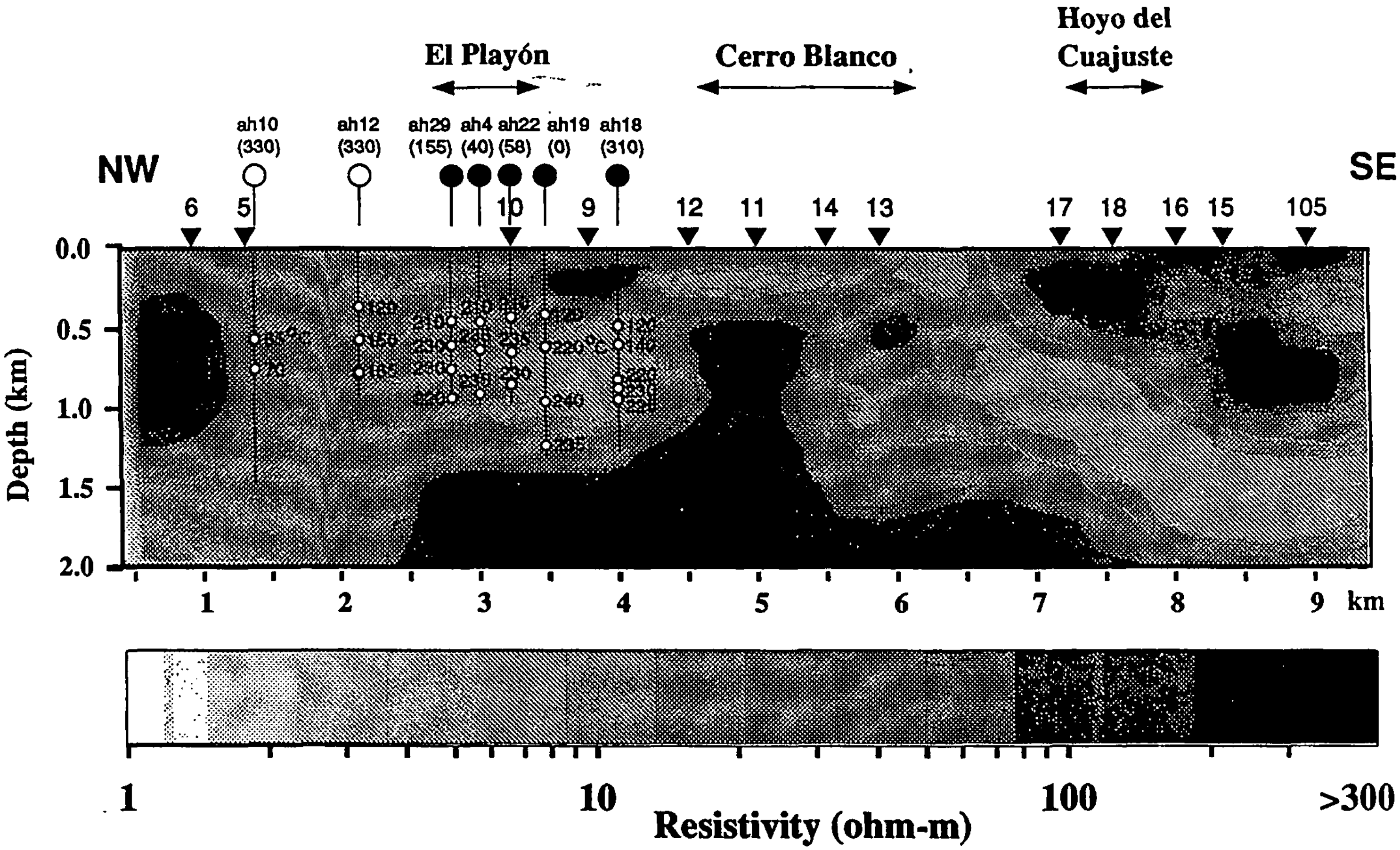


Fig. 13
Proposed drilling zones


Line N2
NW
SE
6
5
10
9
12
11
14
13
17
18
16
15
105
0.0
0.5
1.0
1.5
2.0
Depth (km)
1
2
3
4
5
6
7
8
9
km
(a)
(b)
1
10
100
>300
Resistivity (ohm-m)


Line N3
NNW
SSE
19 20 21 22 23 24 25 26 85 27 28 92 29 30 32 31 107
Depth (km)
0.0
0.5
1.0
1.5
2.0
3 4 5 6 7 8 9 10 km
(a)
(b)
1
10
100
>300
Resistivity (ohm-m)

Line N2

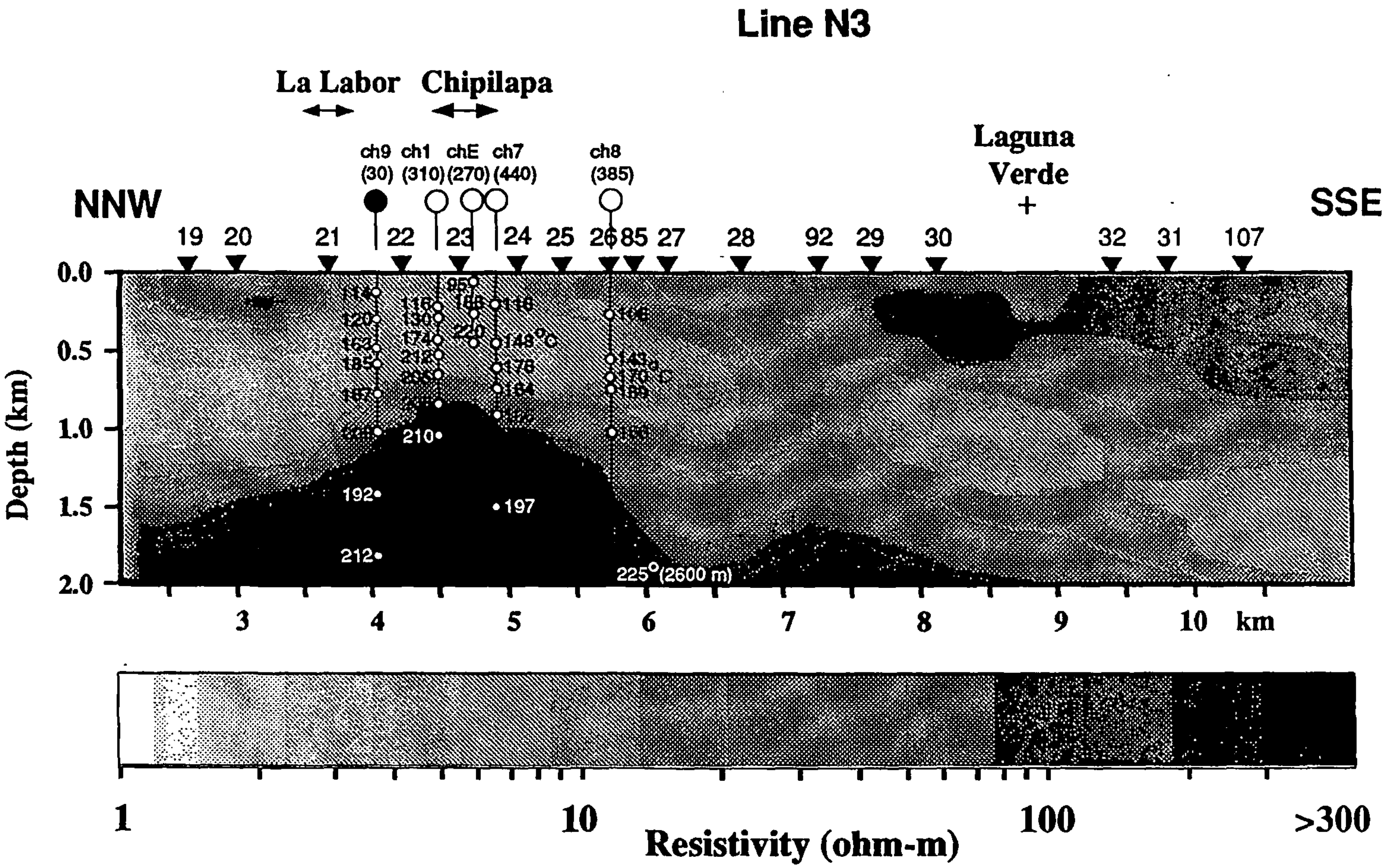


SYMBOLS:

13 ▼ Magnetotelluric station 13

ah18 (310) ● Productive well ah-18 (310 m off-line)

ah10 (330) ○ Non-productive well ah-10 (330 m off-line)


Line N3
La Labor
Chipilapa
ch9 (30)
ch1 (310)
chE (270)
ch7 (440)
ch8 (385)
Laguna Verde
+
NNW
SSE
19
20
21
22
23
24
25
26
85
27
28
92
29
30
32
31
107
Depth (km)
0.0
0.5
1.0
1.5
2.0
114
120
163
185
187
116
130
174
212
95
220
118
148°C
178
164
106
143
170 °C
189
210
192
212
197
225°(2600 m)
3
4
5
6
7
8
9
10
km
1
10
100
>300
Resistivity (ohm-m)

Figures.doc

Figure captions

Fig. 1. Location of the MT sites (triangles) and interpreted lines. Also shown are the topographic relief (contours every 200 m), main faults, eruptive centers, and hydrothermal manifestations (ELP: El Playón, CRB: Cerro Blanco, LLB: La Labor, ASH: Agua Shuca, ELT: El Tortuguero, CUY: Cuyanáusul, CHP: Chipilapa, TER: Termópilas).

Fig. 2. Transverse resistance (in $10^3\ \Omega\text{-}m^2$) derived from the VES models. Areas with values less than $10^4\ \Omega\text{-}m^2$ have been shaded. The open dots represent the location of the VES soundings. Also shown are the four dipole-dipole dc-resistivity Lines L-1, L-2, L-4, and L-5.

Fig. 3. Apparent resistivity (after static shift correction) and phase data of three representative sites. The error bars represent one standard deviation.

Fig. 4. Apparent resistivity and impedance phase pseudosections for Line E4. The isolines are in $\Omega\text{-}m$ and degrees, respectively. Areas with apparent resistivity values greater than 10 $\Omega\text{-}m$ have been shaded to emphasize the conductive zones. The small dots under each sounding site indicate the data points used for contouring.

Fig. 5. 1-D inversions of the *yx*-mode for Line E4 using the Niblett-Bostick transformation (Bostick, 1977) and the Occam algorithm (Constable et al., 1987). The iso-resistivity lines are in $\Omega\text{-}m$. The small dots in the Bostick section indicate the data points used for contouring.

Fig. 6. Two-dimensional model for Line E3: *a)* Interpreted model with block resistivities in $\Omega\text{-}m$. *b)* Schematic model incorporating the topographic relief, the mapped faults (fault dips are not true dips), drillholes with reported temperatures in °C and depth intervals cutting the Pyroclastic Flows (PF) and Volcanic Breccia (VB) horizons (a dashed arrow indicates an off-section hole). Also shown at the top: zones of radon emission, seismic clusterings with indicated hypocenter depth range, hydrothermal alteration zones (dashed lines indicate an off-section location), and the crossover location of the other MT lines.

Fig. 7. Observed and calculated apparent resistivity and impedance phase for Line E3 (*yx*-mode).

Fig. 8. Two-dimensional model for Line N2: *a)* Interpreted model with block resistivities in $\Omega\text{-}m$. *b)* Schematic model incorporating the topographic relief, the mapped faults (fault dips are not true dips), drillholes with reported temperatures in °C and depth intervals cutting the Pyroclasitic Flows (PF) and Volcanic Breccia (VB) horizons (a dashed arrow indicates an off-section hole). Also shown at the top: zones of radon

emission, seismic clusterings with indicated hypocenter depth range, hydrothermal alteration zones (dashed lines indicate an off-section location), and the crossover location of the other MT lines.

Fig. 9. Deep conductors.

Fig. 10. Intermediate depth conductors.

Fig. 11. Shallow conductors and hydrothermal alteration zones.

Fig. 12. Deep conductors and drillholes.

Fig. 13. Proposed drilling zones.

Fig. A-1 (a) Resistivity image for Line N2 constructed from magnetotelluric data. The numbers in the horizontal scale (in km) are the same as that in Pérez Flores and Gómez Treviño (this issue) for the dipole-dipole resistivity image of Line L-1. (b) Resistivity forward model for the Line N2.

Fig. A-2 (a) Resistivity image for Line N3 constructed from magnetotelluric data. The numbers in the horizontal scale (in km) are the same as that in Pérez Flores and Gómez Treviño (this issue) for the dipole-dipole resistivity image of Line L-4. (b) Resistivity forward model for the Line N3.

Fig. A-3 Correlation of the resistivity image for Line N2 with temperatures (in °C) measured in deep wells.

Fig. A-4 Correlation of the resistivity image for Line N3 with temperature (in °C) measured in deep wells.

Preprint

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DIPOLE-DIPOLE RESISTIVITY IMAGING OF THE AHUACHAPÁN-CHIPILAPA GEOTHERMAL FIELD, EL SALVADOR

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ABSTRACT

The application of a fast imaging technique to dipole-dipole resistivity data from the Ahuachapán-Chipilapa geothermal field, produces resistivity sections comparable to those obtained by trial and error methods using relatively intensive forward computations. The imaging technique is an approximate inverse method based on low resistivity variations, that produces reasonably good results for moderate and high resistivity contrasts. The method considers distributions of minimum structure for representing the earth and uses quadratic programming in the search of acceptable solutions. The images are obtained in a single iteration in the fashion of a fast transformation of apparent resistivity pseudo-sections into true sections of resistivity versus depth. The transformation was applied to four long-offset dipole-dipole lines. The same lines were also interpreted independently using exact forward modelling by different interpreters. In general, the images reproduce the main features of the forward models but also include subtle variations that are difficult to recognize in trial-and-error results. In some cases, the images combine features of the different individual models obtained by the interpreters. The application to Ahuachapán-Chipilapa illustrates the usefulness of the imaging technique in the interpretation of dipole-dipole resistivity survey data from geothermal fields.

INTRODUCTION

A number of geological and geophysical studies have been carried out in recent years in the Ahuachapán-Chipilapa geothermal area to complement earlier investigations. Most surveys have been designed to improve the delineation of the Ahuachapán field, currently under exploitation, and to investigate its possible extension to the Chipilapa area. Geophysical studies include gravity (Rodríguez and Rivas, 1986; Flores, 1991), Schlumberger vertical electrical soundings (Díaz, 1983; Rodríguez, 1985; Flores et al., 1991), long-offset dipole-dipole resistivity profiles (Rodríguez, 1988; Fink et al., 1989), and closely-spaced magnetotelluric soundings (Romo, 1990; Flores et al., 1991).

The dipole-dipole resistivity measurements have been the subject of a number of interpretations using standard modeling techniques. In the present paper we describe alternative models for these data. Our results are based on the application of a new automatic method for generating resistivity distributions of the subsurface. We compare these distributions or images with the models obtained by the other authors. The object of our work is to illustrate the usefulness of the new method and to improve our knowledge of the subsurface conditions in the Ahuachapán-Chipilapa area.

The dipole-dipole array of electrical prospecting has several advantages over other resistivity arrays when used in areas of complex geology. These advantages include a very high sensitivity to lateral variations of electrical resistivity, a greater depth of penetration as compared to other popular arrays and, regarding field work, the shortest cables and least cable moving to achieve comparable depth of exploration. In the mining industry it is preferred mainly because of its higher sensitivity to lateral features. For the same reason, it is also very useful in geothermal exploration when the objective is the delineation of lateral variations of resistivity at depth.

Perhaps the main disadvantage of the dipole-dipole array data concerns interpretation.

Qualitative interpretation by means of inspecting pseudo-section contours is not practical in complex environments, because shallow resistivity anomalies propagate to larger dipole separation and mix with the signatures of deeper targets. For the same reason it is not possible to assemble two-dimensional models by stringing together one-dimensional interpretations. Some automatic inverse methods have been reported in the literature (*e.g*. Tripp *et al*., 1984), but these are not widely available, and, in general, they require relatively extensive computations. At present, the most used approach is to employ a forward modelling scheme and through trial-and-error attempt to match the observed pseudo-section. This is a powerful technique in the hands of experienced interpreters. However, good fits to the data are usually obtained only after long hours of hard work, unless down hole electrical logs are available to help constrain the interpretation. The final models tend to be user dependent, reflecting the intrinsic nonuniqueness of the inverse problem.

To aid in the interpretation of dipole-dipole resistivity data, we have been experimenting with a number of fast-algorithm approximations (*e.g*. Cavazos-Garza, 1986; Comparán *et al*., 1989; Cavazos-Garza and Gómez-Treviño, 1989), for implementation on personal computers. The results we present here are based on the approximation given by Cavazos-Garza and Gómez-Treviño (1989), although the actual algorithm we use has been substantially modified from its original version to properly accommodate complex structures and to improve the fit to the data. The details of the method were presented by Pérez-Flores *et al*. (1992a, 1992b) and are described in Pérez-Flores (1994). Our purpose here is to present examples and applications of the method to geothermal data and to compare the results with the models obtained independently by other workers.

GEOLOGICAL BACKGROUND

The main morphological features around the Ahuachapán-Chipilapa geothermal area are the edifices of the Laguna Verde, Las Ninfas, El Hoyo de Cuajuste and El Cerro de Cuyanáusul volcanoes (Fig. 1). They all lie within the Plio-Pleistocene Concepción de Ataco Caldera. There is important surface hydrothermal activity in the area: El Playón, Cerro Blanco, El Sauce, San Carlos, Agua Shuca, Chipilapa, La Labor, Termópilas and El Tortuguero. Four mayor units in the lithologic column are reported in Ahuachapán: surface material, young agglomerates, Ahuachapán Andesites and older agglomerates (*e.g.* Aunzo et al., 1991; González-Partida, 1992). The surface material contains a shallow aquifer which responds very fast to rainfall. The young agglomerates contain a regional aquifer which responds to seasonal variations in precipitation. In the depth range of 500 to 800 m the Ahuachapán Andesites contain a saline aquifer, which is directly related to the geothermal reservoir and is recharged through the Laguna Verde and Las Ninfas volcanoes (Romagnoli et al., 1976; Aunzo et al., 1991). From Na-K-Ca geothermometer measurements and from the geochemical analysis of Ahuachapán well fluids, Steingrimsson et al. (1991) reported before exploitation reservoir temperatures ranging from 239 to 260 °C and salinity concentrations from 6900 to 8600 mg/kg. Since exploitation temperatures in 1987 fall to 228-260 °C and salinities to 5900-8300 mg/kg (Truesdell et al., 1989). From these measurements they are able to locate zones of fresh water recharge on the basis of where salinity changes most after exploitation. The hydrological model proposed by Steingrimsson et al. (1991) for Ahuachapán also takes into consideration the principal known faults. On the other hand, it is common knowledge that solutions of Na, K, Ca chlorides at high temperatures in pores of a resistive matrix behave as a very good electrical conductor. This implies that geothermal reservoirs in this area will show as very good conductor in a resistivity model. In general, good conductors are associated with dissolved chlorides in the geothermal fluids, to clays produced by alterations, and to a combination of both effects.

THE DATA

The deep penetration dipole-dipole resistivity survey was sponsored by Los Alamos National Laboratory and funded by the United States Agency for International Development. The data were taken along the four lines labeled L-1, L-2, L-4 and L-5 on Fig. 1 (Rodríguez, 1988). Logistical problems prevented to run line L-3. All lines are over 10 km long and were surveyed using dipole lengths of 500 and 1000 m. In the first case, the largest dipole separation was 7000 m with measurements every 500 m. Using standard notation this means that measurements were taken at integer multipliers on the dipole length from n=1 to n=14. In the case of the 1000 m dipole length, the largest dipole separation was 6000 m with measurements taken again every 500 m. That is, from n=0.5 to n=6 with steps half the dipole length. In both cases measurements were also taken using rather small 100 m dipole separations. More details of the survey can be found in Rodríguez (1988) and Fink *et al.* (1989). We will only add that the transmitter source used a 35 kW motor generator, and that to avoid the unwanted effects of electromagnetic induction, the waveform consisted of a square wave with rather long injection semi-periods of 20 s.

In many ways the dipole-dipole resistivity data from the Ahuachapán-Chipilapa area are a unique data set. For one thing, the survey was designed to reach greater depths than most surveys. Also, despite the low resistivities found in some areas, the data are free from electromagnetic induction effects. A third asset is that the data are highly redundant. In fact, the survey can be treated as two separate, independent experiments, each with its own dipole length. This has allowed cross-checkings and comparisons that confirm the excellent quality of the data. In this paper we use only the 1000 m dipole data because it is less affected by topographic effects than the shorter dipole data (Fink *et al.*, 1989).

The data for the four lines are presented in Fig. 2 in a standard pseudo-section format. The apparent resistivity values are plotted on the horizontal axis at the mid-point of the symmetric array, and on the vertical axis at the indicated dipole separations. The plotting of dipole-dipole data in pseudo-section format is intended to represent vertical sections of the earth below the survey lines. They are useful in the first stage of interpretation to estimate the order of magnitude of the resistivities in the ground, and to detect and locate approximately the anomalous zones. More realistic sections of the earth can be obtained only after interpretation of the data in terms of true variations of the resistivity distribution. This is a most important step because it allows the estimation of the true position and depth of an anomalous region. Also, it is possible to estimate the actual electrical resistivity of the region and relate it to its physical state.

The apparent resistivity data represent spatial averages of rock resistivity over volumes that in the present case, range from one to tens of cubic kilometers surrounding the electrode array. The process of interpretation can be viewed as an attempt to "deaverage" the set of apparent values to convert them into smaller-volume, specific values. In the next section we describe in simple terms the method we use to "deaverage" the apparent resistivity pseudo-sections, to convert them into images of the subsurface.

THE IMAGING TECHNIQUE

An imaging technique is intended to be a relatively simple transformation of apparent resistivity pseudo-sections into sections of true resistivity versus depth. The transformation takes into account only the most fundamental relationships between the measurements and the resistivity distribution, and it is not intended to be a rigorous inverse method. We use a linear relationship of the form

$$\rho_{ai} = \int F_i(\mathbf{r})\, \rho(\mathbf{r})\, dr^3, \tag{1}$$

where ρ_{ai} represents the i-th apparent resistivity measurement and F_i is a scalar function of the position vector $\mathbf{r}$ and of the position vectors of the current and potential electrodes for the *i-th* measurement. The unknown resistivity distribution of the earth is represented by $\rho(\mathbf{r})$, which in general can be a function of the three space variables. In the present case we assume that the resistivity distribution varies only over the cross-section defined by the survey line, which is the same assumption made by the other interpreters of the dipole-dipole resistivity data from El Salvador.

The explicit mathematical expression for the scalar function $F(\mathbf{r})$ is given by Cavazos-Garza and Gómez-Treviño (1989). The function represents the Fréchet derivative of the data with respect to the resistivity distribution for the case of a homogeneous half-space. In general, the Fréchet derivate depends on the resistivity distribution, in which case the integral equation that relates ρ_{ai} to ρ is nonlinear (Gómez-Treviño, 1987). Equation (1) is a particular linear case that we have found useful and practical in the interpretation of field data.

The volume integral in equation (1) extends over the entire half-space representing the earth. The half-space is divided into a large number of volume elements, each infinite in length normal to the section, as illustrated in Fig. 3. The elements have a width equal to one-half the dipole length, but their vertical dimensions increase with depth, beginning at a small fraction of the dipole length for the shallow elements. Keeping the dimensions of the elements fixed, the problem of interpretation consists of finding an adequate set of values for the resistivities of the elements, in such a way that the response of the composite model resembles in some fashion the set of measured data.

The discrete version of equation (1) can be written in standard form as

$$\mathbf{y} = \mathbf{A}\mathbf{x}, \tag{2}$$

where the vector $\mathbf{y}$ represents the set of apparent resistivity measurements, and the element A_{ij} of the matrix A the integration of the function $F_i(\mathbf{r})$ for the i-th measurement over the j-th volume element. The vector $\mathbf{x}$ contains the unknown resistivities of the volume elements in the ground. In general, $\mathbf{x}$ is a vector of higher dimension than $\mathbf{y}$, *i.e.* the system of equations defined by (2) is underdetermined, which in practical terms leads to an infinite number of solutions. The solution we find follows the philosophy of Tikhonov and Arsenin (1977) and its recent version known as Occam's inversion (Constable *et al.*, 1987). The basic idea is to find an adequate compromise between the fit to the data and the spatial variation of the solution. We accomplish this using a standard quadratic programming technique (Gill *et al.*, 1986).

We find a vector $\mathbf{x}$ that minimizes the quadratic form

$$\| \mathbf{y} - \mathbf{A}\mathbf{x} \|^2 + \beta\, \mathbf{x}^T \mathbf{D}^T \mathbf{D}\mathbf{x}, \tag{3}$$

subject to $L_j \leq x_j \leq U_j$, j=1, m, where m is the dimension of $\mathbf{x}$. The second term represents the roughness of the model, because the matrix **D** is constructed for the whole term to represent $\beta\nabla\rho \cdot \nabla\rho$, where ρ represents the resistivity distribution. The factor β is a trade-off parameter that can be varied by the interpreter depending on the desired fit or roughness of the model.

At this point, and before we present the models for the four dipole-dipole lines, it is convenient to explain with examples the procedure outlined above. The input to the algorithm is the set of apparent resistivity values and the corresponding positions of the current and potential electrodes. Also required is the number and the geometrical dimensions of the iso-resistivity volume elements that represent the earth. The other quantity needed is the value of the parameter β. The output of the algorithm is the vector $\mathbf{x}$, which contains the resistivities of the different ground elements. This vector represents the model of the earth.

Fig.4 shows three models obtained for line L-1, each for a different parameter β. Fig. 5 shows the corresponding pseudo-sections calculated from the three models according to equation (1). In all three cases the data consist of the same 131 apparent resistivity values, and the number of ground elements of unknown resistivities was 216. A 486 personal computer took 15 minutes to compute matrix **A**, and one extra minute to solve for each image. The values chosen for the parameter β were $10^{-3}, 10^{-2}$ and 10^{-1}. The effect of increasing β is to smooth the spatial variations of the models and to deteriorate the fit to the data. The problem of deciding which model best represents the earth is a question of how much we want the observed and calculated pseudo-sections to resemble one another. The key point to notice is that while the models change significantly when increasing β, the calculated pseudo-sections do not change as much. Even for the relatively large value of $\beta = 10^{-1}$, the calculated pseudo-section in Fig. 5 reproduces many of the features of the observed data shown in Fig. 2(a) for line L-1. This means that some of the features of the model for $\beta = 10^{-3}$ are not actually required by the data, because a much simpler model is still capable of reproducing the observed pseudo-section. The philosophy of the imaging technique is then to choose the simplest model that reproduces the data reasonably well, so as to avoid the inclusion of unnecessary variations that are not actually resolved by the data. We have found that $\beta = 10^{-2}$ or $\beta = 10^{-1}$ are adequate for most applications.

The broken lines at the lower corners of the sections separate the areas that are not well covered by the dipole-dipole array. The lines are drawn following the standard rule of 45 degrees used in the preparation of pseudo-sections when the vertical scale is intended to represent depth. Notice that below these lines the images change most when varying the smoothing parameter β. This is because these areas are less well sampled by the array.

RESISTIVITY IMAGES

Prior to any type of interpretation of resistivity data, it is very important to consider the possible existence of systematic errors in the data, such as electromagnetic induction or topographic effects. As explained earlier, the first source of errors was avoided in the field by using long periods of current injection. The second effect depends on the site and must be corrected if shown to be significant. Most interpretation techniques, ours included, assume a flat ground. The topographic effect can be corrected to a certain degree when normalizing the data by the effect of a homogeneous earth with the same topographic relief (Fox *et al.*, 1980). We computed the topographic effect for line L-1, which is the one most affected by topography of the four that were interpreted. The correction factors were computed using the finite-difference algorithm of Dey and Morrison (1979), as described by Flores *et al.* (1991). The factors were applied to the data to obtain a corrected apparent resistivity pseudo-section. We then proceeded to obtain images using the original and the corrected data, and compared the results for different values of the parameter β. Only for the smallest value of $\beta = 10^{-3}$ were the images slightly different. For $\beta = 10^{-2}$ and 10^{-1} there was no significant difference when using the original or the corrected pseudo-sections.

Fig. 6 shows the computed pseudo-sections for the four dipole-dipole lines, in the same order and using the same scale as for the observed data shown in Fig. 2. The corresponding pseudo-sections look very much alike, indicating that the models reproduce most of the significant features of the observed pseudo-sections. It must be noted that a good fit to the data is not a guarantee of the adequacy of the image to the real earth. This is true in general for all inversion algorithms, and more so for our first-order approximation to the full nonlinear inverse problem. For this reason we include in our analysis the models that have been obtained by other interpreters, as a way to validate and demonstrate the usefulness of our method in the interpretation of field data.

LINE L-1

Line L-1 was interpreted by Quijano (1989), Fink (1990) and Flores et al. (1991), all of them used the two-dimensional forward modelling algorithm of Dey and Morrison (1979). The three models are shown in Fig. 7 together with the resistivity image obtained using the procedure outlined above. It is interesting to note that the degree of complexity of the three models obtained through forward modelling follows their chronological order. The first and simplest model A is that of Quijano (1989), followed by model B of Fink (1990) and finally model C by Flores *et al.* (1991). More than casual, we believe that this relative complexity is most natural when using trial and error methods. Successive modellers will always try to improve the fit of previous interpretations. This is usually accomplished only by adding new features and complicating an existing model.

The aim of comparing the models is not to decide which of the four represents better the real earth. This a very difficult question that could only be answered with extensive drilling and well log analysis down to several thousand meters depth. Rather, one of our purpose here is to demonstrate that the imaging technique is a practical and viable alternative to forward modelling. The object of the exercise is to inspect the three forward models and contrast them with the resistivity image, so as to find differences and similarities and, at the same time, increase our knowledge of the subsurface conditions below line L-1.

This is the method that we follow. First, we choose the most significant conductive features in each model, and then proceed to find them in the resistivity image. Model A, the first to be postulated to explain the data for line L-1, presents a low resistivity zone that begins at the NW edge of the section and extends SE up to km 4. This conductor corresponds to the Ahuachapán producing zone. Moving next to model B, its most significant feature is a very good conductor that is also associated with the Ahuachapán reservoir, but in contrast to model A, the interpreter added a deep vertical conductive "channel" intended to simulate a zone of upflow. This channel is located at km 3.5 and extends down to a depth of 2 km. Model C includes two conductors in the area of the Ahuachapán reservoir. One is very shallow centered at km 2, and a deeper one centered at km 3.5.

All three models, A, B, and C, include conductive bodies in the NW half of the section which corresponds to the Ahuachapán producing zone and its surroundings. In the same area the resistivity image (model D) presents a conductive zone centered at a depth of 800 m. This is the view of the reservoir offered by our method. It can be observed that it correlates reasonably well with the other models, and in particular with model C. In a following section we compare the resistivity image with information obtained from deep wells.

Model C includes a long, deep conductor that extends from km 6 to the SE end of the section, a low resistivity zone present in neither model A nor model B. This conductor represents a possible feeder zone for the Ahuachapán geothermal field from the Laguna Verde and Las Ninfas volcanoes. Turning now our attention to the resistivity image (model D), we also notice the presence of a deep conductor that extends from km 6 to the SE end of the section. The existence of this conductor is also supported by the magnetotelluric data (Flores et al., 1992).

The analysis given above is centered on the main conductive features of the models presented in Fig. 7. Although the discussion could be extended to include other low resistivity zones, we prefer to stop here and leave any further analysis to the reader. Our only point is to demonstrate that an approximate imaging technique, can be applied to field data in a rather simple and automatic fashion, and obtain models that are comparable to those using more tedious forward modeling. The reader may also refer to Fig. 4 which presents the resistivity images for three values of the parameter β. The conductive features discussed above are present in all three images, indicating that the conductors are required by the data.

LINE L-4

Line L-4 runs almost parallel to line L-1, about 3 km to the east, crossing the Chipilapa area (Fig. 1). Only two forward models are available for this line. Model A in Fig. 8 is from Quijano (1989) and model B from Fink (1990). The other two models, C and D, are resistivity images obtained using values for the smoothing parameter β equal to 10^{-2} and 10^{-3}, respectively. Again, the object of the exercise is to analyze the forward models and identify their most significant conductive features, and then check to see if these are also present in the resistivity images. A second, and perhaps more important objective, is to identify any new feature in the resistivity images that could increase our understanding of the Chipilapa area.

Model A shows a conductive structure that extends from the NW edge of the section (km 1) to just over km 4. The depth to the top of the conductor is 200 m over its entire length, the depth to the bottom is variable and ranges from 1,100 m at km 2.5 and linearly increases to 2,000 m at km 3.5. Moving in the SE direction from the conductor there is a gradual increase in resistivity modeled by a series of vertical blocks. Turning our attention now to model C (the resistivity image for $\beta = 10^{-2}$), we notice the general resemblance of the two models. The depth to the conductive zone is well defined and coincides with that in model A. The conductor itself is centered at a depth of about 700 m and it extends dipping towards the SE, imitating the geometry of the deep conductive block of model A. We notice also the overall gradual increase in resistivity towards the SE, that in this case presents undulations that reveal a deep conductor at the SE edge of the model. The role of this conductor will be discussed later. For the moment the point under consideration is to show that the most relevant conductive feature of forward model A is also contained in the resistivity image.

We now turn to model B. In this case the relevant features are a layered conductor that runs over almost the entire section, and a local conductive zone within the layering with a vertical channel below km 2. In this model the gradual increase of resistivity beyond km 4, is modelled by gradually reducing the thickness of the deeper and more conductive layer. In model A, this was accomplished simply by placing vertical blocks of different resistivities. The corresponding effects are obviously not exactly the same on a pseudo-section, but the two interpretations certainly represent independent views of how to fit the observed pseudo-sections. The resistivity images offer another version that represents a compromise between the two. The undulations of the resistivity distribution beyond km 4 represent both a layered earth and a gradual increase in resistivity towards the SE.

Model B also includes within the layering a more conductive body with a vertical channel extending downwards to 2 km depth. In the resistivity image this body corresponds to the low resistivity zone centered at a depth of 700 m below km 2.5. We notice that in this case there is some discrepancy in that in model B the conductive body is centered at a depth of 1000 m below km 2. There is also an offset in the relative location of the channel that communicates the conductor with deeper regions. In the resistivity images the conductor extends downwards and intercepts the bottom of the section around km 4. In this respect the images are closer to model A.

The resistivity images in Fig. 8, both show a conductive feature below 1000 m depth that extends beyond km 6, towards the SE edge of the section. This conductor seems to be connected to the shallower low resistivity zone at the other end of the line. The situation is similar to that observed in relation to line L-1 in Fig. 7. As in that instance, it is most likely that this deep conductor represents the hot fluid upflow to the Chipilapa area. Neither model A nor model B show this possible upflow zone, although this may be partly present in model B, considering the lower conductive layer that extends almost across the entire section. The existence of the deep conductor and its connection to the shallower low resistivity zone is also supported by the magnetotelluric study (Flores *et al.*, 1992).

LINE L-5

Line L-5 runs SW-NE and crosses both the Ahuachapán and the Chipilapa areas. Again, there are only two independent forward modeling interpretations for this line (Fig. 9). Model A is taken from Quijano (1989) and model B from Fink (1990). Models C and D are resistivity images for smoothing parameters β equal to 10^{-2} and 10^{-3}, respectively.

Model A presents a broad low resistivity zone between km 4 and 7, that reaches a maximum depth of 1400 m. Just below the low resistivity zone there is a relatively resistive triangular feature that rests on the bottom of the section. Both the upper conductive and the lower resistive zones can be easily identified in the resistivity images. The resistive zone corresponds to the barrier that separates two large conductors, the first centered at km 2.5 and the second at km 6. This last conductor corresponds to the Ahuachapán geothermal reservoir.

Model B shows two low resistivity layers of large horizontal extents. They are separated by a zone or barrier of relatively larger resistivity. Again, comparing models A and B, we have two qualitatively different models that produce similar effects in a pseudo-section. The resistivity images combine the two different views by placing a dipping barrier between the two localized conductors, one shallower than the other, simulating in this way the two conductive horizontal layers.

Notice that lines L-1 and L-5 cross each other approximately over the Ahuachapán geothermal field (Fig. 1). Comparing the two images below this point we can check the bidimensionality of the structures. Obviously, three-dimensional effects are present because in a true two-dimensional situation, one of the two perpendicular sections would be laterally uniform. What we are seeing in each case is a complex projection of a three-dimensional structure over a vertical plane defined by the survey line. When the line goes exactly over the structure there is usually no distortion of the image, and this can be safely interpreted as a two-dimensional cut of the structure (Cavazos-Garza and Gómez-Treviño, 1989). In this respect, it is important to compare the vertical distribution of resistivities at the cross-point of the two lines. They should be very similar if the two images represent accurate perpendicular cuts of a three-dimensional structure. We can see that in the present case, the vertical distributions of resistivity below the crossing point (at km 3.6 on line L-1 and km 6.2 m on line L-5) are very similar. They both indicate a zone of low resistivity centered at about

800 m depth. This corresponds to the Ahuachapán geothermal field.

Line L-5 also crosses line L-4, the cross point is at km 9.5 along L-5 and at km 5.1 on L-4 (Fig. 1). In this case we notice that there is no major feature, either resistive or conductive, that we can use as a reference to compare the vertical profiles of resistivity. In both sections, below the crossing point the variations of resistivity are very weak. This is confirmed by looking at the images of the same line for different β parameters. The variations change and some even disappear because they are not well constrained by the data. However, comparing the images of the two lines for $\beta = 10^{-2}$ (models C; Figs.8 and 9), we can see that the vertical profiles are quite similar for the upper 700 m. Below this depth the two profiles depart from each other. Although the differences may not be considered significant for the reasons given above, they are a reminder of the limitations of two-dimensional interpretations.

Neither model A nor model B show the deep conductor present in the resistivity images beyond km 9, towards the NE end of the section. The existence of this conductor is also supported by the magnetotelluric study (Flores et al., 1992).

LINE L-2

Line L-2 runs E-W and crosses both the Ahuachapán and the Chipilapa areas. Line L-2 and line L-5 intersect at an angle of about 30° (Fig. 1). Their mutual proximity has been used by Quijano (1989) and Fink (1990) to justify a single model for the two. Both interpreted line L-5 and proposed the same model for L-2.

In the present case we can not expect a close resemblance of models and images, except in the vicinity of the crossing point. Fig. 10 shows the three resistivity images for line L-2 for β parameters equal to 10^{-1}, 10^{-2} and 10^{-3}. They are identified as models A, B, and C, respectively.

The resistivity image for $\beta = 10^{-2}$ shows three conductive bodies that stand out from the more resistive background. The first body from west to east corresponds to the Ahuachapán reservoir. It is centered at about km 4 and at a depth of around 800 m. The second conductor in the resistivity image is centered at km 6.5 and at about 500 m depth. This indicates that the Ahuachapán field extends further to the east. The third conductor in the resistivity image is located further to the east at around km 11, and could not be included in the modelling of line L-5 by Quijano (1989) and Fink (1990) because of the offset of the lines.

Line L-2 runs parallel and very close to one of the magnetotelluric lines described by Flores *et al.* (1992). The interpretation of this MT line confirms the existence of the three conductors that are shown in the resistivity images. Furthermore, their horizontal positions, approximate depths and resistivities agree quite closely.

Lines L-1, L-2 and L-5, all cross each other in the vicinity of the Ahuachapán geothermal field. This occurs around km 3 and 4 along L-1, between km 4 and 5 on L-2 and between km 5.5 and 6.5 on line L-5 (Fig. 1). We can see by inspecting the corresponding images (Fig. 7, 9 and 10), that in all three cases the vertical variation in resistivity consists of a low resistivity zone centered at around 800 m depth, and that the lowest resistivity is of the order of 1 ohm-m. This zone corresponds to the Ahuachapán geothermal reservoir.

ANALYSIS OF RESISTIVITY IMAGES

Some of the conductive features observed in the resistivity images, correspond to outcropping conductors and must therefore in some way correlate with surface geological features or with particular local conditions. In the Ahuachapán-Chipilapa area the outcropping conductors are related to the presence of nearby hydrothermal manifestations (fumaroles, hot springs, etc.). The deep conductors are correlated with information available from deep wells and with results of the Flores et al. (1992) magnetotelluric study.

Line L-1 shows two surface conductors that correlate with the El Playón and Cerro Blanco hydrothermal manifestations as illustrated in Fig. 11(a). Both surface expressions seem to be connected to the deep conductor identified as the Ahuachapán reservoir. In the same figure it can be observed that the producing wells in the Ahuachapán field are all located in the conductive region at depth. Notice also that the temperature decreases at the bottom of the deepest wells, that this happens at depths where the resistivity increases. The ideal relationship between high temperatures and low resistivities is of course only an approximation in complex geological environments. Wells ah-10 and ah-12 reach the conductive zone but show low temperatures at depth. This is probably related to the inflow of cool water that is believed to enter the reservoir laterally from the north (Steingrimsson et al., 1991). Taking this into account, the degree of correlation suffices to demonstrate the usefulness of the resistivity images as approximate indicators of temperature at depth. The correlation is also reasonably good with what is known about the saline aquifer in the Ahuachapán Andesites. Fig. 11(b) shows a structural model taken from Aunzo at al. (1991). It can be observed that the most conductive regions correlate with the saline aquifer within the Ahuachapán Andesites, particularly near the normal faults that connect the aquifer to deeper regions.

Line L-4 crosses the Chipilapa area which is currently under exploration and might soon be exploited to a limited extent. Fig. 12 illustrates the resistivity images and the relevant information for this line. There is no major outcropping conductor in this case except for a slight decrease in surface resistivity between km 4 and 5. This feature is probably related to the La Labor and Chipilapa hydrothermal manifestations which are nearby the line in this part of the section (Fig. 1). This is also the area that has been drilled for exploration and exploitation purposes. Fig. 12(a) shows the temperature profiles of four wells drilled on one side of the main conductor detected along line L-4. As discussed in the previous section, the presence of this conductor is known from previous interpretation. It is located in the zone of groundwater discharge and therefore it is not considered a potential geothermal reservoir. The wells were drilled between this zone of outflow and the volcanic area associated with the recharge of the system. Information obtained from the wells indicates the presence of three aquifers (CEL, 1992) as shown in Fig. 12(b). It can be observed that the shallow aquifer R0 correlates very well with the low resistivity zone centered at a depth of 500 m. Between R0 and R1 there is a resistive zone that clearly separates the two aquifers. Below R1 the resistivity decreases and shows no indication of a barrier between R1 and the deep aquifer R2. Both, R2 and R1, appear as a single conductor. The resistivity image does not possess enough resolution to distinguish a possible resistive barrier between the two. However, it is interesting to note that the dipping nature of R1 and R2 is predicted by the resistivity distribution. It is also worth mentioning that the conductor at the SE end of the section is also required by the magnetotelluric data as described in Flores et al. (1992).

Line L-5 crosses the Ahuachapán field over its southern flank. The corresponding image and the temperature profiles for eight nearby wells are presented in Fig. 13. It can be observed that there are three deep conductive zones and that the central conductor correlates very well with the producing zone of the Ahuachapán field. Notice also that the producing wells are located over the most conductive part of the central conductor. Again, the resistivity increases at depth where the temperature begins to decrease. Once again, the correlation is good enough to consider the resistivity images as a useful tool in quantitative interpretations. The results also justify the resistivity method to be a useful tool in geothermal exploration, in combination with the magnetotelluric method. The deep conductor towards the NE end of the line was recommended by Flores et al. (1992) as one of possible area for exploitation. Their conclusions are based on closely spaced magnetotelluric soundings that extend beyond km 11. The present interpretation of the resistivity data confirms the presence of the deep conductor at least up to km 11. The two wells ch-7 and ch-8 lie on the edge of the conductor and are non-productive.

Line L-5 also includes a large conductor at the SW part of the section that can not be confirmed by the magnetotelluric study because there were no soundings made on this side of the line. Finally, it is interesting to note that the Agua Shuca hydrothermal manifestation has a surface electrical expression and that this is apparently connected to the Ahuachapán reservoir.

The correlation of the resistivity image for line L-2 with the available information is illustrated in Fig. 14. Only three wells from the Ahuachapán field fall near the line. It can be appreciated that the corresponding low resistivity zone correlates reasonably well with the temperature profiles of the wells. The next conductor to the west corresponds to a possible zone for exploitation that had been recommended by Flores at al. (1992) on the basis of their magnetotelluric study. The deep conductor at the end of the line was also detected by the magnetotelluric survey and the present interpretation of the resistivity data confirms its existence. Other features about this line worth considering are the two surface conductors associated with hydrothermal manifestations. The first, from west to east, corresponds to El Playón; the second to an area that includes the Cuyanaúsul, Termópilas and El Tortuguero manifestations. In both cases, the surface conductors appear to be connected to the deeper low resistivity zones.

FINAL REMARKS

We have shown that a fast imaging technique can successfully extract the information content of dipole-dipole resistivity measurements taken in complex geological environments. The method that we use is relatively fast. It takes about 15 minutes in a 486 personal computer for a typical pseudo-section of 150 measurements. The resistivity images reproduce many of the features obtained by trial and error methods and include subtle variations that are difficult to recognize by inspection. The images correlate reasonably well with surface hydrothermal manifestations, with the available information derived from deep wells and with the results of an extensive magnetotelluric survey. It is hoped that our results stimulate further interest for the application of traditional resistivity methods in geothermal exploration.

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FIGURE CAPTIONS

Fig. 1. Location of the four dipole-dipole resistivity lines in the Ahuachapán-Chipilapa area. Numbers on the lines indicate distances, in km, from the lines' origins. The small triangles represent magnetotelluric sounding sites. The shaded areas indicate zones of surface hydrothermal activity. Contours interval 200 m.

Fig. 2. Apparent resistivity data in the four lines in standard pseudo-section format.

Fig. 3. Schematic representation of the two-dimensional model used in the construction of the resistivity images.

Fig. 4. Three different resistivity images for line L-1. The image with $\beta = 10^{-1}$ is the smoothest, followed by that with $\beta = 10^{-2}$. The image with $\beta = 10^{-3}$ is the one that shows the largest variations of resistivity from place to place.

Fig. 5. Calculated pseudo-sections for line L-1. The best fit is achieved with $\beta = 10^{-3}$, followed by $\beta = 10^{-2}$ and $\beta = 10^{-1}$. Notice that all three cases reproduce the main features of the observed pseudo-section shown in Fig. 1.

Fig. 6. Calculated pseudo-sections for the four lines. The pseudo-sections were computed using $\beta = 10^{-2}$. This figure can be directly compared with Fig. 1, which shows the observed pseudo-sections in the same order.

Fig. 7. Models for line L-1. Model A is from Quijano (1989); model B from Fink (1990); and model C from Flores *et al.* (1991). Model D is the resistivity image obtained in the present study using $\beta = 10^{-2}$.

Fig. 8. Models for line L-4. Model A is from Quijano (1989) and model B from Fink (1990). Models C and D are resistivity images for β equal to 10^{-2} and 10^{-3}, respectively.

Fig. 9. Models for line L-5. Model A is from Quijano (1989) and model B from Fink (1990). Models C and D are resistivity images for β equal to 10^{-2} and 10^{-3}, respectively.

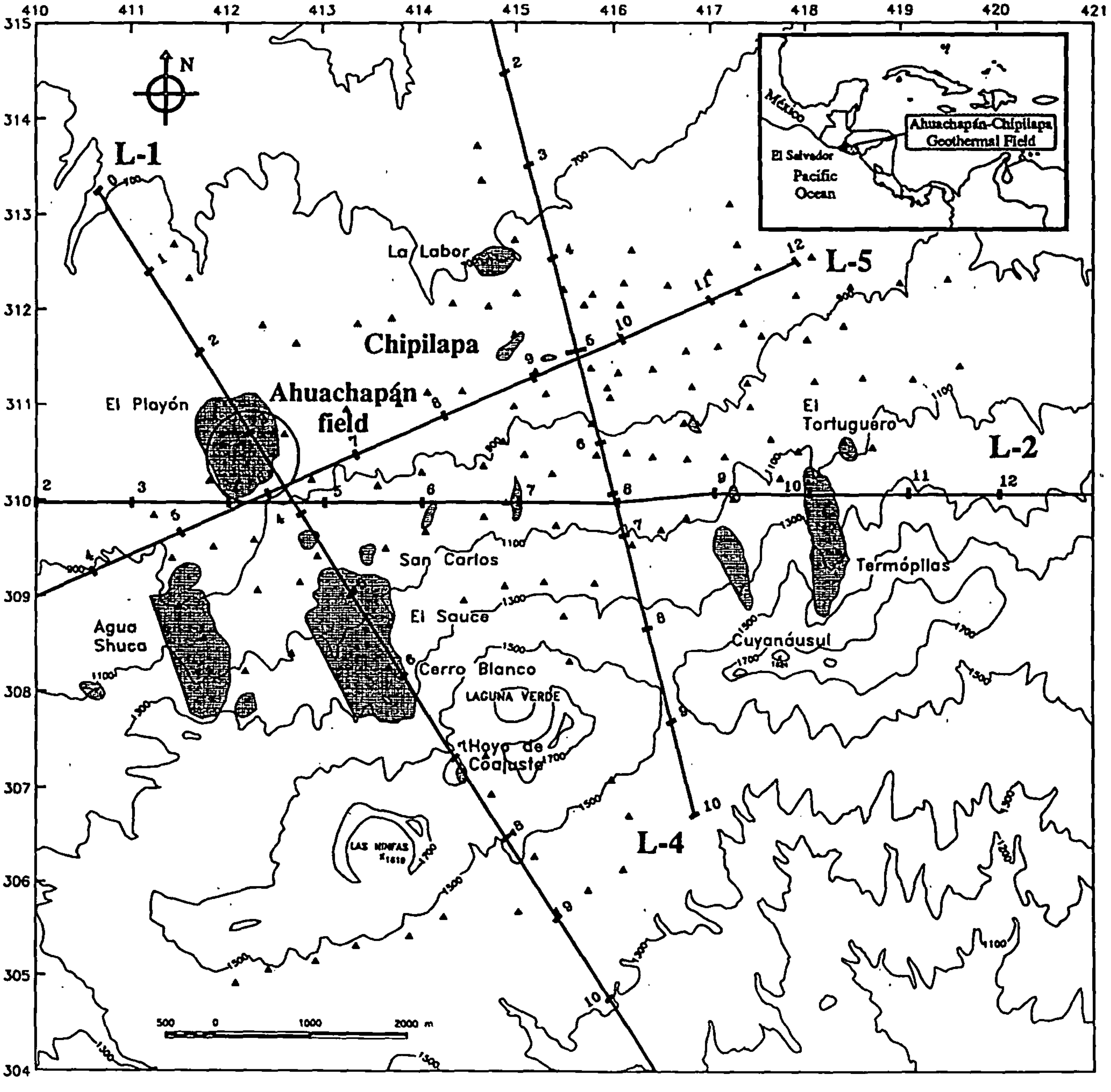
Fig. 10. Models for line L-2. Models A, B, and C are resistivity images for β equal to 10^{-1}, 10^{-2}, and 10^{-3}, respectively.

Fig. 11. (a) Correlation of the resistivity image for line L-1 with surface hydrothermal manifestation and temperatures (in °C) measured in deep wells. (b) Correlation of the same image with the structural model of Aunzo et al. (1991).

Fig. 12. (a) Correlation of the resistivity image for line L-4 with temperatures (in °C) measured in deep wells. (b) Correlation of the same image with the system of aquifers proposed by CEL (1992). Well symbols same as in Fig. 11.

Fig. 13. Correlation of the resistivity image for line L-5 with surface hydrothermal manifestations and with temperatures (in °C) measured in deep wells. Well symbols same as in Fig. 11.

Fig. 14. Correlation of the resistivity image for line L-2 with surface hydrothermal manifestations and with temperatures (in °C) measured in deep wells. Well symbols same as in Fig. 11.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Ahuachapán-Chipilapa Geothermal Field
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El Salvador
Pacific Ocean
La Labor
Chipilapa
El Playón
Ahuachapán field
El Tortuguero
San Carlos
El Sauce
Agua Shuca
Cerro Blanco
LAGUNA VERDE
Hoyo de Cóalusto
Cuyanáusul
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Fig. 1

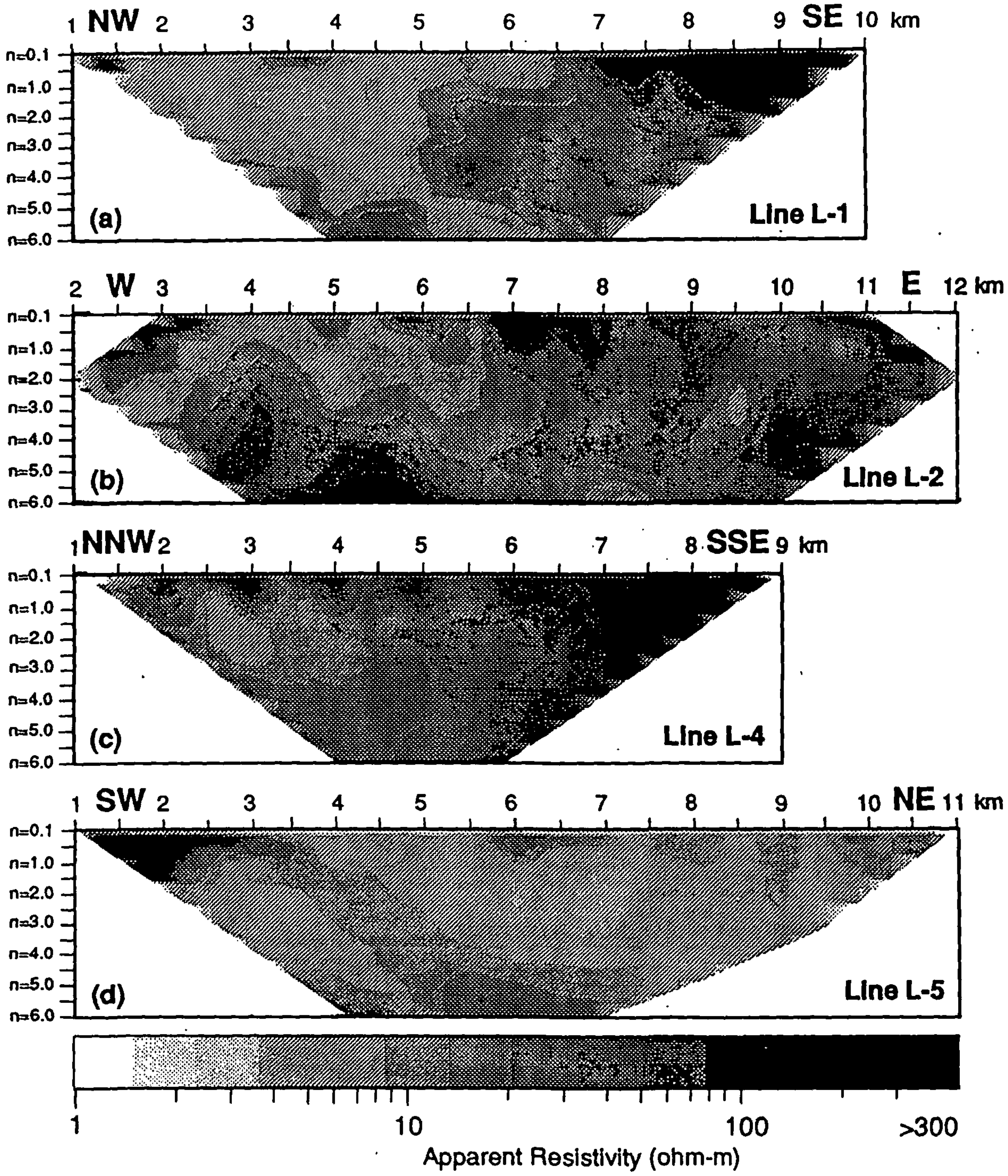

1 NW 2 3 4 5 6 7 8 9 SE 10 km
n=0.1
n=1.0
n=2.0
n=3.0
n=4.0
n=5.0
n=6.0
(a)
Line L-1
2 W 3 4 5 6 7 8 9 10 11 E 12 km
n=0.1
n=1.0
n=2.0
n=3.0
n=4.0
n=5.0
n=6.0
(b)
Line L-2
1 NNW 2 3 4 5 6 7 8 SSE 9 km
n=0.1
n=1.0
n=2.0
n=3.0
n=4.0
n=5.0
n=6.0
(c)
Line L-4
1 SW 2 3 4 5 6 7 8 9 10 NE 11 km
n=0.1
n=1.0
n=2.0
n=3.0
n=4.0
n=5.0
n=6.0
(d)
Line L-5
1
10
100
>300
Apparent Resistivity (ohm-m)

Fig. 2

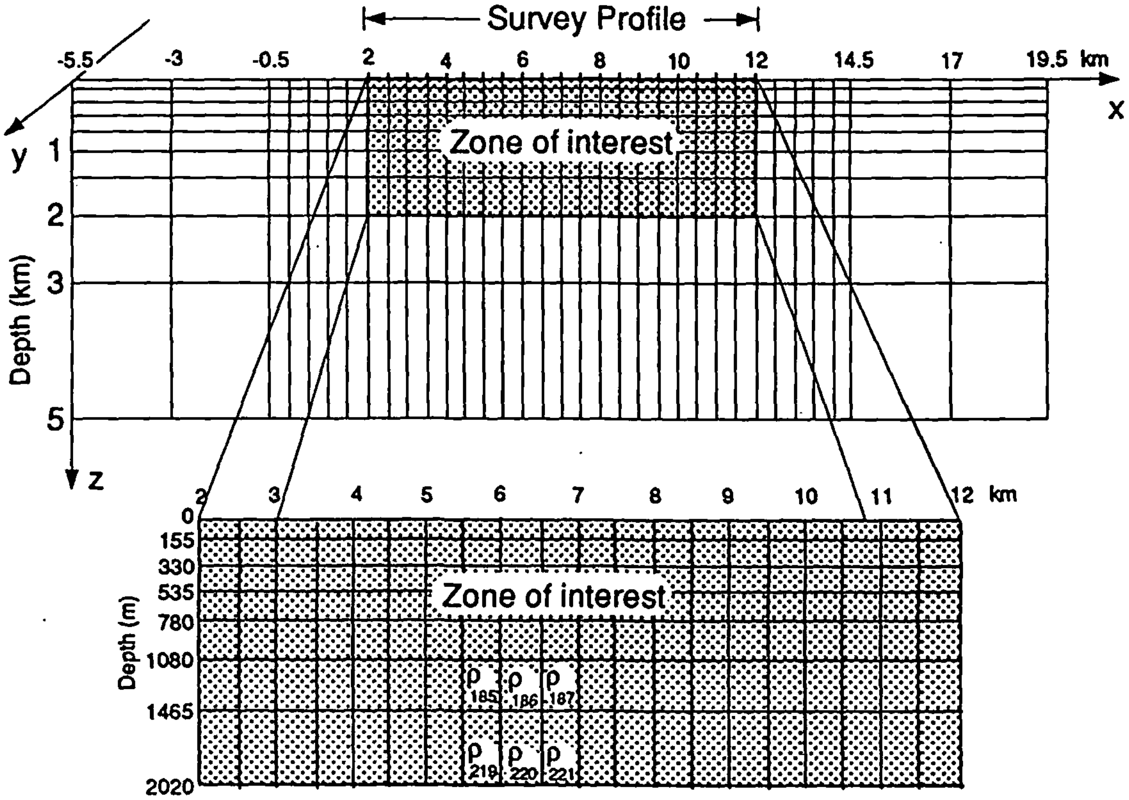

Survey Profile
-5.5
-3
-0.5
2
4
6
8
10
12
14.5
17
19.5 km
x
y
1
2
3
5
Depth (km)
z
Zone of interest
2
3
4
5
6
7
8
9
10
11
12 km
0
155
330
535
780
1080
1465
2020
Depth (m)
Zone of interest
ρ 185
ρ 186
ρ 187
ρ 219
ρ 220
ρ 221

Fig 3

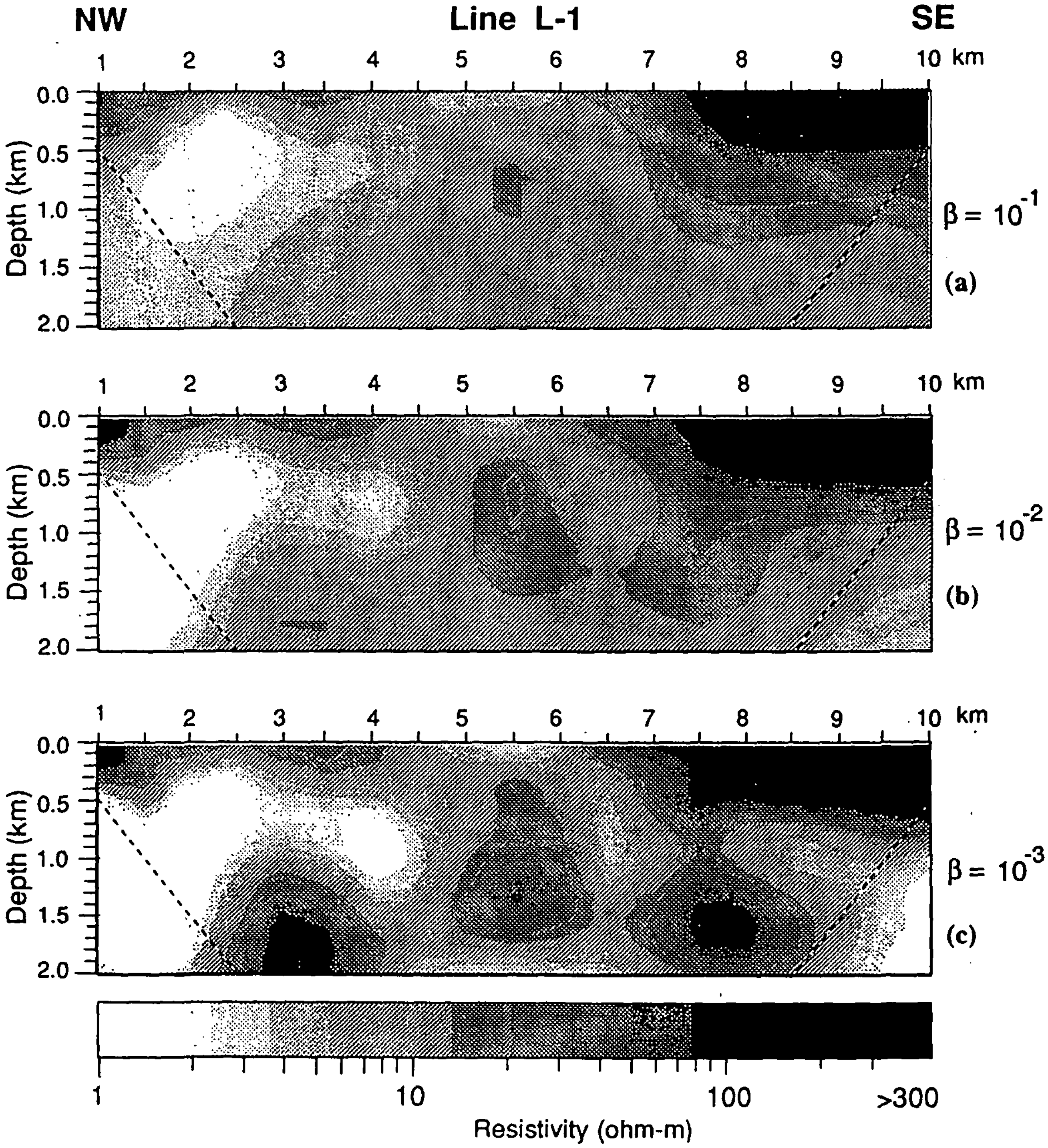

NW
Line L-1
SE
1 2 3 4 5 6 7 8 9 10 km
Depth (km)
0.0 0.5 1.0 1.5 2.0
$\beta = 10^{-1}$
(a)
$\beta = 10^{-2}$
(b)
$\beta = 10^{-3}$
(c)
1 10 100 >300
Resistivity (ohm-m)

Fig. 4

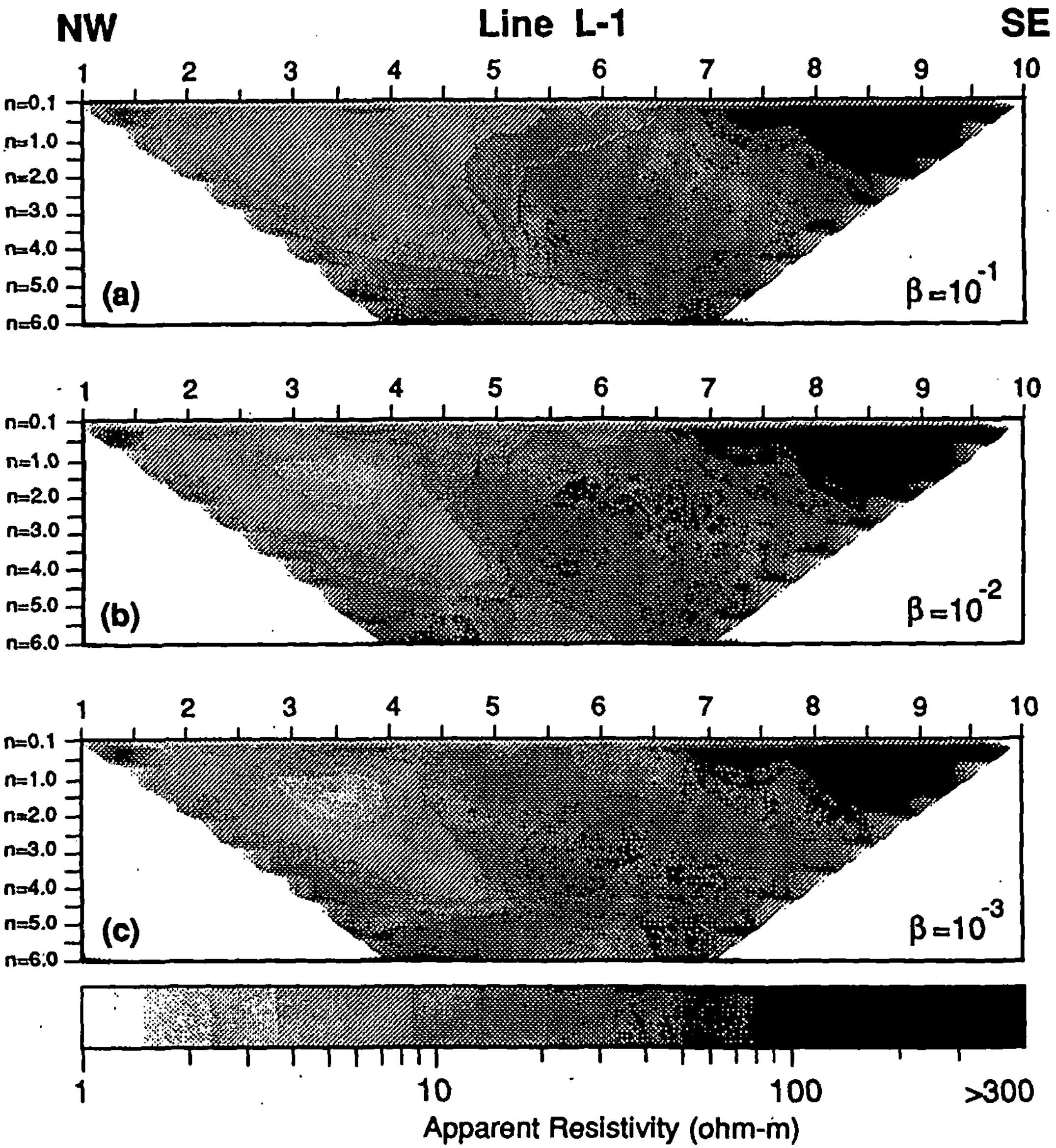

NW
Line L-1
SE
1
2
3
4
5
6
7
8
9
10
n=0.1
n=1.0
n=2.0
n=3.0
n=4.0
n=5.0
n=6.0
(a)
β=10^-1
(b)
β=10^-2
(c)
β=10^-3
1
10
100
>300
Apparent Resistivity (ohm-m)

Fig. 5

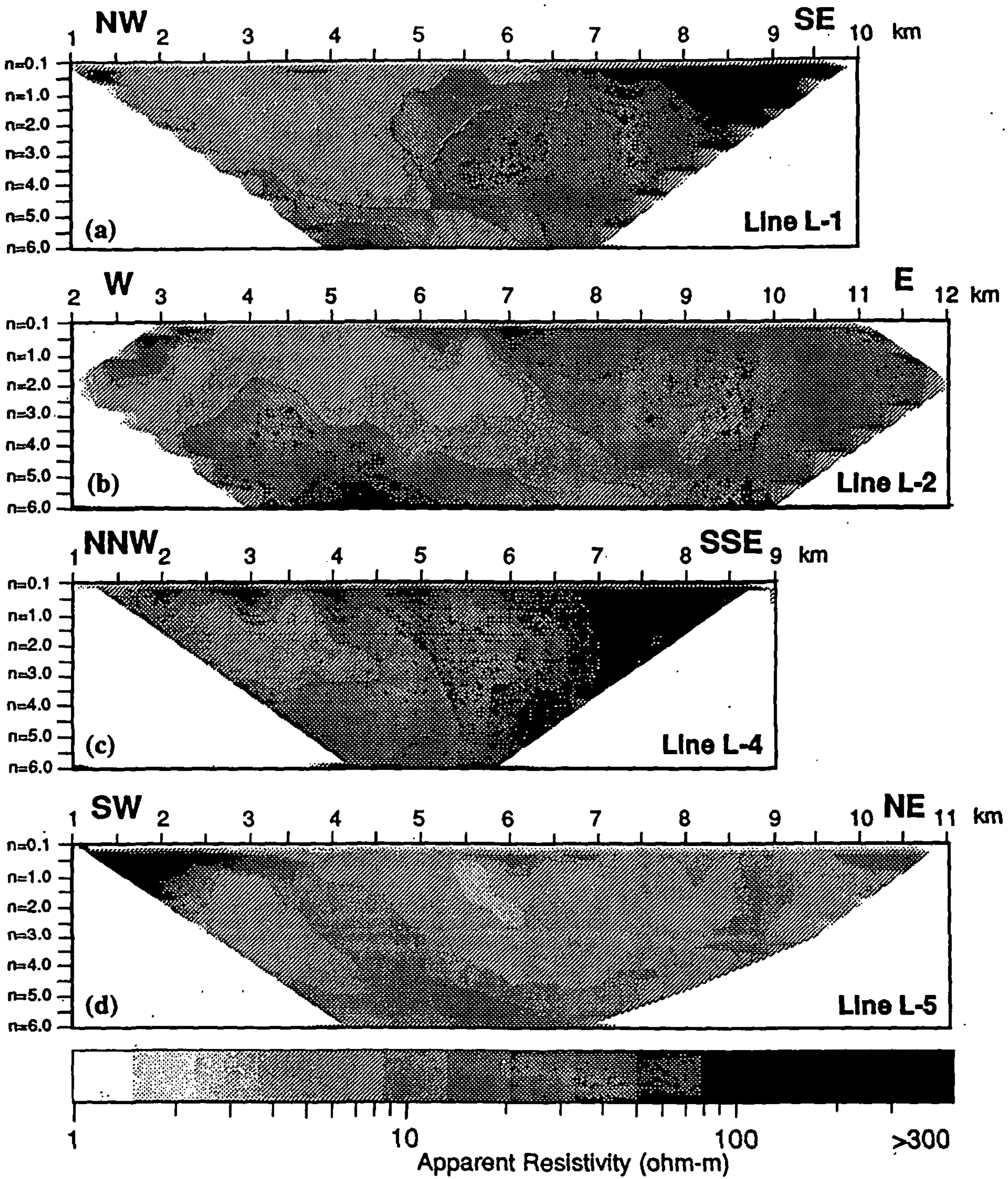

NW
SE
1
2
3
4
5
6
7
8
9
10
km
n=0.1
n=1.0
n=2.0
n=3.0
n=4.0
n=5.0
n=6.0
(a)
Line L-1
W
E
2
3
4
5
6
7
8
9
10
11
12
km
(b)
Line L-2
NNW
SSE
(c)
Line L-4
SW
NE
(d)
Line L-5
1
10
100
>300
Apparent Resistivity (ohm-m)

Fig. 6

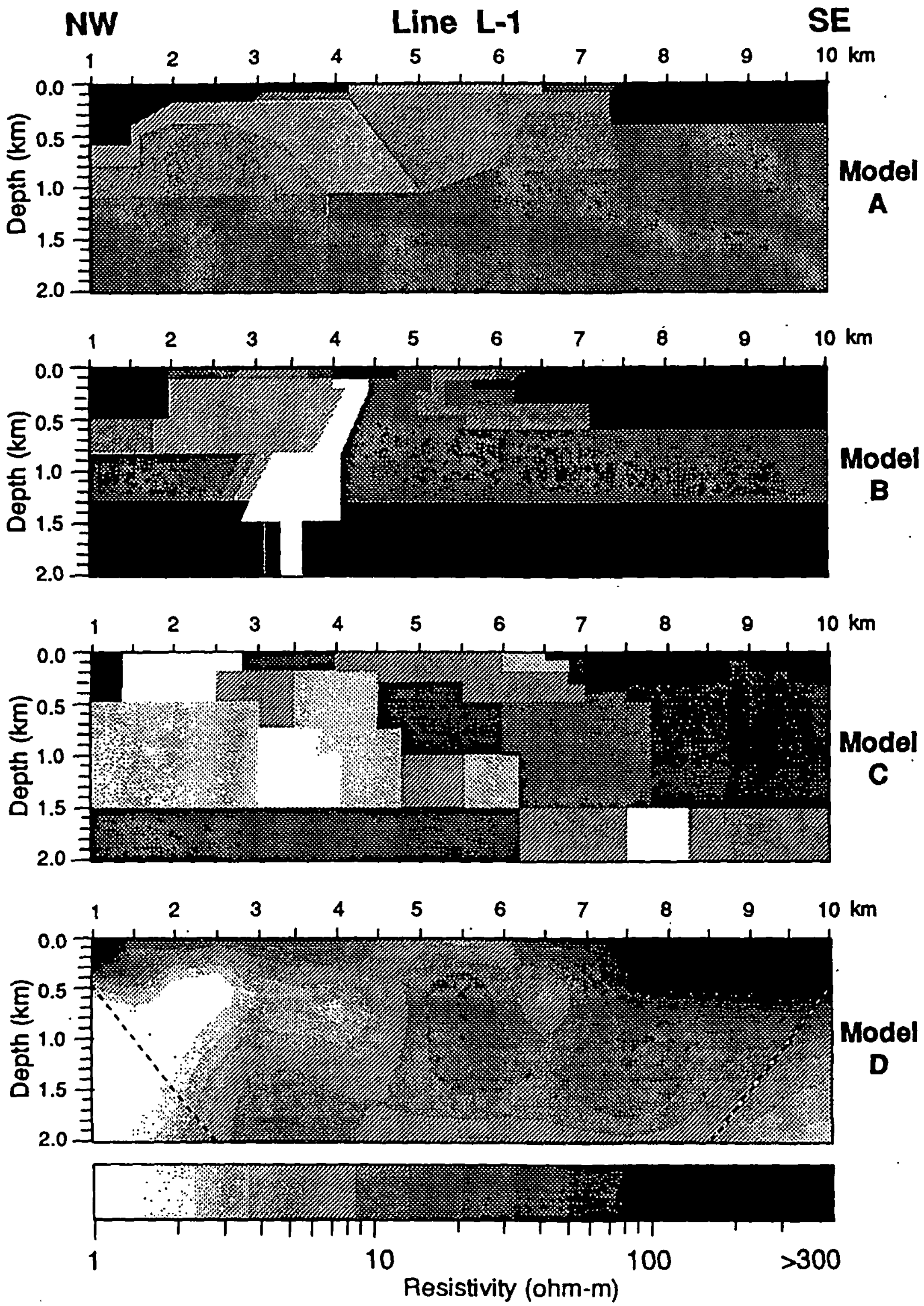

NW
Line L-1
SE
1
2
3
4
5
6
7
8
9
10 km
Depth (km)
0.0
0.5
1.0
1.5
2.0
Model A
Model B
Model C
Model D
1
10
100
>300
Resistivity (ohm-m)

Fig. 7

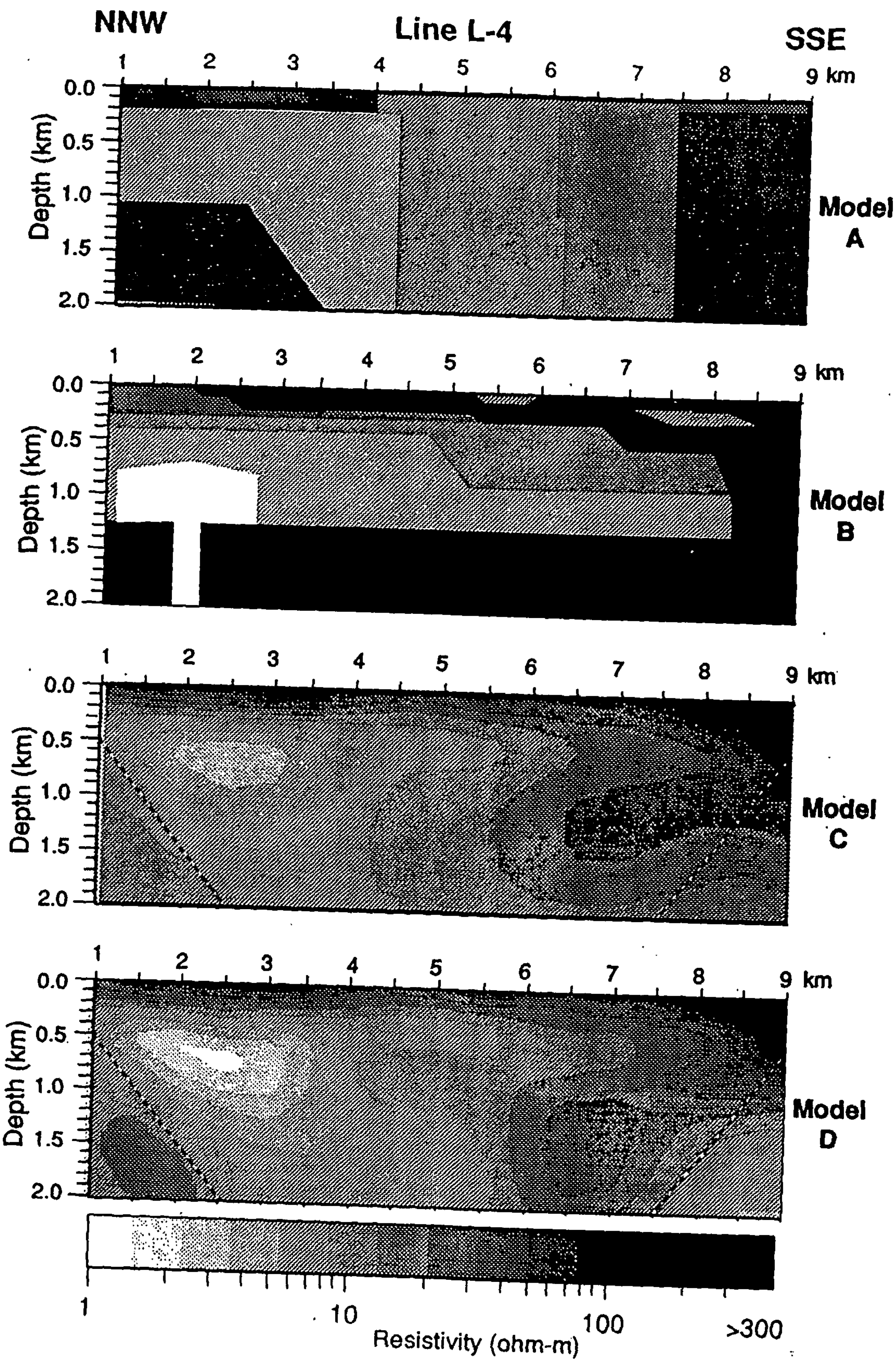

NNW
Line L-4
SSE
1
2
3
4
5
6
7
8
9 km
0.0
0.5
1.0
1.5
2.0
Depth (km)
Model A
Model B
Model C
Model D
1
10
100
>300
Resistivity (ohm-m)

Fig. 8

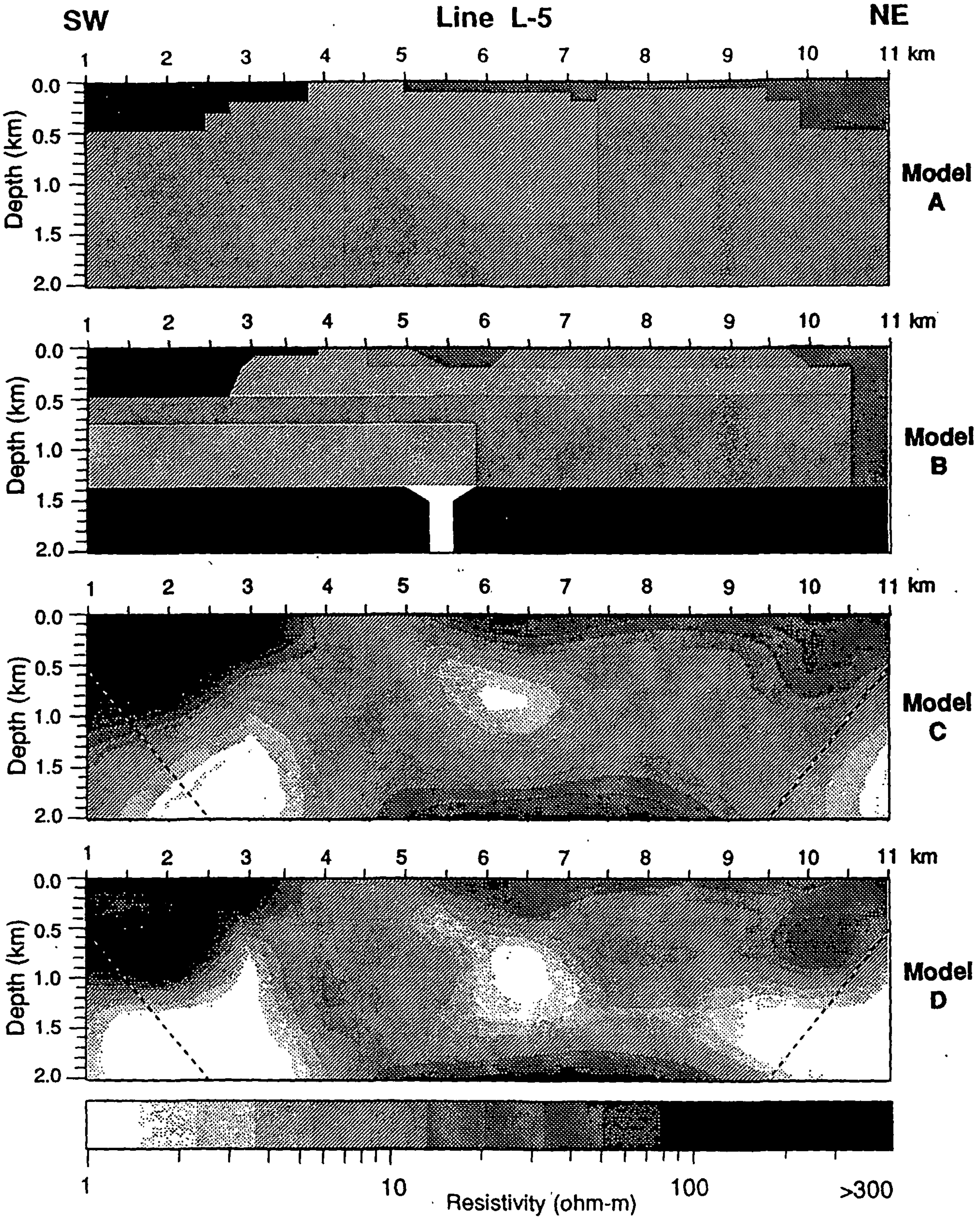

SW
Line L-5
NE
1 2 3 4 5 6 7 8 9 10 11 km
Depth (km)
0.0
0.5
1.0
1.5
2.0
Model A
Model B
Model C
Model D
1
10
100
>300
Resistivity (ohm-m)

Fig. 9

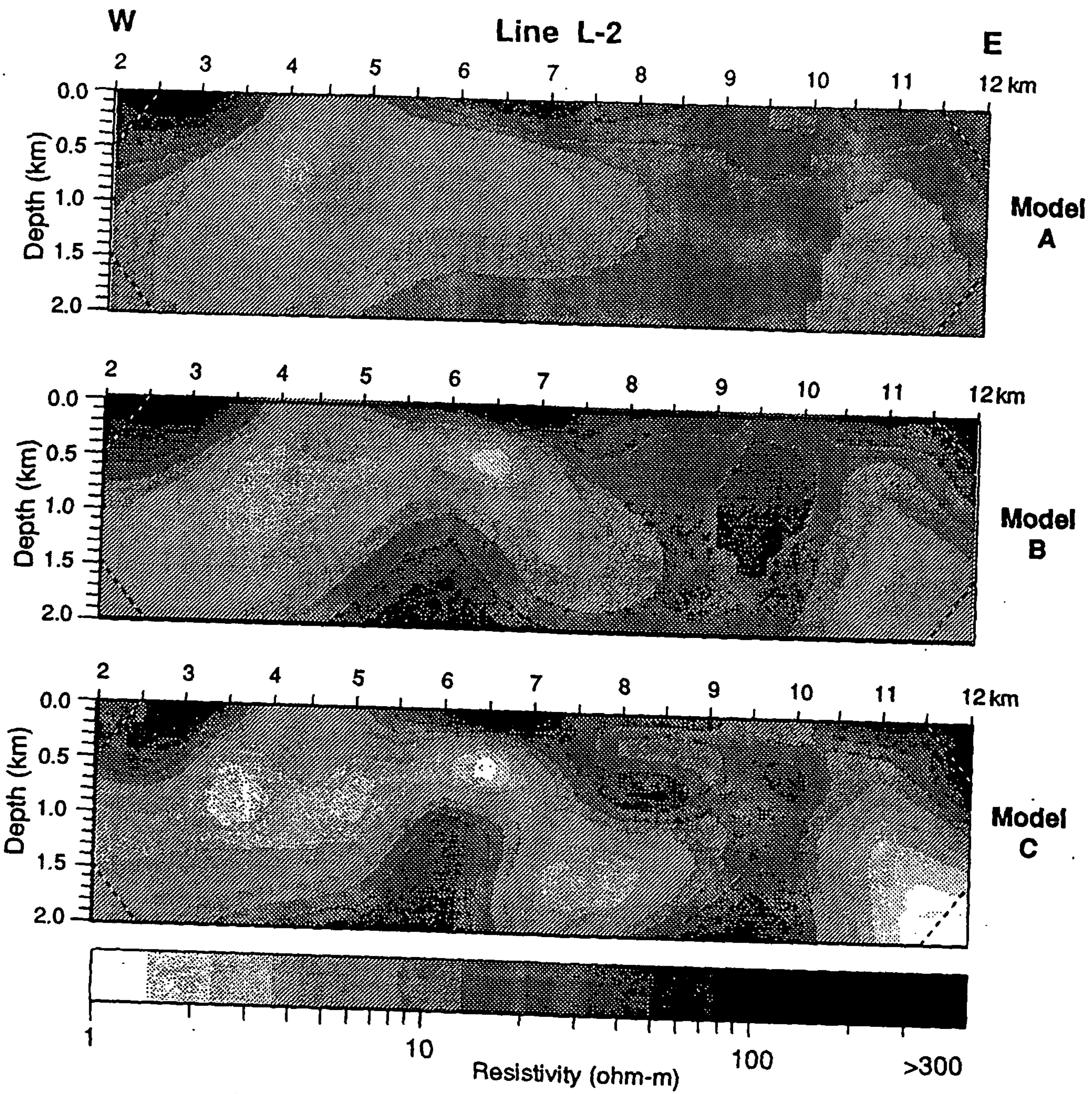
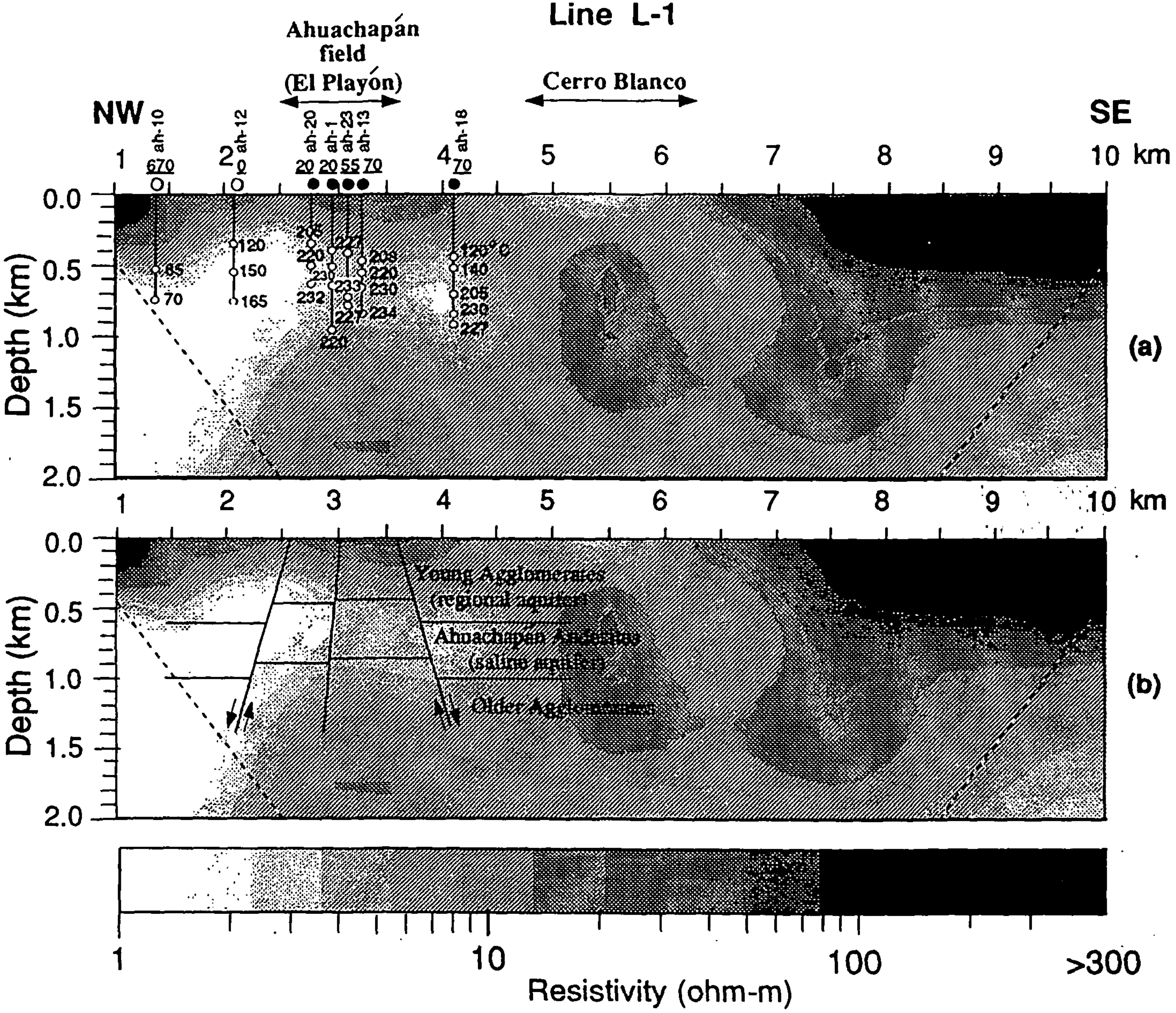

W
Line L-2
E
2
3
4
5
6
7
8
9
10
11
12 km
0.0
0.5
1.0
1.5
2.0
Depth (km)
Model A
Model B
Model C
1
10
100
>300
Resistivity (ohm-m)

Fig. 10

√



WELL SYMBOLS

670 ○ Non-productive well 670 m off-line

20 ● Productive well 20 m off-line

Fig. 1

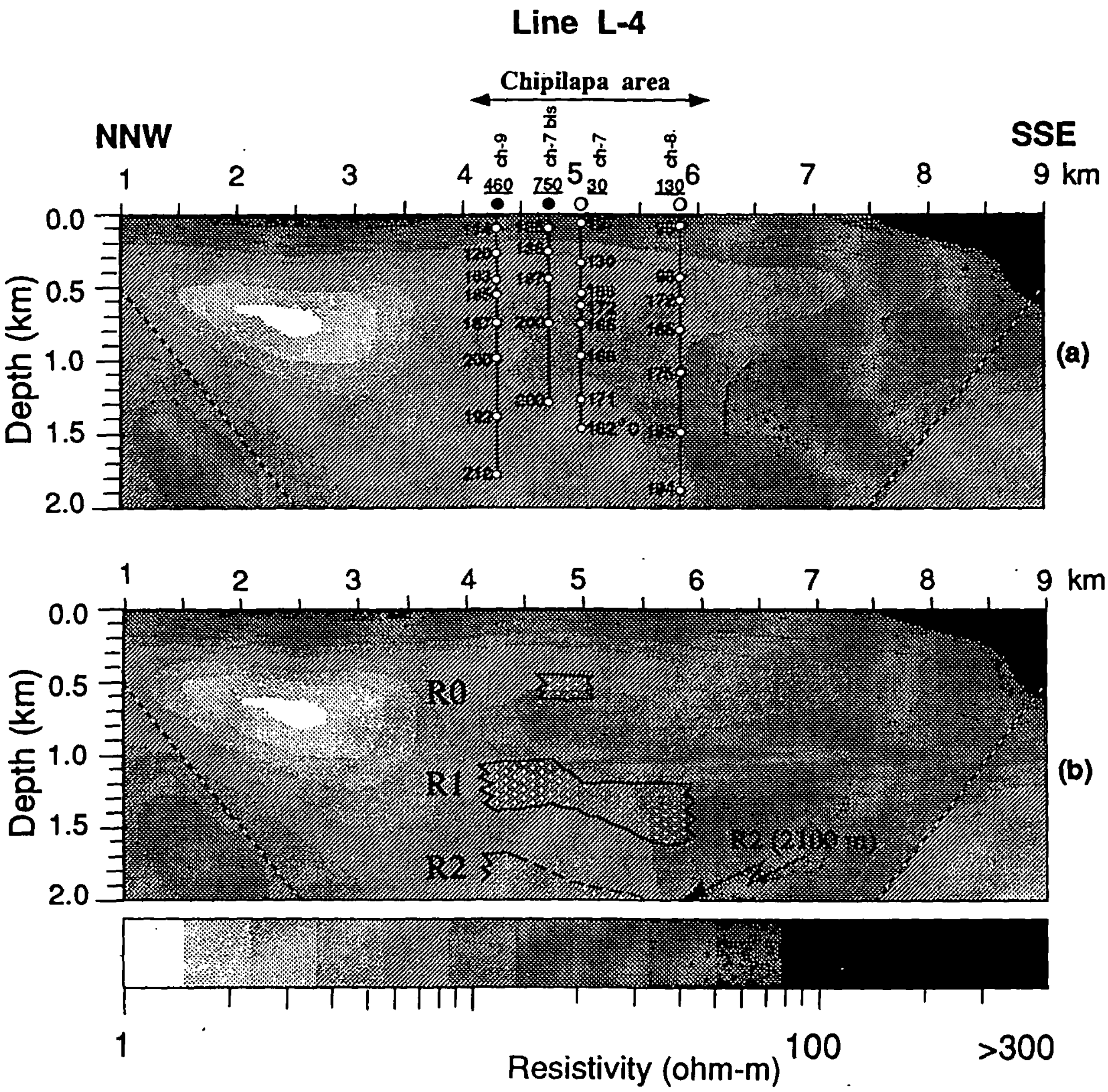

Line L-4
Chipilapa area
NNW
SSE
ch-9
ch-7 bis
ch-7
ch-8
460
750
30
130
1
2
3
4
5
6
7
8
9 km
0.0
0.5
1.0
1.5
2.0
Depth (km)
120
130
171
162
200
184
(a)
(b)
R0
R1
R2
R2 (2100 m)
1
100
>300
Resistivity (ohm-m)

Fig. 12

Line L-5

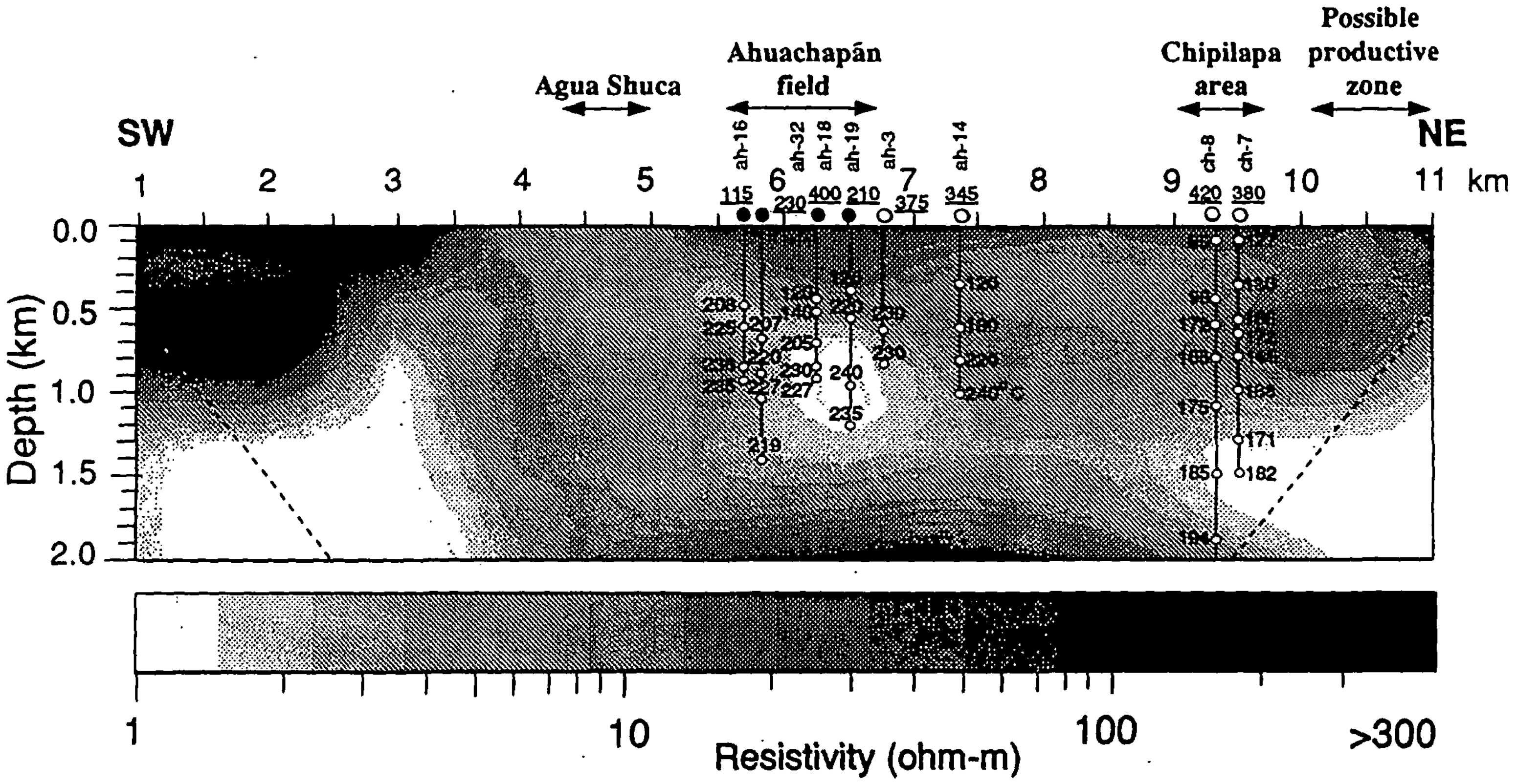


Fig. 13

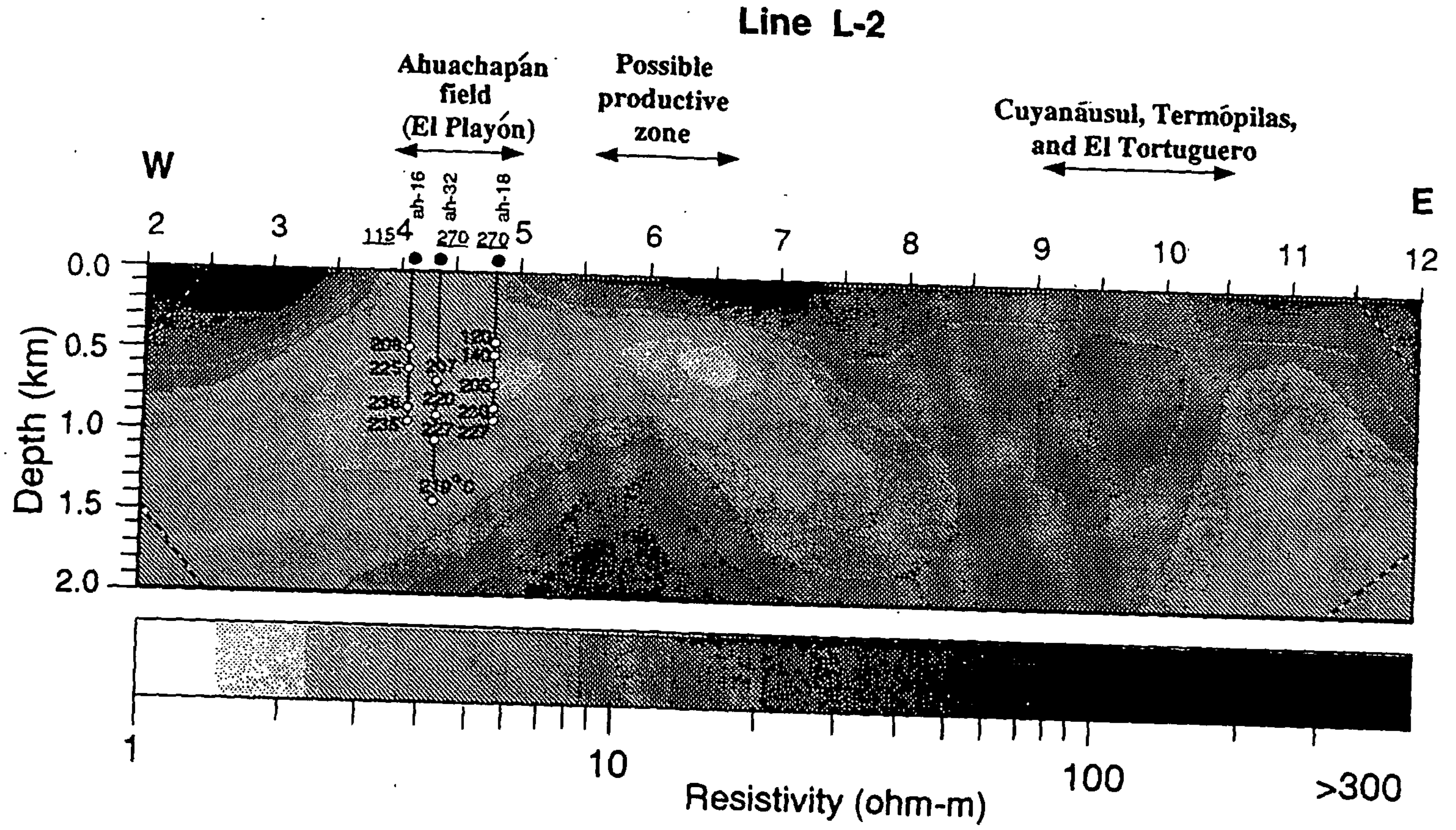
Line L-2
Ahuachapán field (El Playón)
Possible productive zone
Cuyanáusul, Termópilas, and El Tortuguero
W
E
2
3
115
4
ah-16
ah-32
270
ah-18
270
5
6
7
8
9
10
11
12
0.0
0.5
1.0
1.5
2.0
Depth (km)
208
225
236
235
207
220
227
219°C
120
140
206
224
229
1
10
100
>300
Resistivity (ohm-m)

Fig. 14

Preprint.

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TEMPORAL AND SPATIAL DISTRIBUTION OF LOCAL SEISMICITY IN THE CHIPILAPA-AHUACHAPAN GEOTHERMAL AREA

(EL SALVADOR)

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ABSTRACT

The microseismic monitoring of the Chipilapa-Ahuachapán area was carried out during August-November 1988 and October 1991-April 1992. The objective was to use the study of microearthquakes as an exploration tool to investigate the geothermal potential of the Chipilapa area and to evaluate the main characteristics of the seismic activity, prior and during the exploitation tests. Since 1989, seven wells were drilled in the area, two of them encountered three geothermal aquifers, that could allow electricity generation based upon binary cycle technology.

The 1988 survey detected important, shallow and low magnitude seismic activity, located mainly south and southwest of the explored area. This activity is possibly related to the recharge zone of the Chipilapa-Ahuachapán geothermal system, laying south, beneath the Pleistocene Pacific Volcanic Chain.

The 1991-1992 survey confirmed the existence of seismicity beneath the southern volcanic axis, but other important clusters of activity were recorded northward, related to the deeper structures of the Central Graben, and southwest of the Ahuachapán geothermal field, close to the 1990 hydrothermal eruption of Agua Shuca. Shallow microseismic activity appeared also along the faults limiting the Chipilapa geothermal field to the east. Although it is probable that this seismicity is due to fluid circulation in fractures, no geothermal reservoirs were

intercepted by wells CHA and CH8. Moreover, no significant induced seismicity was recorded during production and injection tests.

KEYWORDS: Geothermal exploration, microseismic monitoring, induced microseismicity, reservoir assessment.

INTRODUCTION

The Chipilapa geothermal field is sited near the Ahuachapán geothermal field, 80 km west of San Salvador (Figs. 1 and 2). The explored area covers circa 25 km^2 and lies in the northern foothills of the Pacific Volcanic Chain of Pleistocene age. Volcanism and deep seismicity are related to the subduction of the Cocos Plate beneath the Caribbean Plate. The Pacific Volcanic Chain is limited northward by the main E-W structure of the Central Graben, and is locally characterized by many young volcanoes and hydrothermal manifestations.

Three kilometres west of Chipilapa, the Ahuachapán field is controlled by a complex fault system which limits the geothermal reservoir northward and westward. The Ahuachapán field has been extensively studied (Laky et al., 1989) and is producing at present 45 MWe (Campos Romero, 1994). There is general agreement now that both fields are two distinct lateral flows recharged by a common upflow zone area laying southward, under the southwest-northeast trending volcanic axis of Cerro Las Ninfas-Cerro Laguna Verde (Fig. 2).

Nevertheless, the hydrological connection between both reservoirs is still being debated.

Up to now, seven wells were drilled in the Chipilapa area and only two of them, CH9 and CH7bis, located close to Hacienda La Labor, are actually productive, at least for binary cycle electrical production. Three geothermal aquifers were found in those wells :

- R0 - depth range: 550 m to 600 m, temperature = 187-200 °C
- R1 - depth range: 1000 m to 1600 m, temperature = 175-195 °C
- R2 - depth range: 1800 m to ?, temperature = 214-220 °C

The colder R0 and R1 aquifers are heated by R2, which in turn is heated by deep volcanic gases (CEL, 1992). Wells CHA and CHAbis (deviated from the first), drilled 500 m to the north of Cuyanausul fumarole, found temperatures above 250°C at 2700 m depth, but not enough permeability. From the geophysical point of view, the Chipilapa area was investigated using gravity, dipole-dipole, magnetotelluric (MT) and microseismic monitoring techniques. A correlation map (Fig. 2) of the residual Bouguer gravity and the deep (500-1000 m) conductors detected by MT (Romo et al., 1996) shows a good correlation (i.e. positive residual anomaly coinciding with the presence of a deep conductor) along a wide band running from south to north and crossing wells CH7bis and CH9. This band is limited to the east by a succession of faults. These faults run from Cerro Laguna Verde to well CH7bis and seem to correspond to the eastern limit of the Chipilapa geothermal field since they act as a hydrological and thermal barrier. The Escalante fault (SSW-NNE) is one of those faults. Moreover, the north end of the NNW-SSE Agua Shuca fault, which extends approximately from Cerro Cuyanausul to north of well CH9, crossing the area of wells CHA and CH7, intersects the Escalante fault and constitutes the northeast limit of the Chipilapa geothermal field.

Two microseismic surveys were carried out in 1988 and in 1991-1992, with two main objectives :

- To better define the reservoir, its recharge and associated structures ;
- To record the microseismicity during the production and injection tests to determine the existence, if any, of induced microseismicity possibly related to changes in reservoir pore pressure.

The seismic network used covered a 10-15 km^2 area (Fig. 3) and included seven vertical and three three-component (Sta. I, II and III on Fig. 3) geophones (natural frequency: 1Hz), all linked by wires to a central station (Finca Los Angeles, FLA). There, a computer digitized the data with a 200 samples/sec/channel sampling frequency and performed preliminary event detection when the recorded signals of three stations exceeded a given threshold, using the Short Time Average vs. Long Time Average algorithm (STA/LTA). Then, the computer calculated in real time a preliminary hypocenter determination with an homogeneous velocity model and backuped data on tape.

In 1988, two months of almost continuous monitoring were performed from 26 August to 7 November, before the start of drilling operations (Fabriol et al., 1990). The 1991-1992 survey lasted from 7 October 1991 to 5 April 1992. Two mobile digital recorders were added to the wire-linked network during the second survey in order to increase the covered area and the accuracy of the hypocenter determinations (Fabriol et al., 1992).

These two earlier papers dealt with the description of temporal characteristics and spatial distribution of the seismic activity recorded during both surveys. Here, those data are compared with recent information on the Chipilapa and Ahuachapán reservoirs in order to evaluate the contribution of microseismic monitoring to reservoir assessment.

TEMPORAL CHARACTERISTICS OF THE SEISMICITY

Prior to 1988, a microseismic survey was carried out from December 1969 to August 1970 for geothermal exploration purposes (Ward and Jacob, 1971). The recorded seismicity was rather high: more than 150 local events (Ts-Tp<8 s) and 350 regional events (Ts-Tp>8 s). Compared with the 1988 and 1991-1992 surveys these event rates are lower, but that could be explained by the lower sensitivity of the older equipment.

Since the objective of our surveys was to study the geothermal area, only local microseismicity was examined. Earthquakes with S-P times larger than 3 s were discarded, although they are the most important in number and magnitude in this region. More than 500 regional earthquakes with S-P times ranging from 3 s to more than 30 s were recorded during the 1988 survey and around 1300 during the 1991-1992 survey. This high level of seismic activity is mainly related to the structural framework of the area, i.e. the subduction of the Cocos Plate under the Caribbean Plate and its associated volcanic activity. Fig. 4 shows the seismicity map of El Salvador (Schulz, 1965 in Weyl, 1980) using events recorded until 1965. The earthquakes occurring offshore beneath the Pacific Ocean have focal depths between 10 to 120 km, dipping from the Central America Trench towards the continent. Inland, the number of reported earthquakes is lower and focal depths are shallower, less than 15 km. This activity should be distinguished from the deep earthquakes in the subduction zone and interpreted as a reaction of the crust to subduction. The shallow inland earthquakes are associated directly either to the major young fracture systems of the area and are responsible for most of the destructive earthquakes, or to the volcanic activity in the Pacific Volcanic Chain. The regional seismic activity recorded was not used in the present geothermal exploration study.

Both of our surveys pointed out the continuous character of the local seismic activity in the Chipilapa area: 508 and 1070 microearthquakes were recorded during the 1988 and the 1991-1992 surveys, respectively. On the chronological histograms (Fig. 5) it can be observed that daily rate of events ranges from 5 to 10 events with small bursts of activity every 5 to 10 days, corresponding to swarms of events clustered in time and space. These swarms can include up to many hundreds of events, like the one of 12-18 November 1991, with more than 300 events recorded.

The mean rate of events for the 1991-1992 survey (6 events/day) was lower than for the first one (8 events/day). It should be noted that most of the 1991-1992 activity was recorded during several swarms. Also, from October 1991 to March 1992, the noise level was higher in the area, due to the drilling of CHA close to the Cuyanausul fumaroles, production tests in CH9 and CH7bis and coffee harvest.

The magnitude formula of Lee et al. (1972) was used to evaluate duration magnitudes (Md) in the Chipilapa area, since it was used until recently by the Centro de Estudios Geotécnicos of the Ministerio de Obras Públicas (CIG), in charge of the El Salvador seismic network (Martínez et al., 1995) :

$$Md = -0.87 + 2 \log(d) + 0.0035\, \delta$$

Where d is the duration of the earthquake in seconds and δ the hypocentral distance in km. The highest magnitudes recorded were Md=2.3 in 1988 and Md=2.9 in 1991. Those low magnitudes are characteristic of a low level stress state at the source (Scholz, 1968), as expected for the upper part of the volcanic area sited above the subduction zone. Figure 6 shows the chronograms of duration magnitudes for both surveys, highlighting the low and continuous level of the seismic activity. During the second period, the higher background noise made the recording of events of negative magnitude difficult, while earthquakes with magnitudes ranging from Md=2 to Md=3 were common. Frequency-magnitude diagrams are presented in Fig. 7. The cumulative number of microearthquakes of magnitude higher or equal to a given magnitude is plotted vs. magnitude.The *b* value, that is the slope of the right part of the curve, is calculated by linear regression. For the first survey, the *b* value is equal to 1.14, using 377 events, and 0.95 for the second survey, using 1028 events.

In the next section, we show how the events were classified into six groups depending on their spatial location (see Figs. 9 and 10). Consequently it was possible to calculate frequency-magnitude diagrams for each of these groups. As an example, the 246 events recorded during the second survey close to the Chipilapa area (Group D) yield *b*=1.13, which is similar to value calculated in 1988 for the entire area. On the contrary, we find *b*=0.87, using 343 events of the 12-18 November 1991 swarm (Group B), located north of the Ahuachapán field. Values larger than 1 are characteristic of volcanic areas (Patané et al., 1992), while values lower than 0.8 are related to tectonic earthquakes for which higher magnitudes are expected. As explained below, events sited northward are deeper and reflect the distinct structural framework of the Central Graben, neither volcanic nor geothermal, in agreement with a *b* value lower than 1. Nevertheless, due to the short duration of the November 1991 swarm, this low *b* value should not be considered as representative for a longer period in this specific area. With respect to the Chipilapa-Ahuachapán area and the volcanic range, due to the lack of earthquakes with magnitude larger than Md=3 during the monitoring period, the value of *b* is larger than 1. This absence may be explained by the low stress state at the source and possibly by the circulation of fluid in the fractures of the geothermal reservoirs.

We conclude that spatial variation of *b* is useful to distinguish between seismicity of tectonic and volcanic-geothermal origin, assuming that the frequency-magnitude diagrams are calculated over a long enough time period. High values of *b* have been reported in the same way for the Larderello-Travale geothermal area (Batini et al., 1984). On the other hand, Arnott and Foulger (1994) reported *b*=0.77 for the Krafla-Námafjall geothermal area in Iceland. Nevertheless, the geological context and the stress regime are totally different, since they correspond to a crustal spreading environment.

SPATIAL DISTRIBUTION OF SEISMICITY AND GEOTHERMICS

Hypocenters were determined using HYPO71 (Lee and Lahr, 1975) and the layered model shown in Fig. 8. This model was evaluated using surface calibration shots for the first two layers, drilling information and results from other geophysical methods (Dipole-dipole and MT) for Layer 3. Layer 1 (Vp=2 km/s) corresponds to tuff agglomerates; Layer 2 (Vp=3.2 km/s) to the Ahuachapán andesites of the Ahuachapán geothermal reservoir; and Layer 3 (Vp=4.2 km/s) to the Formación Bálsamo (basement).

Modeling of the location errors was performed using a modified version of the Uhrhammer (1980) algorithm (R. Jones, pers. comm., 1994). Results show that horizontal and vertical error are smaller than 180 m at 2 km depth and within a 5 km radius circle centered at Finca Los Angeles (FLA; Fig. 3), using seven P-wave and two S-wave arrival times. These errors are larger than 750 m at 4 km depth, using ten P-wave and three S-wave arrival times. As for the first survey, HYPO71 yielded respectively 430 m and 590 m for the root mean square (RMS) horizontal and vertical errors averaged over the 118 located microearthquakes. For the second survey the mean RMS errors averaged over the 245 located microearthquakes are 520 m and 530 m for the horizontal and the vertical error, respectively. In order to compare mean location errors with those predicted by error modeling, we have to take into account that errors of events located inside or close to the network are averaged with those of events located more than several kilometres away. Consequently, we estimate that horizontal and vertical errors are smaller than 300 m for shallow microearthquakes, i.e. those less than 2 km deep, and located inside or close to the network. For microearthquakes deeper than 4 km or located more than 5 km from the center of the array, the minimum horizontal error is 800 m and the vertical error, 1 km.

Microearthquakes located during both surveys are presented in Figs. 9 and 10, to point out areas where seismicity was active or inactive during both periods. Several groups of seismicity were defined to distinguish between the various active zones, their significance is discussed below.

Spatial distribution of the 1988 seismic activity.

Figure 9 presents the locations of 118 events recorded in 1988. Most of the microearthquakes (Groups 1, 3 and 5) are located south of the area of interest under the Cerro Las Ninfas-Cerro Cuyanausul volcanic axis, with depths ranging from few hundreds meters down to 4 km. A small swarm (Group 2) is located north of the Cuyanausul fumarole, close to the Agua Shuca fault and the CHA well. It was proposed previously that this swarm was linked to geothermal fluid circulation through fractures, since microearthquakes could be triggered by sudden changes in pore pressure. However, that was not sufficient to detect a geothermal reservoir, since, as said before, wells CHA and CHAbis were non-productive. The fluid-filled fractures may exist, but a 300 m error in hypocenter location is critical in defining a wellhead site, if the drilling target is very limited in space, as fluid-filled fractures are.

From a more general point of view, the microseismic activity beneath the volcanic axis indicates high fracturing and sofar high permeability in the upper 4 kilometers, linked to the upflow area which is supposed to feed both Chipilapa and Ahuachapán geothermal fields. An alternative hypothesis could be that microearthquakes occurring close to the volcanic axis are simply due to tectonic stress release in the upper subducted crust. It is interesting to note on the vertical cross-section of Fig. 9, how hypocenter depths decrease from south (Group 1 and 3) to north (Group 2), possibly pointing out the ascent of geothermal fluid from the upflow zone to the discharge area. Nevertheless, none or few events were located under either the Ahuachapán geothermal field or beneath the monitoring network. This situation changed, at least respect to the second area, during the 1991-1992 survey. Several epicenters were located close to Turín (Group 6), north of the area and deeper than 8 km. Prior to our 1988 survey, CIG recorded from 18 May to 17 August 1988, 134 microearthquakes in the area, among which 22 were felt by the population. About half of them were located north of Turín, and the other half beneath the northern flank of the volcanic range (Alvarez and Martínez Torres, 1988). As mentioned before, the northern activity must be related to the faults of the Central Graben. As far as there are no surface indications of deep geothermal reservoirs in that area, it is likely those microearthquakes are of tectonic origin.

Spatial distribution of the 1991-1992 seismic activity.

Data from the 1991-1992 survey allowed to locate 245 events using HYPO71 (Fig. 10). The activity was spread over the entire area. Again, six groups of seismicity were defined according to spatial concentration of microearthquakes: Groups 1 and 2-3 are identical to those defined for the 1988 survey; A, B, C and D are new ones. Moreover, in order to increase the set of microearthquakes in each group, an algorithm was developed to classify into these groups the events for which the number of arrival times was insufficient to use HYPO71. The method is based on the visual correlation of the waveforms of an microearthquake with the set of waveforms of the master event selected for a given group. Belonging to a group implies specific arrival times and waveforms which allow to discriminate between groups. That yields a set of events large enough to evaluate time distribution and *b* values for each group. Finally about 84 % of the 982 recorded events were located either precisely by HYPO71 or roughly by this method.

Groups A and B

Group A is sited 2 km north of well CH9, and Group B 1.5 km north of the Ahuachapán geothermal field. As in 1988, the activity toward the north is deeper than 6 km and should be related to the tectonic framework of the Central Graben. It is important to note that Group A activity was continuous during the six-month 1991-1992 survey: 213 recorded events from which 72 are located, with a maximum duration magnitude of Md=2.4. Group B corresponds to the 12-18 November 1991 swarm, with more than 343 events recorded and a maximum magnitude close to Md=3. Only the hypocenters of the larger events appear on Fig. 10, although the number of microearthquakes that could be located is much higher. These were discarded since this group is not directly related to the geothermal fields.

Group C

Group C is located 3 km southwest of the Ahuachapán geothermal field and less than 1km from the Agua Shuca hydrothermal manifestations where a hydrothermal eruption occurred in October 1990 killing 25 people (Escobar et al., 1992). Sixty events were recorded in less than one month reaching a peak on 9 December 1991, with a maximum magnitude of Md=2.9. Sixteen events were located at depths shallower than 2 km, but at that distance from the network vertical errors are about 1 km. No activity was recorded in this area during the 1988 survey. Nevertheless, due to the short duration of the first survey and to the swarm character of this activity, we cannot conclude that this area was inactive in 1988. This group of microearthquakes lies below the northern flanks of Cerro Las Ninfas volcano where many hydrothermal manifestations are found around Agua Shuca (ASHM, Fig. 10) and close to the NS fault which is supposed to limit the Ahuachapán geothermal field to the west. Therefore, there is a direct link between this fault, the hydrothermal manifestations and the microearthquakes of Group C. The destructive character of the 1990 explosion and the relatively high magnitude of the seismic activity recorded in 1991 show this area as a high risk zone and should be carefully monitored to prevent future catastrophes.

Group 1

Aligned along a trend parallel to the Cerro Las Ninfas-Cerro Laguna Verde volcanic axis, the 65 recorded microearthquakes of Group 1 (26 located) confirmed the existence in this area of a continuous and low level seismic activity, already recorded in 1988. As mentioned before, this activity should be linked first to the upflow of the geothermal system which is supposed to occur to the south underneath the volcanic axis, and second to the movement of geothermal fluid through the Ahuachapán and Chipilapa geothermal fields, in a south-north direction. As noted previously on Fig. 9, the fact that microearthquake depths vary from 4 km to the southwest to less than 1 km to the northeast close to the Chipilapa area, supports the idea of a link between seismicity and fluid circulation from the deep and subvertical upflow zone towards the shallow and more horizontal outflow zone. Indeed seismicity suggests high fracturing and consequently high permeability beneath the Cerro Las Ninfas-Cerro Laguna Verde volcanic axis. A way to detect the presence of fluid could be by studying the variations of Vp/Vs ratio, using Wadati diagrams, for example. That did not yield concluding results, since the small number of stations with horizontal sensors, i.e. 3, limited severely reliable S-time pickings.

Group 2-3

There are many similarities between Group 1 and Group 2-3 (87 events recorded, 25 located). Both show continuous activity, low magnitudes, they existed also in 1988 and their depths decreased from 4 km in the south to less than 1 km in the north. The relationship of these groups with an upflow below Cerro Cuyanausul volcano and a circulation of geothermal fluid in a northwest direction toward Chipilapa could also be invoked. Nevertheless there are three arguments against this hypothesis:

- Cuyanausul volcano is older than the Laguna Verde-Las Ninfas volcanic group,
- wells CHA and CHAbis, located close to the Cuyanausul fumarole, encountered high temperatures but not enough permeability,
- Magnetotellurics (Romo et al., 1996) did not detect any low conductivity anomaly in this area, unlike the Group 1 area.

On the contrary, it makes more sense to link Group 2-3 seismic activity to a regional NNW-SSE tectonic axis crossing the Pacific Volcanic Chain between Cerro Laguna Verde and Cerro Cuyanausul. That is not inconsistent with the direction of fluid circulation, as discussed previously respect to the 1988 swarm located close to the Cuyanausul fumaroles, but it is not sufficient to prove the existence of a geothermal reservoir. Group A microearthquakes are also located on this NNW-SSE axis and may be considered as a deeper extension of Group 2-3.

Group D

During the 1991-1992 survey an important activity (97 events recorded, 57 located) appeared in the center of the Chipilapa area (Group D, Fig. 10). Seismicity was continuous and spatially distributed in many swarms. Hypocenters were shallow (less than 1 km depth) and mainly clustered along known faults: the SSW-NNE Escalante and NNW-SSE Agua Shuca faults. Due to the limited number of available monitoring stations, only two composite fault plane solutions were evaluated (Fig. 11), corresponding to each of these faults. Faulting is of strike-slip type with a small normal component. This agrees with the observed directions of faulting in the area, NNW-SSE (Fig. 11a) and NW-SE (Fig. 11b), respectively. The Escalante fault is considered to be the eastern limit of the known Chipilapa reservoir. East of this fault, wells CH7, CH8 and CHA are non-productive, while west of it wells CH7bis and CH9 are productive. Swarms of microearthquakes located along this fault indicate high permeability or at least intense fracturing favourable to the circulation of the fluid coming from the south.

Agua Shuca fault microearthquakes should be related to another swarm located close to well CH-A, coinciding with the 1988 swarm recorded close to the Cuyanausul fumarole. Both clusters are the prolongation of Group 2-3 activity, mentioned above. This activity corresponds to the main regional NNW-SSE axis which crosses the Chipilapa area between Cerro Laguna Verde and Cerro Cuyanausul. From a general point of view, the seismic activity of Group D corresponds to the intersection of the Escalante and Agua Shuca faults. Nevertheless, it should be noticed that no microearthquakes were located inside the array (i.e. in the group D area) during the 1988 survey. That means a temporal increase of seismic activity at the end of 1991, insofar as there were no continuous seismological records between both monitoring periods.

Microseismicity and production tests

A relationship between this increase of seismic activity and the 1991-1992 production tests in wells CH7bis and CH9 and injection tests in well CH7 is not straightforward. The mechanism commonly invoked to explain induced seismicity is the Mohr-Coulomb criterion: an increase in pore pressure decreases the effective pressure normal to a weakness plane and produces failure (Grasso, 1992). Another example is the induced microseismicity observed in The Geysers geothermal field: fluid extraction converts aseismic deformation due to regional stress field into stick slip failure by an increase of friction along fault planes (Oppenheimer, 1986).

In the particular case of Chipilapa, 20,000 m^3 of fluid extracted from CH9 were injected by gravity into well CH7 during 47 days (Fig. 5b). During or after injection operations, no epicenters were located around the injection well and those which occurred in the area were sited too far from the well to be reasonably related to injection. Nevertheless some events occurred just after the CH9 production test was stopped. Although it was not possible to locate them correctly due to poor data quality, they occurred near the well area, since they were recorded only by the closest stations. We suggest that these particular events were induced by a sudden increase in reservoir pressure, due to production well shut-in, combined with the effect of the injection which was still in progress at that time. The monochromatic frequency content of their spectra, centered around 10 Hz, shows these microearthquakes to be similar to long-period events, and very different from the other microearthquakes commonly recorded in the area, with a wider frequency content.

Examples of long-period events have been observed at Mount St. Helens by Fehler and Chouet (1982) or during hydrofracturing experiment at Fenton Hill (Ferrazzini et al., 1990). Long-period events and harmonic tremors are generated by the resonance of a fluid-driven crack induced by an impulsive pressure transient (Chouet, 1988). Therefore, an alternative mechanism for inducing seismicity could be the extension of fluid paths, due to the boiling of the fluid injected into the reservoir, which generates some type of long-period events.

CONCLUSIONS

The microseismic monitoring carried out in the Chipilapa-Ahuachapán geothermal area in 1988 and 1991-1992 was focused on geothermal exploration. Local microseismicity was quite continuous and, as expected, superimposed to an important regional seismicity. The latter is the consequence of the subduction of the Cocos Plate under the Caribbean Plate, and up to now it has not been used for structural evaluation. Magnitudes did not exceed Md=3 and *b* value for the Chipilapa-Ahuachapán area was equal to 1.13. Hydrothermal manifestations and geothermal fluid circulation could explain the release of seismic energy through low magnitude earthquakes. Time and spatial distribution of microearthquakes were investigated and correlations were found between zones of high seismicity and fluid circulation zones inferred from the conceptual model of the geothermal system.

Clusters of local seismicity are associated mainly to the volcanic axis south of the Chipilapa-Ahuachapán area and which corresponds to the recharge zones for both the Chipilapa and Ahuachapán geothermal reservoirs. Shallow microearthquake depths in Group 1, 2-3 and D show that the upper 4 kilometers must be highly fractured beneath the volcanic axis and the monitoring network. Beneath the Chipilapa area an important microearthquake activity was recorded in 1991-1992, but only a few microearthquakes in 1988. It is difficult to link this change to production tests. Moreover, apart from some events which seem to be induced by well testing, no evidences of a direct relationship between microseismicity and fluid extraction or injection were found, mainly due to the limited amount of fluid involved and that injection was by gravity. Those particular events have something in common with the long-period events observed in volcanic areas, since their spectral characteristics are rather monochromatic.

The Escalante and Agua Shuca faults showed to be seismically active, particularly in 1992. Those faults correspond respectively to the eastern and northeastern limits of the Chipilapa reservoir. As a matter of fact, several faults are seismically active in all the area, but few of them are actually related to the geothermal system. A good example could be the faults located east of the Escalante fault. The seismicity is high in that area, but wells CH8 and CHA were non-productive. An explanation could be that seismicity is effectively linked to fluid circulation, but permeability is concentrated around the main fractures, which, unfortunately, were not intersected by the wells.

This study shows that hypocenters mapping is an helpful tool in geothermal exploration to define axes of high fracturation, some of which have fluid-filled fractures. Other methods are needed to investigate if those fractures are linked to geothermal reservoirs. Precision in hypocenters location is critical when faults or wellhead sites should be determined through microseismic studies. A further use of this type of microseismicity studies would be for structural studies, i.e., to detect lateral variations of wave velocities, using a 3-D inversion of arrival times (see for example Arnott and Foulger, 1994). However, because of the limited number of seismic stations and the non-uniform spatial distribution of events respect to the area of interest and to the network, this method could not be used with the existing data set.

Finally, it is noteworthy that no significant seismic activity was located in the Ahuachapán geothermal field area during both surveys. Distance from the recording network is not a valid explanation, since the Group C seismicity is located farther away and a digital recorder was operating successively south and north of the field during the second survey. One reason could be that microearthquakes in the Ahuachapán field are very shallow and rapidly attenuated. Another reason is related to the induced seismicity mechanism: fluid extraction results in a decrease in reservoir pressure, i.e. an increase in effective stress. This could prevent failure along fault planes and consequently impede earthquakes generation. Then all the deformation due to reservoir contraction should be purely aseismic. Nevertheless, stress accumulation could produce larger earthquakes later on. Geodetical measurements should be undertaken as well as seismic monitoring to assess surface deformation effects and possible seismic hazards.

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LIST OF FIGURES

Fig. 1: Location map of El Salvador and of the Chipilapa-Ahuachapán geothermal area.

Fig.2: Chipilapa-Ahuachapán area: correlation map of residual Bouguer gravity and the deep magnetotelluric (MT) conductor. Correlation degree is calculated as follows: the residual map is transformed in such a way that a weight equal to the residual is assigned to areas of positive gravity anomaly and equal to zero to areas of negative or null anomaly. Respect to the MT map, weight one is assigned to areas where a deep conductor is present below 500 m depth, weight zero elsewhere. The correlation map is the sum of both maps. Note that the highest correlation degrees occur beneath the Ahuachapán geothermal field and, eastward, along a winding North-South channel crossing productive the area of the productive wells CH9 and CH7bis.

Fig. 3: Seismic network used for monitoring the Chipilapa area. Sta. I, II and III are the three-component stations. FLA: Finca Los Angeles, central recording station.

Fig. 4: Seismicity map of El Salvador, using earthquakes recorded by a regional network until 1965 (from Schulz, 1965, in Weyl, 1980). Open circles denote

shallow seismicity (0 to 30 km depth); filled circles intermediate and deep seismicity (30 to 120 km depth).

Fig. 5: Chronological histograms of local seismicity (Ts-Tp< 3s): a) 1988 survey; b) 1991-1992 survey.

Fig. 6: Chronogram of duration magnitudes of local seismicity: a) 1988 survey (377 events); b) 1991-1992 survey (1028 events).

Fig. 7: Frequency-magnitude diagrams: a) 1988 survey (377 events); b) 1991-1992 survey (1028 events).

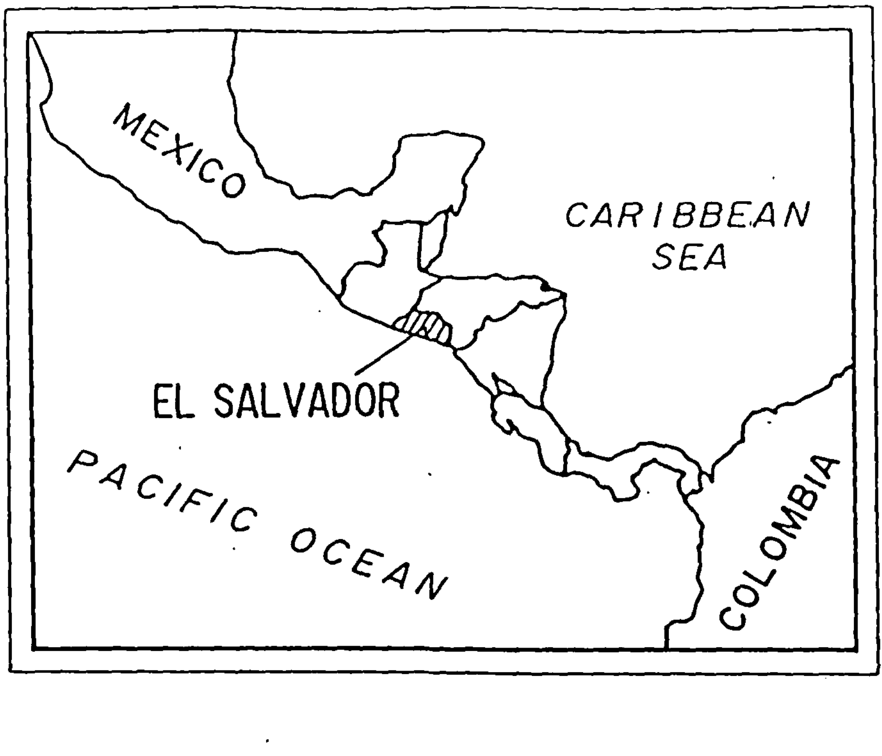
Fig. 8: P wave velocity model used for HYPO71.

Fig. 9: 1988 Survey: map and section views of the 118 located events. ASF: Agua Shuca Fault. Clusters of microearthquakes define the six groups (1 to 6) described in the text.

Fig. 10: 1991-1992 Survey: map and section views of the 245 located events. ASF: Agua Shuca Fault; EF: Escalante Fault; ASHM: Agua Shuca Hydrothermal Manifestations. Clusters of microearthquakes define the six groups described in the text. Rectangle *1* denotes the location of the events used for the composite

fault plane solution shown in Fig. 11a and rectangle *2* the events used for Fig. 11b.

Fig. 11: Composite fault plane solutions for two clusters of events recorded during the 1991-1992 survey: a) for the cluster of microearthquakes included in the rectangle denoted by *1* in Fig. 10; b) for the cluster of microearthquakes included in the rectangle denoted by *2* in Fig.10.


MEXICO
CARIBBEAN SEA
EL SALVADOR
PACIFIC OCEAN
COLOMBIA

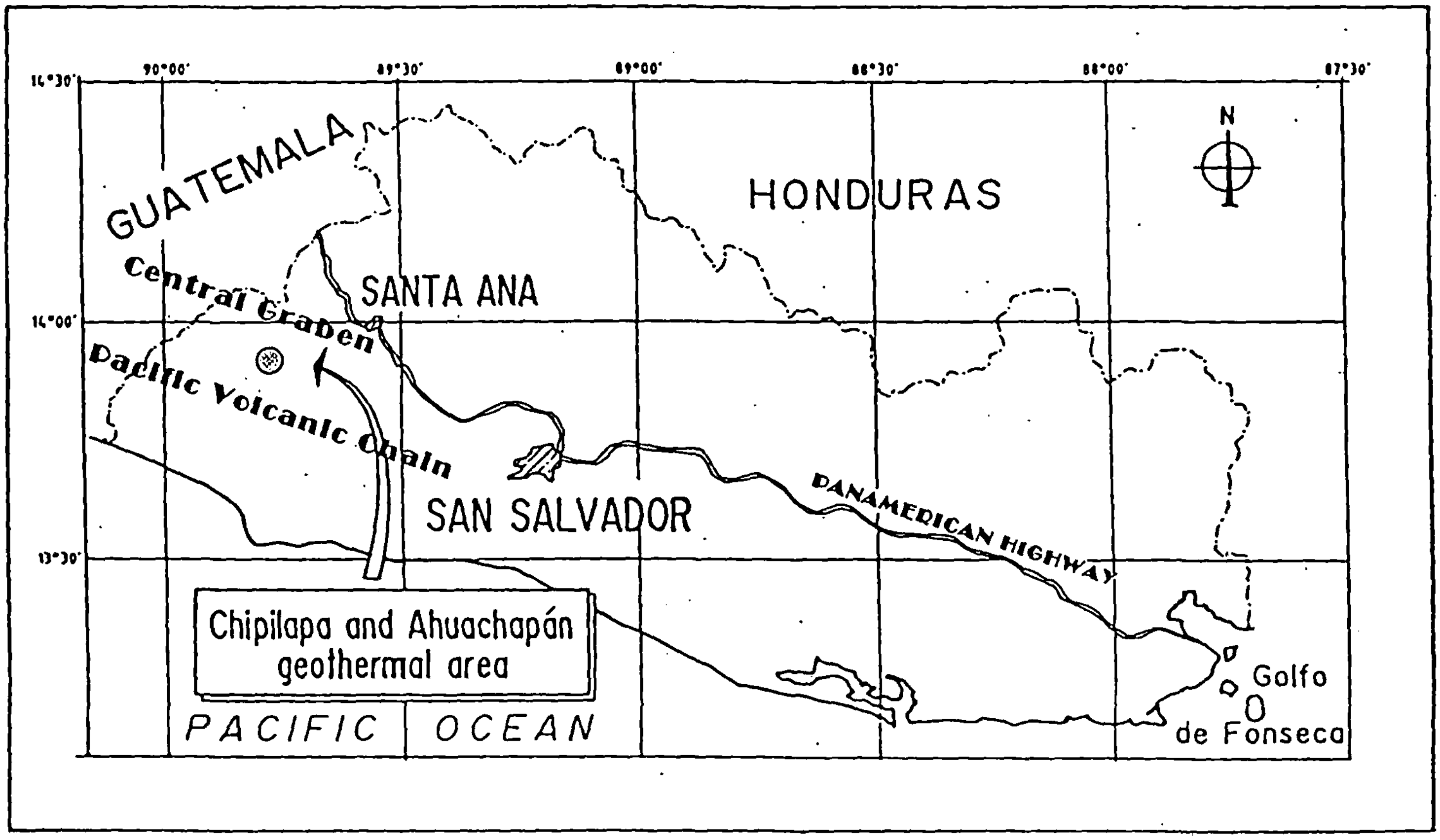
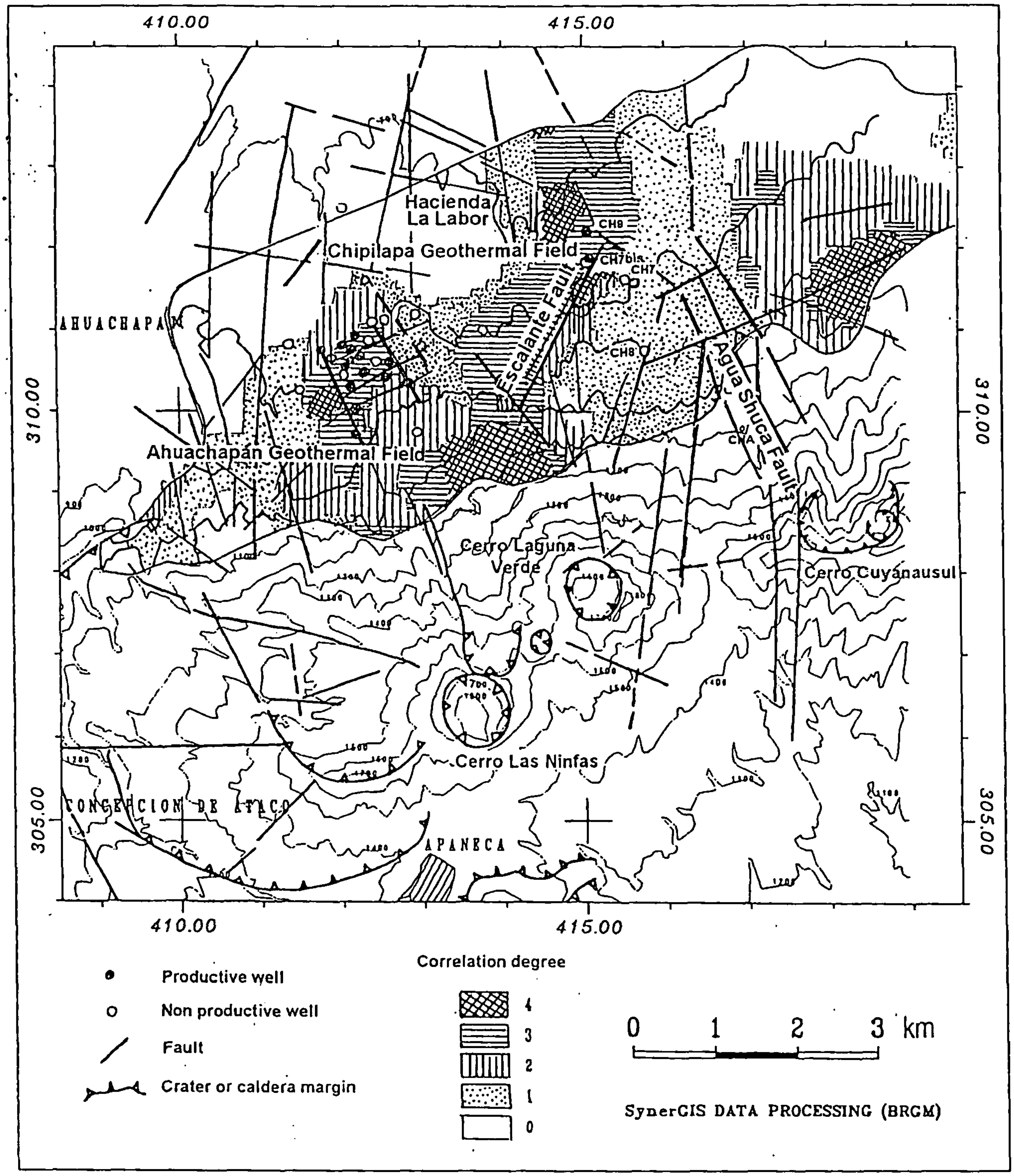

14°30'
90°00'
89°30'
89°00'
88°30'
88°00'
87°30'
14°00'
13°30'
N
GUATEMALA
HONDURAS
SANTA ANA
Central Graben
Pacific Volcanic Chain
SAN SALVADOR
PANAMERICAN HIGHWAY
Chipilapa and Ahuachapán geothermal area
PACIFIC OCEAN
Golfo de Fonseca

Fig. 1



410.00
415.00
310.00
305.00
Hacienda La Labor
Chipilapa Geothermal Field
CH9
CH7bis
CH7
CH8
CHA
Escalante Fault
Agua Shuca Fault
AHUACHAPAN
Ahuachapan Geothermal Field
Cerro Laguna Verde
Cerro Cuyanausul
Cerro Las Ninfas
CONCEPCION DE ATACO
APANECA
Productive well
Non productive well
Fault
Crater or caldera margin
Correlation degree
4
3
2
1
0
0 1 2 3 km
SynerCIS DATA PROCESSING (BRGM)

Fig 2

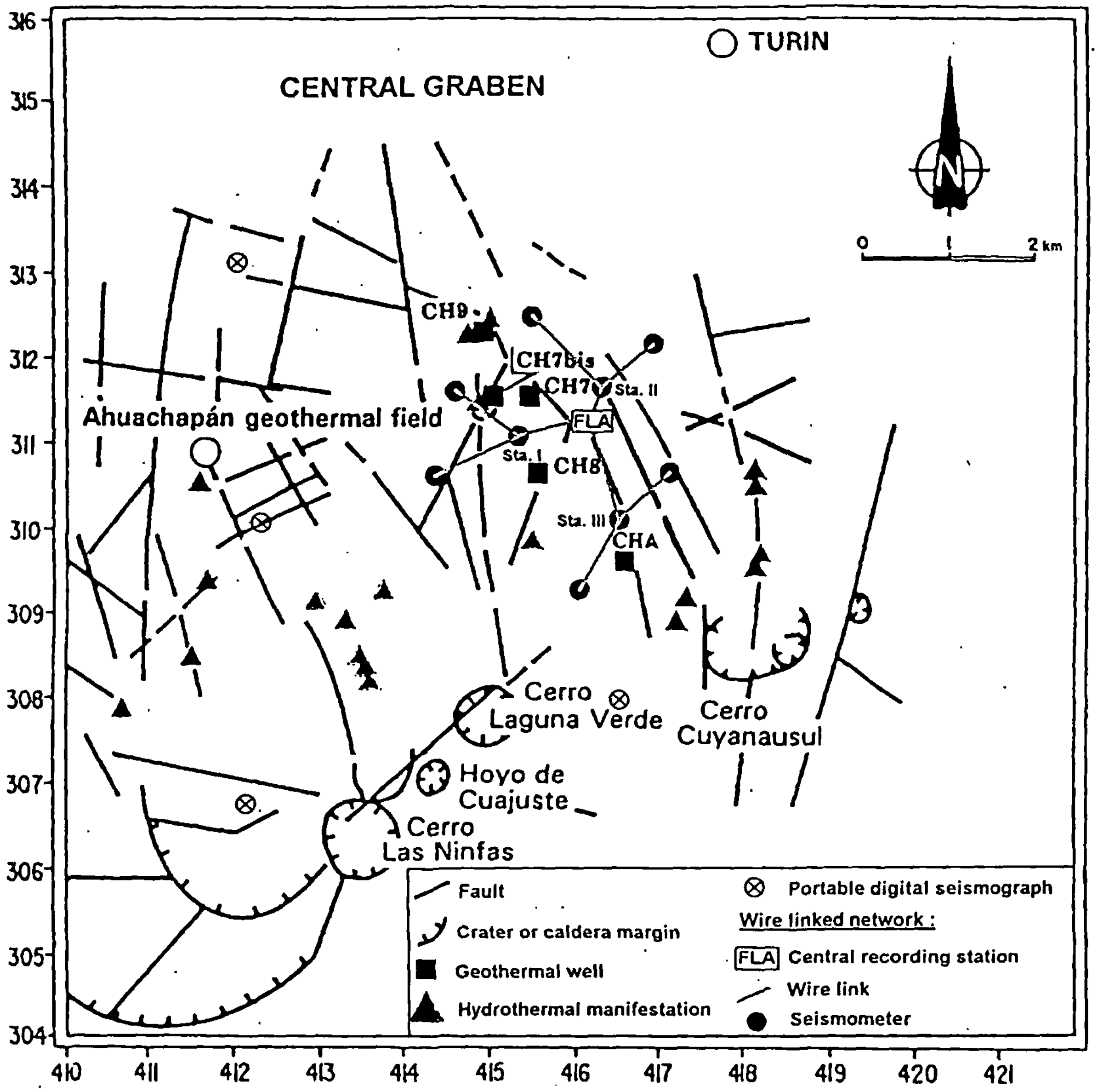

CENTRAL GRABEN
TURIN
N
0
1
2 km
CH9
CH7bis
CH7
Sta. II
FLA
Sta. I
CH8
Sta. III
CHA
Ahuachapán geothermal field
Cerro Laguna Verde
Cerro Cuyanausul
Hoyo de Cuajuste
Cerro Las Ninfas
Fault
Crater or caldera margin
Geothermal well
Hydrothermal manifestation
Portable digital seismograph
Wire linked network :
FLA Central recording station
Wire link
Seismometer
316
315
314
313
312
311
310
309
308
307
306
305
304
410
411
412
413
414
415
416
417
418
419
420
421

Fig. [illegible]

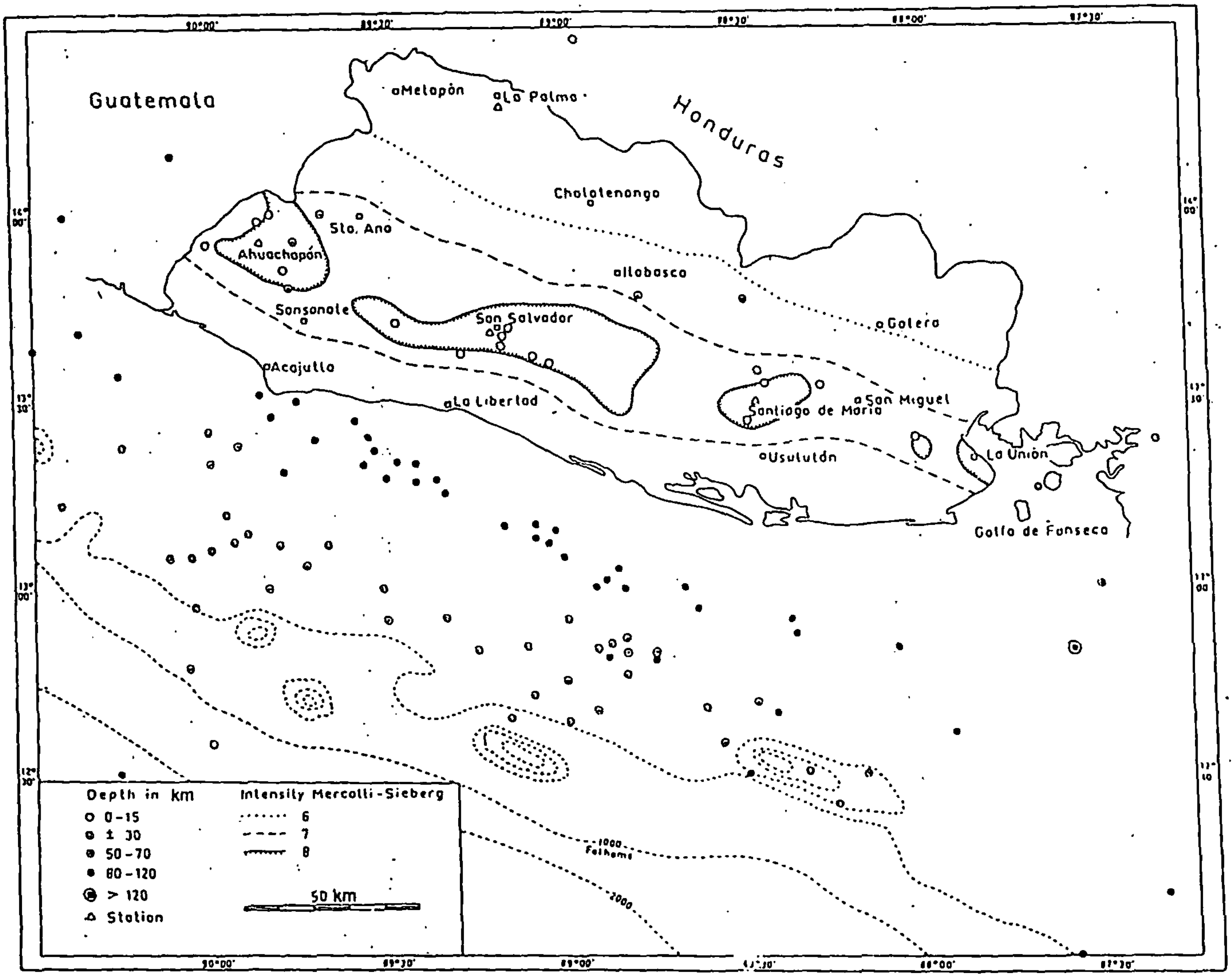
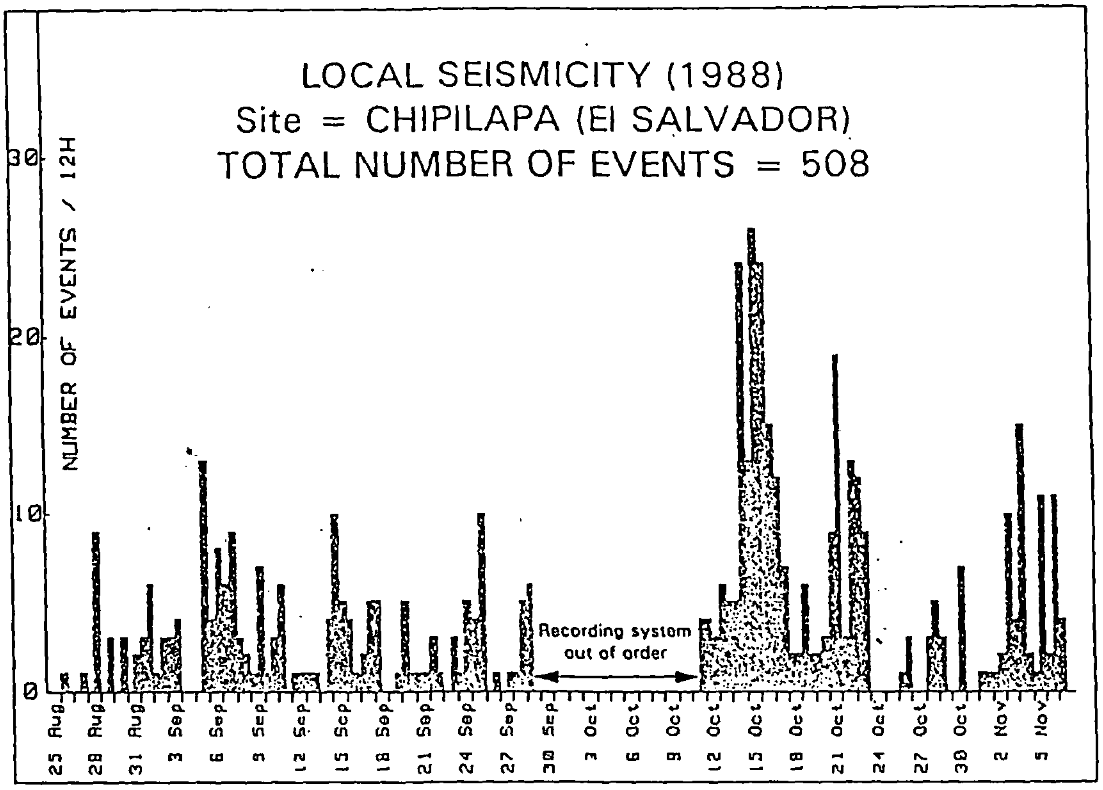

90°00'
89°30'
89°00'
88°30'
88°00'
87°30'
14°00'
13°30'
13°00'
12°30'
Guatemala
Honduras
Metapán
La Palma
Chalatenango
Ilobasco
Gotera
San Miguel
Santiago de María
Usulután
La Unión
Golfo de Fonseca
Ahuachapán
Sta. Ana
Sonsonate
San Salvador
Acajutla
La Libertad
1000 Fathoms
2000
Depth in km
0-15
± 30
50-70
80-120
> 120
Station
Intensity Mercalli-Sieberg
6
7
8
50 km

Fig 4

5a


LOCAL SEISMICITY (1988)
Site = CHIPILAPA (El SALVADOR)
TOTAL NUMBER OF EVENTS = 508
NUMBER OF EVENTS / 12H
0
10
20
30
Recording system out of order
25 Aug
28 Aug
31 Aug
3 Sep
6 Sep
9 Sep
12 Sep
15 Sep
18 Sep
21 Sep
24 Sep
27 Sep
30 Sep
3 Oct
6 Oct
9 Oct
12 Oct
15 Oct
18 Oct
21 Oct
24 Oct
27 Oct
30 Oct
2 Nov
5 Nov

5b

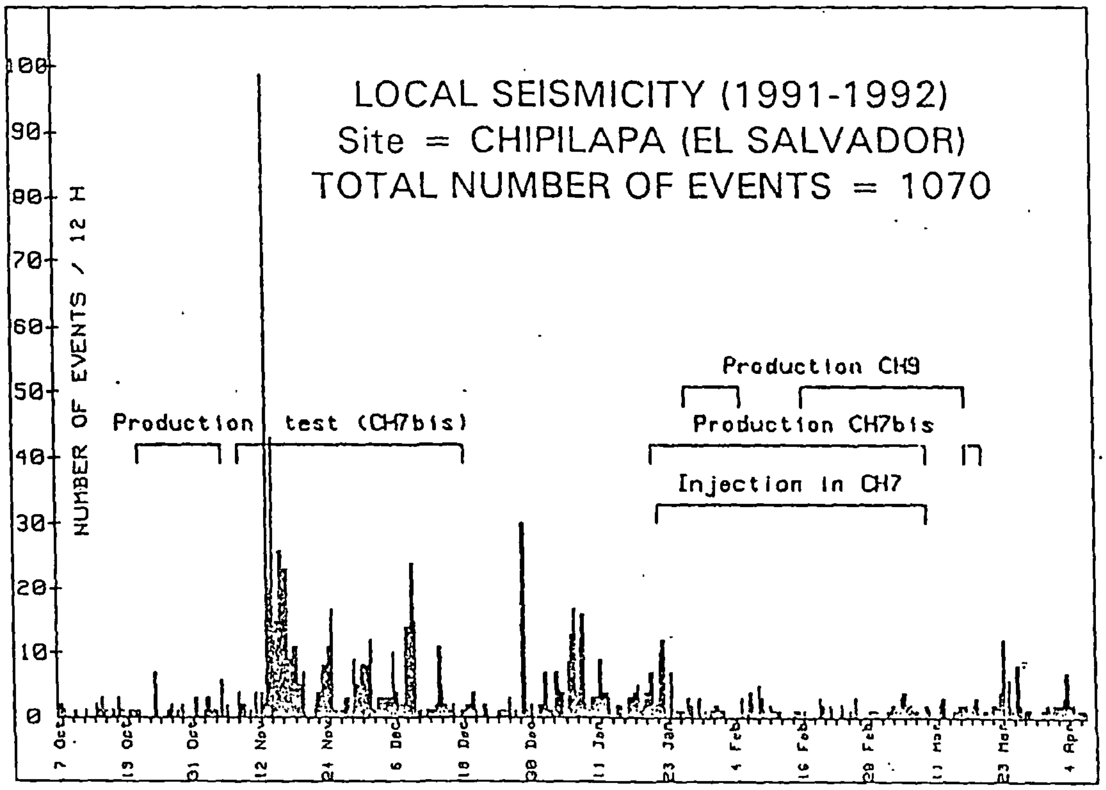

LOCAL SEISMICITY (1991-1992)
Site = CHIPILAPA (EL SALVADOR)
TOTAL NUMBER OF EVENTS = 1070
NUMBER OF EVENTS / 12 H
0
10
20
30
40
50
60
70
80
90
100
Production test (CH7bis)
Production CH9
Production CH7bis
Injection in CH7
7 Oct
19 Oct
31 Oct
12 Nov
24 Nov
6 Dec
18 Dec
30 Dec
11 Jan
23 Jan
4 Feb
16 Feb
28 Feb
11 Mar
23 Mar
4 Apr

Fig. 5

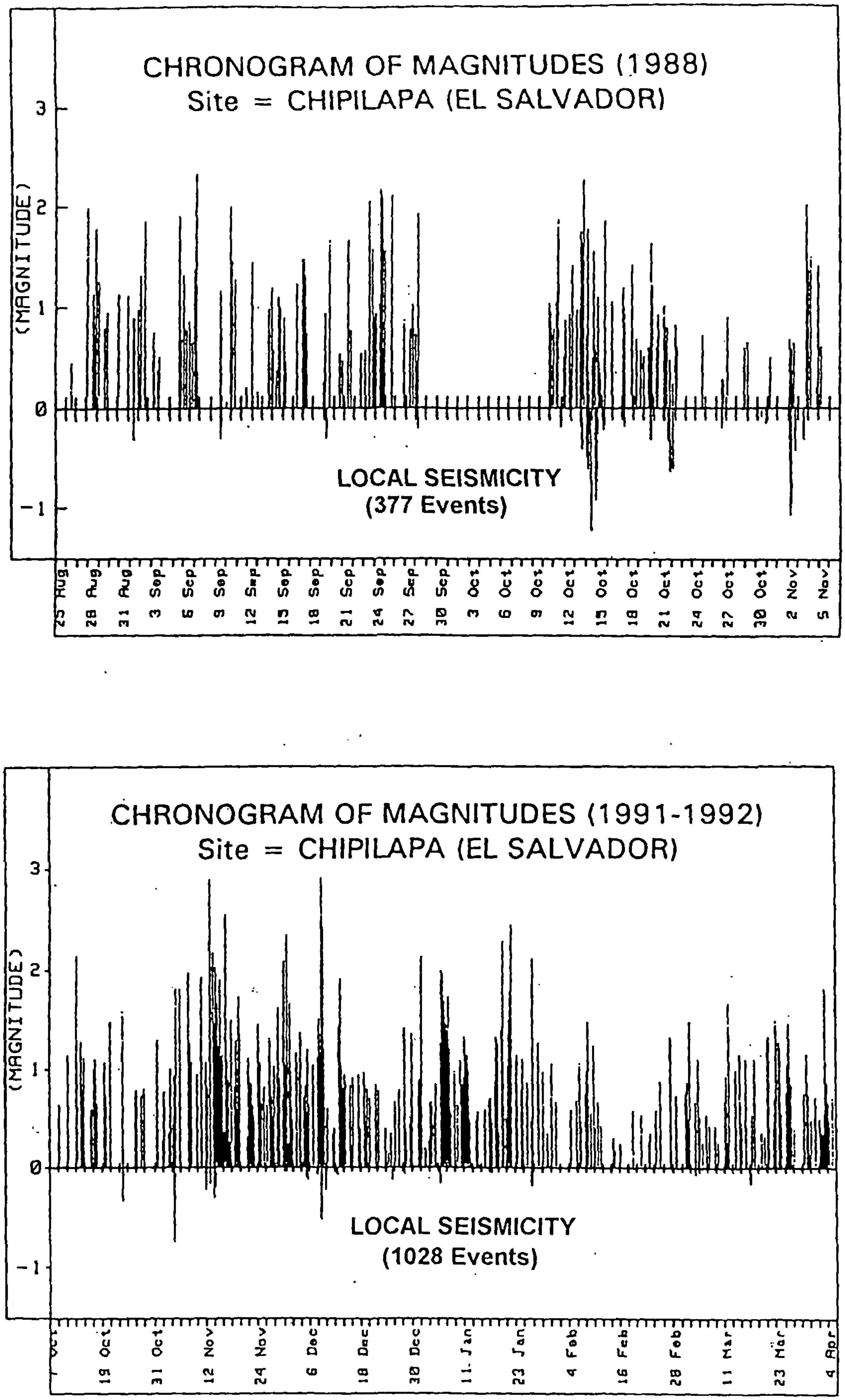
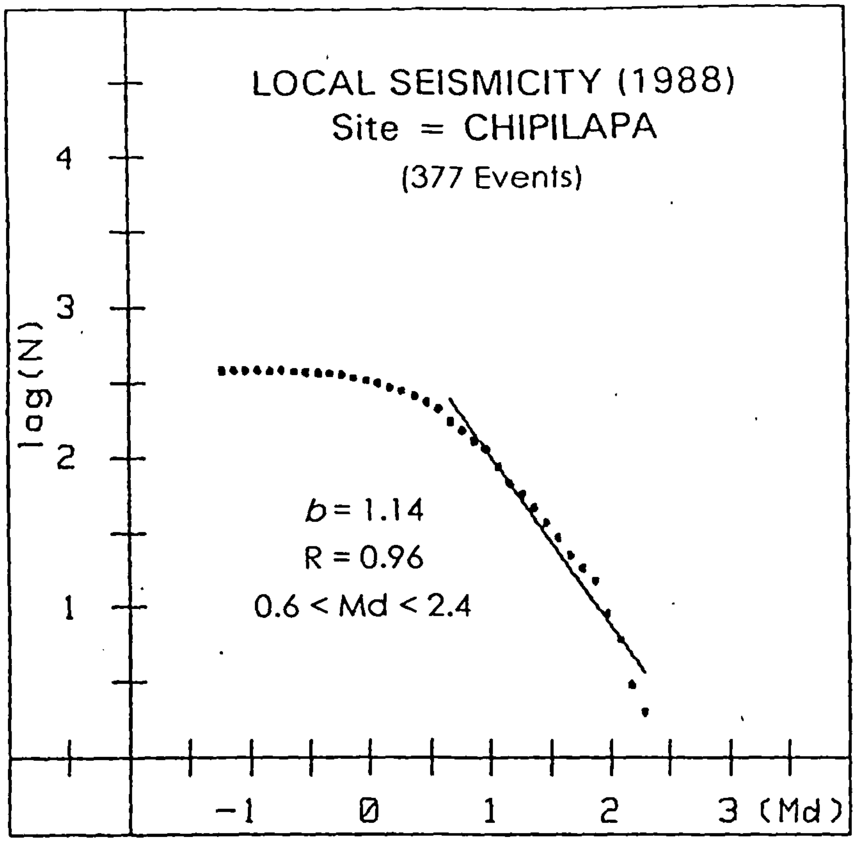

CHRONOGRAM OF MAGNITUDES (1988)
Site = CHIPILAPA (EL SALVADOR)
(MAGNITUDE)
3
2
1
0
-1
LOCAL SEISMICITY
(377 Events)
25 Aug
28 Aug
31 Aug
3 Sep
6 Sep
9 Sep
12 Sep
15 Sep
18 Sep
21 Sep
24 Sep
27 Sep
30 Sep
3 Oct
6 Oct
9 Oct
12 Oct
15 Oct
18 Oct
21 Oct
24 Oct
27 Oct
30 Oct
2 Nov
5 Nov
CHRONOGRAM OF MAGNITUDES (1991-1992)
Site = CHIPILAPA (EL SALVADOR)
(MAGNITUDE)
3
2
1
0
-1
LOCAL SEISMICITY
(1028 Events)
Oct
19 Oct
31 Oct
12 Nov
24 Nov
6 Dec
18 Dec
30 Dec
11 Jan
23 Jan
4 Feb
16 Feb
28 Feb
11 Mar
23 Mar
4 Apr

Fig. 6


LOCAL SEISMICITY (1988)
Site = CHIPILAPA
(377 Events)
b = 1.14
R = 0.96
0.6 < Md < 2.4
log(N)
4
3
2
1
-1
0
1
2
3 (Md)

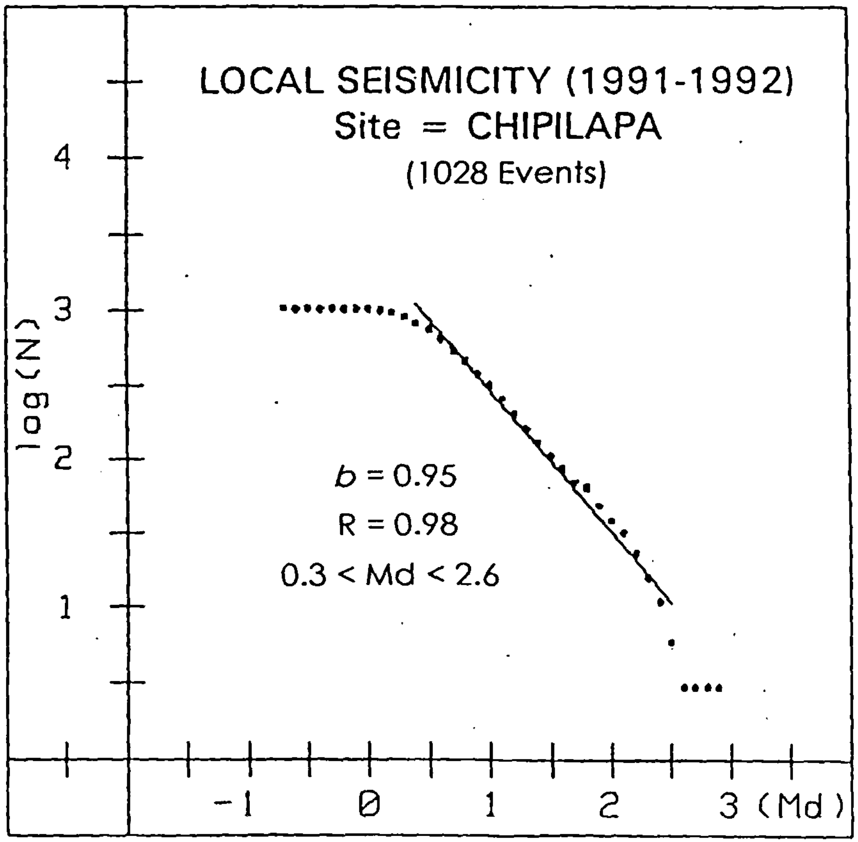
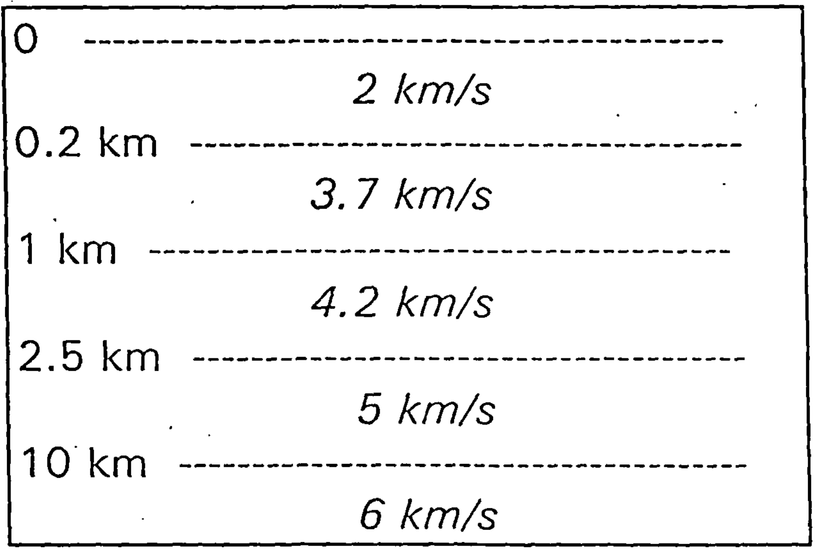

LOCAL SEISMICITY (1991-1992)
Site = CHIPILAPA
(1028 Events)
b = 0.95
R = 0.98
0.3 < Md < 2.6
log(N)
4
3
2
1
-1
0
1
2
3 (Md)

Fig. 7



P-wave velocity model used for HYPO71

Fig. 8

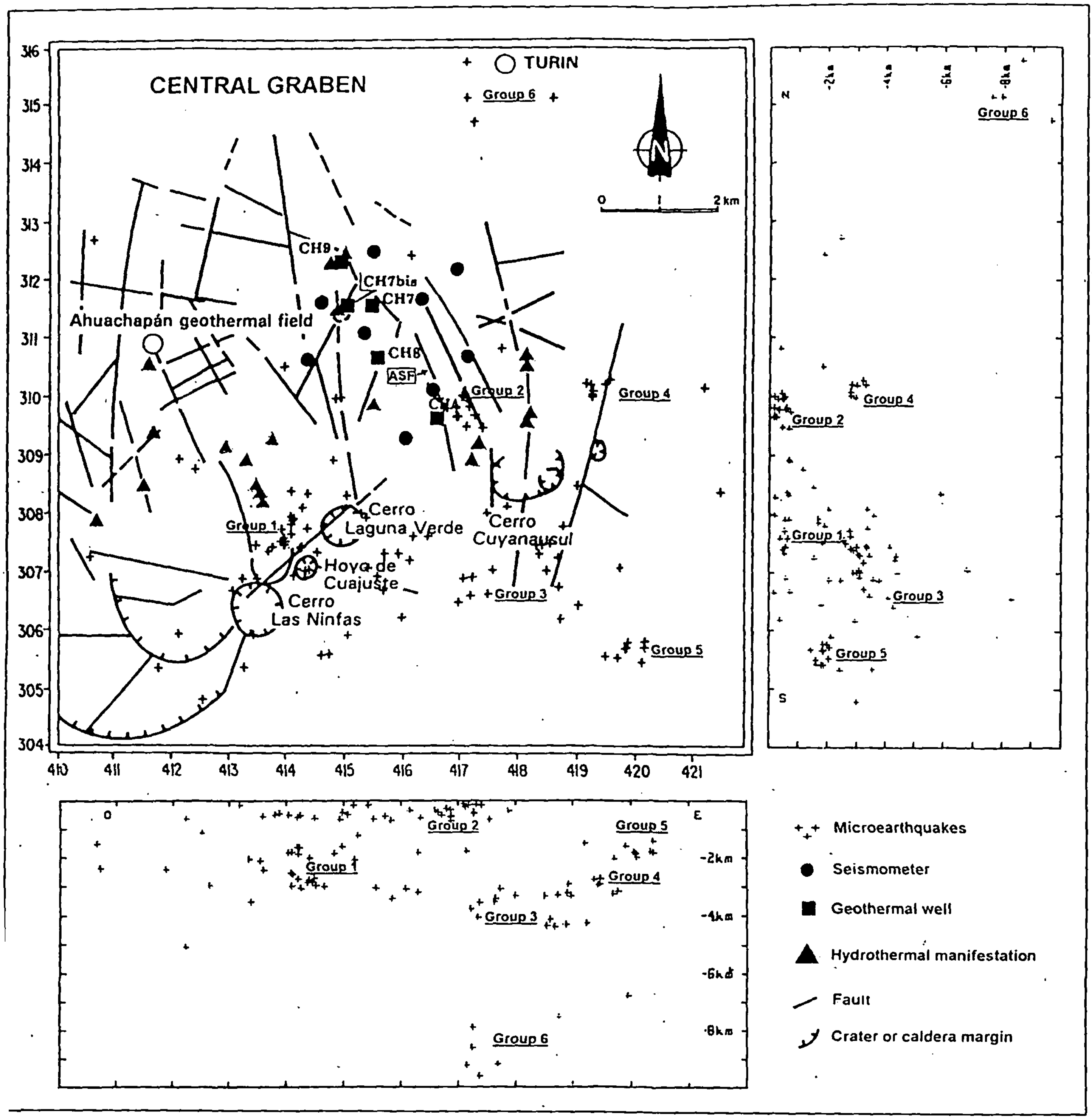

CENTRAL GRABEN
TURIN
Group 6
0 1 2 km
N
CH9
CH7bis
CH7
CH8
ASF
CH4
Ahuachapán geothermal field
Group 1
Group 2
Group 3
Group 4
Group 5
Cerro Laguna Verde
Cerro Cuyanausul
Hoya de Cuajuste
Cerro Las Ninfas
316
315
314
313
312
311
310
309
308
307
306
305
304
410
411
412
413
414
415
416
417
418
419
420
421
N
S
-2km
-4km
-6km
-8km
O
E
Microearthquakes
Seismometer
Geothermal well
Hydrothermal manifestation
Fault
Crater or caldera margin

Fig 9

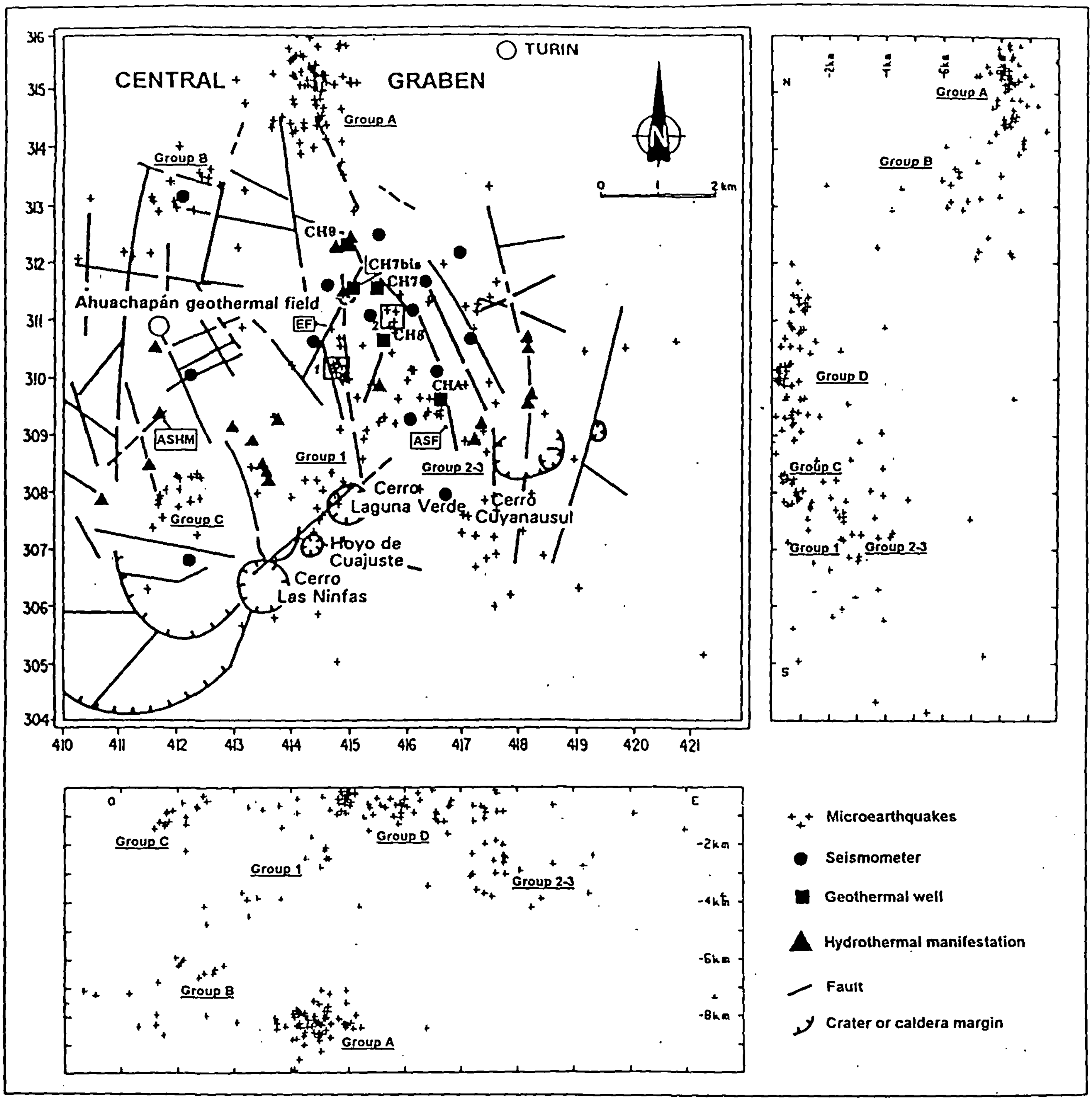

CENTRAL GRABEN
TURIN
Group A
Group B
Group C
Group D
Group 1
Group 2-3
CH9
CH7bis
CH7
CH8
CHA
EF
ASHM
ASF
Ahuachapán geothermal field
Cerro Laguna Verde
Cerro Cuyanausul
Hoyo de Cuajuste
Cerro Las Ninfas
N
0 1 2 km
316
315
314
313
312
311
310
309
308
307
306
305
304
410
411
412
413
414
415
416
417
418
419
420
421
N
S
-2km
-4km
-6km
-8km
O
E
Microearthquakes
Seismometer
Geothermal well
Hydrothermal manifestation
Fault
Crater or caldera margin

Fig 10

COMPOSITE FAULT PLANE SOLUTION
(Schmidt projection - Lower hemisphere;
shaded area: compression)

Plane A: Strike : N 267°
Dip : 53° N
Normal faulting - Dextral

Plane B: Strike : N 155°
Dip : 64° SW
Normal faulting - Sinistral

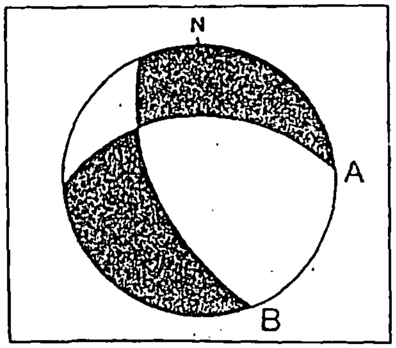


Fig. 11 a

COMPOSITE FAULT PLANE SOLUTION
(Schmidt projection - Lower hemisphere;
shaded area: compression)

Plane A: Strike : N 128°
Dip : 70° SW
Normal faulting - Dextral

Plane B: Strike : N 29°
Dip : 65° SE
Normal faulting - Sinistral

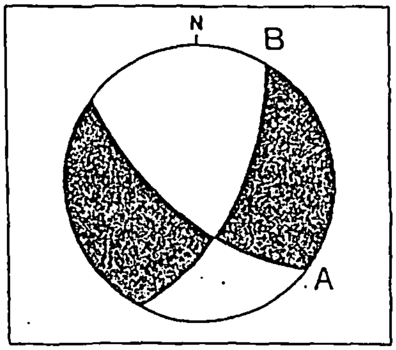


Fig. 11 b