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HYDROGEOLOGIC MODEL OF THE AHUACHAPAN GEOTHERMAL FIELD, EL SALVADOR

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ABSTRACT

A hydrogeological model of the Ahuachapan geothermal field has been developed. It considers the lithology and structural features of the area and discerns their impact on the movement of cold and hot fluids in the system. Three aquifers were identified, their zones of mixing and flow patterns were obtained on the basis of temperature and geochemical data from wells and surface manifestations.

INTRODUCTION

As a part of a reservoir evaluation effort the Earth Sciences Division of the Lawrence Berkeley Laboratory (LBL) in cooperation with the Comision Ejecutiva Hidroelectrica del Rio Lempa (CEL) and the Los Alamos National Laboratory, has developed a hydrogeological model of the Ahuachapan geothermal field in El Salvador, Central America. The model is based upon data on the geologic/stratigraphic structure and initial thermodynamic conditions of the field.

This paper describes the hydrogeological model in terms of geological cross sections, the inferred faults and their effects on fluid flow, the various aquifers present and their temperature distributions.

GEOLOGIC SETTING OF AHUACHAPAN

El Salvador is almost entirely underlain by Tertiary to Holocene volcanic rocks and debris. From the Pacific Ocean toward the north, the country can morphologically be divided into five regions: the Coastal Plains, the Coastal Ranges, the Pacific Volcanic Chain, the Great Interior Valley (or Central Graben), and the Northern Mountain Ranges.

Of interest here is the Pacific Volcanic Chain, which is a line of young volcanoes that extends across El Salvador parallel to the Pacific Coast. It is closely associated with the high enthalpy geothermal fields in the country. Although Ahuachapán is the only area currently being exploited, exploration is being carried out at the Berlin, Chinameca, Chipilapa, San Vicente, Coatepeque and other areas.

The geologic structure of the Ahuachapan area is strongly influenced by the regional tectonics of Central America, where several lithospheric plates interact with one another (Weyl, 1980). El Salvador is located on the Caribbean Plate which is underthrust by the Cocos Plate. This subduction is responsible for the chain of active volcanos extending between Guatemala and Costa Rica and for the fracture tectonics of the area.

El Salvador is one of the world's most intense seismic areas, giving rise to different interpretations of the country's complex geologic structure. Wiesemann (1975) identified seven fault trends listed as: WNW-ESE, NW-SE, NE-SW, NNE-SSW, N-S, E-W, and NNW-SSE. Most faults are considered normal but those with horizontal displacements are said to be right-lateral on the W-E and WNW-ESE fault zones. The NNE- to NE-trending fault system is considered an important zone of left-lateral strike-slip faulting.

The Ahuachapán field is located in the northwestern sector of the Laguna Verde volcanic complex, on the southern flank of the Central Salvadorean Graben. It is about 5 km northwest of Laguna Verde, an extinct, andesitic, stratovolcano, approximately 1800 masl.

METHODOLOGY

This study has been undertaken to better define the stratigraphy and the fault/fracture characteristics in the geothermal system. This information is needed for the evaluation of fluid movement within the system. Careful analysis of the lithology encountered in the 32 deep wells drilled in the field (Fig. 1) revealed the presence of four major lithologic units (Table 1). The lithologic data were supplemented by temperature and pressure logs, data on loss of circulation zones, assumed aquifer locations, and core data. Mineralogical and geochemical data were contoured and the results compared to the inferred fault map (Aunzo et al., 1989). Cross-sections with their corresponding isotherms were drawn through the area. Previous structural maps of the area were analyzed as well as numerous papers and unpublished reports.

Table 1.
Lithologic units and aquifers identified at Ahuachapán

Formation	Rock Type	Unit	Aquifer
San Salvador (Quaternary)	colluvium, altered pyroclastics and lavas (Holocene)	Surficial Materials	Shallow Aquifer
	pyroclastics, andesites (Pleistocene)	Young Agglomerates	Regional Saturated Aquifer
	andesites, tuffs (Plio-Pleistocene)	Ahuachapán Andesites	Saline Aquifer (reservoir)
Balsamo (Pliocene)	breccias, agglomerates andesites	Older Agglomerates	Saline Aquifer

GEOLOGIC MODEL

Lithology

The known lithologic column at Ahuachapán consists mostly of the San Salvador Formation (Table 1) with only the basement rock from the Balsamo. The column has previously been divided into the following units: upper brown tuff, gray ignimbrite, pink ignimbrite, lower brown tuff, gray agglomerate, blue ignimbrite, old andesitic lavas, and ancient agglomerate (Jonsson, 1970). For this study, four major units have been defined, which are similar to those of Aumento et al. (1982). These are: Surficial Materials (SM), Young Agglomerates (YG), Ahuachapán Andesites (AA), and Older Agglomerates (OG).

The Surficial Materials occur in the top 100-150m and contain the "Shallow Aquifer". Beneath this unit there is a sequence of young pyroclastics and andesites, 300 to 800 m thick. These are the Young Agglomerates where losses in circulation are attributed to the "Regional Saturated Aquifer". Below these rocks one finds the Ahuachapán Andesites, a highly fractured 200 to 600 m thick unit that hosts the "Saline Aquifer," which is the main geothermal reservoir. The permeability of this unit is enhanced by columnar jointing and contact surfaces. The lower part of the Younger Agglomerates is highly hydrothermally altered, forming an impermeable barrier between the Saturated and Saline Aquifers. The Older Agglomerates (basement rocks) consist of dense breccias, agglomerates and andesites with little matrix permeability, but some fracturing.

Faults

The structure of the Ahuachapán field appears to be dominated by seven major and five minor faults (Fig. 2). These faults have been identified on the basis of lithologic logs, aerial photographs and existing structural maps.

The Surficial Materials are rarely displaced by the faults.

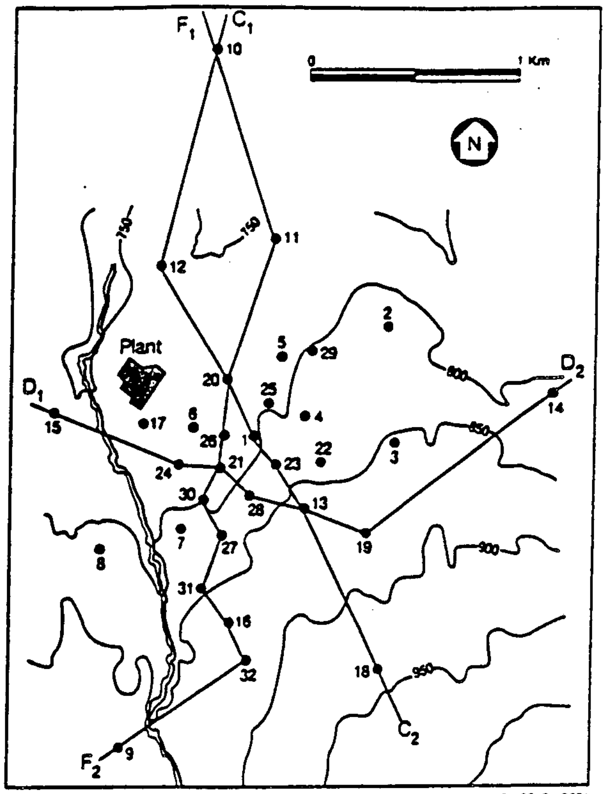

Figure 1. Location of the geothermal wells and cross-sections in the Ahuachapan geothermal field.

Young Agglomerates are of fairly uniform thickness except in wells AH-18 and AH-32, which is believed to be due to a high-angle reverse fault (Fault 10), and in AH-14 on the outskirts of the field. Within the wellfield, the Ahuachapan Andesites are fairly uniform in thickness with small displacements due to recent faulting. However, near the boundaries of the field these andesites have not been found (e.g., in wells AH-8, AH-9, and AH-10). In wells AH-2, AH-11, AH-12, AH-14, AH-18, AH-19, and AH-32 the Ahuachapan Andesites are found at a lower elevation than in the center of the wellfield. The Older Agglomerates are not penetrated by most of the wells so their extent is largely inferred. However, in AH-8, AH-9, and AH-10 these agglomerates are found at the elevation usually occupied by the Ahuachapan Andesites. This suggests an unconformity and a possible erosional surface.

HYDROGEOLOGIC MODEL

Aquifers

Three aquifers have been identified at Ahuachapán: the Shallow Aquifer, the Regional Saturated Aquifer, and the Saline Aquifer. This classification is based on the chemistry of the fluids and the pressure response of the aquifers to seasonal variations in precipitation. The three aquifers appear to coincide with the lithologic units discussed above (Table 1).

The Shallow Aquifer is unconfined and shows very rapid response to precipitation. The waters are generally of calcium carbonate type, locally sulfatic with residues below 0.5 gm/l (Romagnoli et al., 1976). In the wellfield the temperatures in this aquifer range from 40° to 100 °C, with decreasing temperatures toward the north.

The Regional Saturated Aquifer is recharged by direct infiltration but its response to variations in rainfall is much slower than that of the Shallow Aquifer. The water is of calcium-sodium carbonate type, with residues generally below 0.4 g/l (Romagnoli et al., 1976). In the wellfield the temperatures in the Regional Saturated Aquifer range from 110° to 130 °C (Aunzo et al., 1989), decreasing toward the north where a temperature of 46 °C was recorded in M-1, an exploratory drill hole.

The Saline Aquifer (geothermal reservoir) is thought to be recharged from the volcanic belt of Laguna de las Ninfas-Laguna Verde and Cerro de las Ranas, southeast and east of the wellfield. In this belt, deep water infiltration is facilitated by the presence of highly permeable volcanic chimneys. The waters of the Saline Aquifer are of sodium chloride type and high salinity (residues up to about 22 g/l; Romagnoli et al., 1976). The temperatures range from 214° to 240 °C in the reservoir with inferred minimum recharge temperatures of 245° to 250 °C (Aunzo et al., this volume).

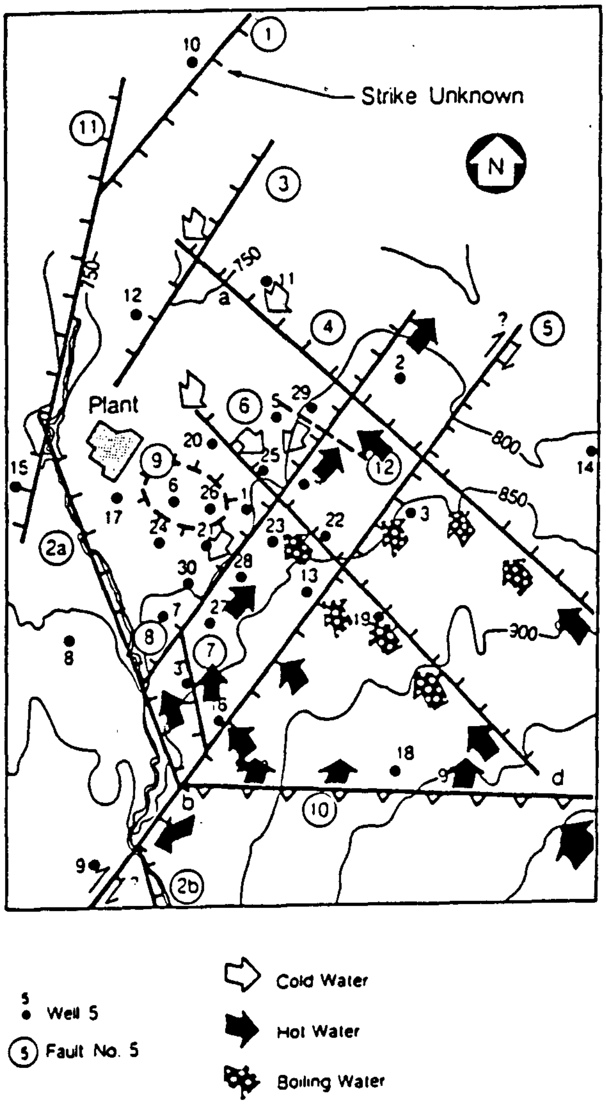

Figure 2. The faults and inferred flow channels in the Ahuachapan field.

Initial Thermodynamic Conditions

The initial pressure in the different aquifers reflect limited hydraulic communication between them as their hydraulic potentials are different (Fig. 3). The hydraulic potential is lowest in the Saline Aquifer and therefore there is a potential for cold water recharge into the reservoir from the overlying Saturated Aquifer. Within the geothermal reservoir (Saline Aquifer) there is no significant variation in hydraulic potential; and at the reference level of 200 masl the pressure is about 36 bar-g. Some of the cold peripheral wells (e.g. wells AH-10, AH-12, AH-15), which are not in hydraulic communication with the geothermal reservoir, have pressures exceeding 40 bar-g at the 200 masl level.

Figures 4 and 5 show the initial temperature distributions at Ahuachapan for 200 masl and sea level elevations, respectively. Both of these distributions basically reflect temperatures in the Ahuachapan Andesites. At 200 masl

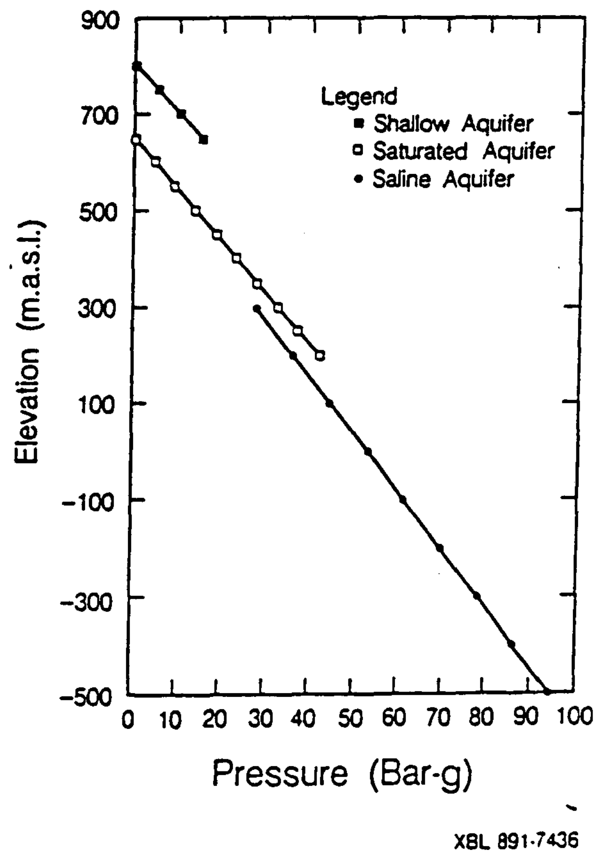

Figure 3. Plots of fluid pressure vs. elevation for the different aquifers.

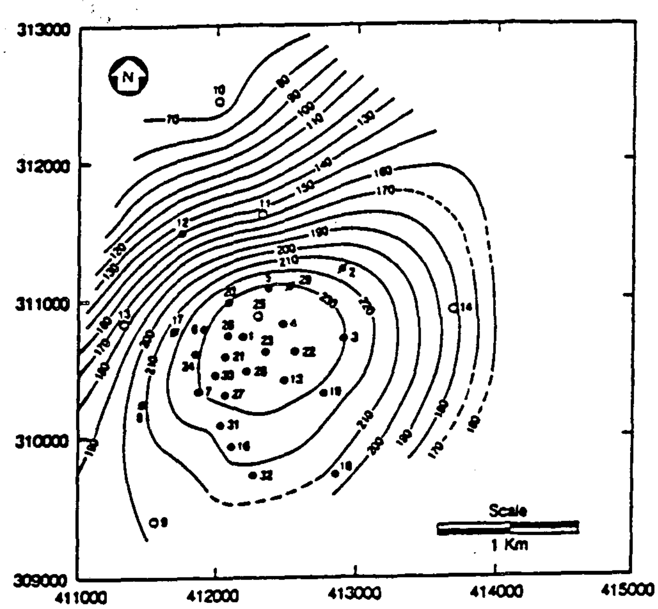

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Figure 4. Initial temperatures distribution (in °C) at 200 masl.

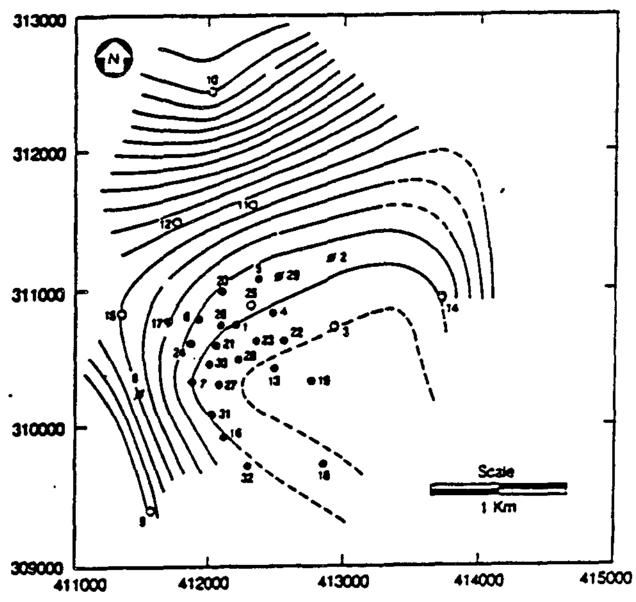

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Figure 5. Initial temperature distribution (in °C) at mean sea level elevation.

the highest temperatures are found in the center of the wellfield (230-235°C), whereas at sea level elevation the highest temperatures (240-245°C) are found in the southeast part of the wellfield. This clearly suggests that the upflow zone is southeast of the present wellfield, probably beneath the Laguna Verde volcanic complex. Exploitation has greatly affected the thermodynamic conditions of the system as discussed by Steingrimsson et al. (this volume).

Fluid Movement

In the field, the groundwater flow in the Shallow Aquifer is not significantly affected by the faults since few movements have been recent enough to displace the Elluvials. A study of well circulation losses suggests a rather uniform permeability in these less consolidated materials.

In the Regional Saturated Aquifer groundwater flow tends to be influenced by the fault pattern. The role of Faults 4, 5, and 6 seems to be especially important (Fig. 2), as indicated by the lost circulation zones observed during drilling.

The flow in the geothermal reservoir is also controlled by the faults. Most notably to the north and west, where Faults 3 and 11 act as barriers and limit the extent of the reservoir. Fault 4 is seen to cause similar effects to the northeast. This is strongly supported by the temperature distributions in the reservoir (Figs. 4 and 5). Other faults act primarily as conduits to flow rather than flow barriers.

Several geologic cross sections have been developed and illustrate the lithology, faulting and temperature distribution in the field (Figs. 6, 7 and 8). The locations of these cross sections are shown in Figure 1. Cross section $C_1 - C_2$ (Fig. 6) traverses the field from north to south. The sharp decline in temperature north of Fault 3 indicates that it acts as a barrier to flow, although the Ahuachapan Andesites are found north of this fault; north of Fault 1 the AA unit is not found. The isotherms clearly show that the Young Agglomerates act as a caprock to the system and the increasing depth to the reservoir (the AA unit) toward the south. The faults offset the AA from 50 to 200 meters. The cross section shows that in the natural state a small two-phase zone was present in the reservoir.

Cross section $D_1 - D_2$ (Fig. 7) represents an west-east traverse of the field. The isotherms indicate that Fault 2a acts as a barrier to the hot water flow, resulting in low temperatures in well AH-15. Only a thin AA unit is found in this well. The section also shows continuity of the reservoir to the east, although the depth to the AA is somewhat greater. In the center of the wellfield, the isotherms suggest reversals in many of the wells, although the extent of the reversals is poorly known due to the limited well depths. The cross section shows a good correlation between temperature contours and lithology.

Cross section $F_1 - F_2$ (Fig. 8) spans the field from the north to the southwest. Due to the circuitous route of this section several of the faults are crossed twice. This does not include Fault 9 which bounds the dome-like structure around wells AH-6 (not shown) and AH-26. Faults 1 and 2b displace the AA unit, which is not found in wells AH-9 and AH-10. This cross section again shows the inferred two-phase zone, evidence of temperature inversions and the good correlation between temperatures and lithology.

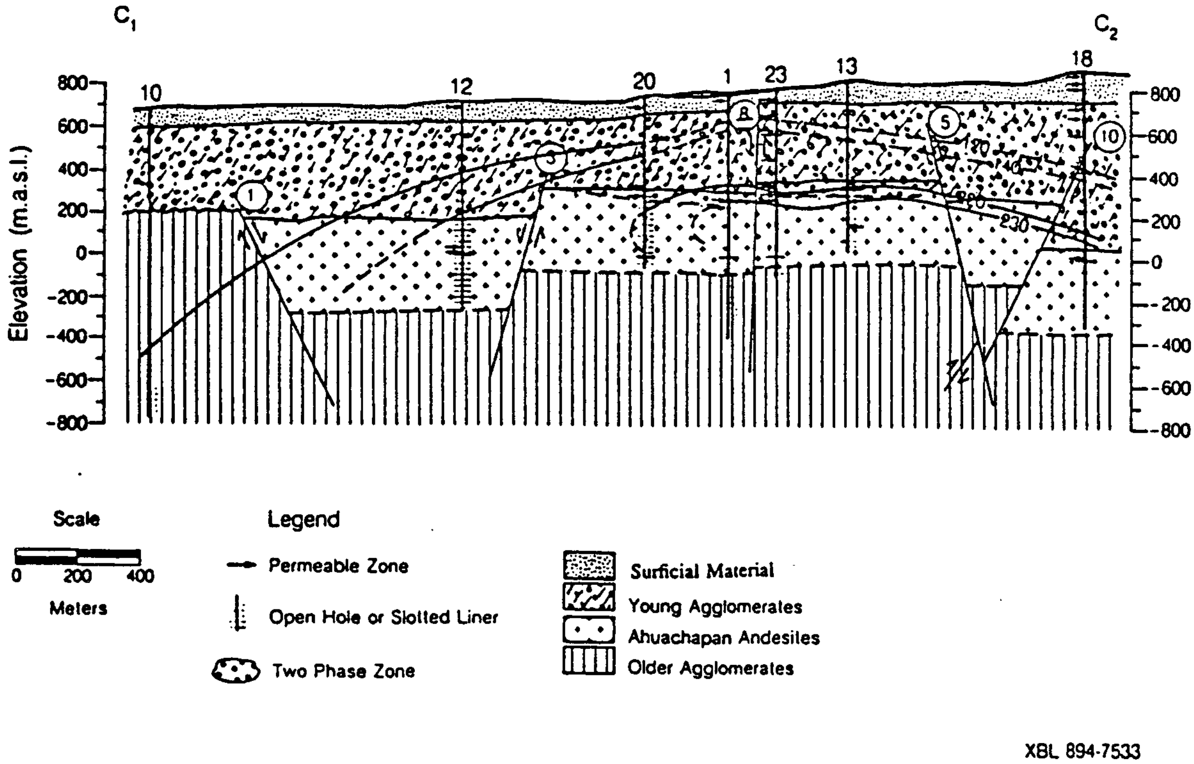

Figure 6. Section $C_1 - C_2$: cross-section through wells AH-10 to AH-18 showing lithology, faults, and isotherms.

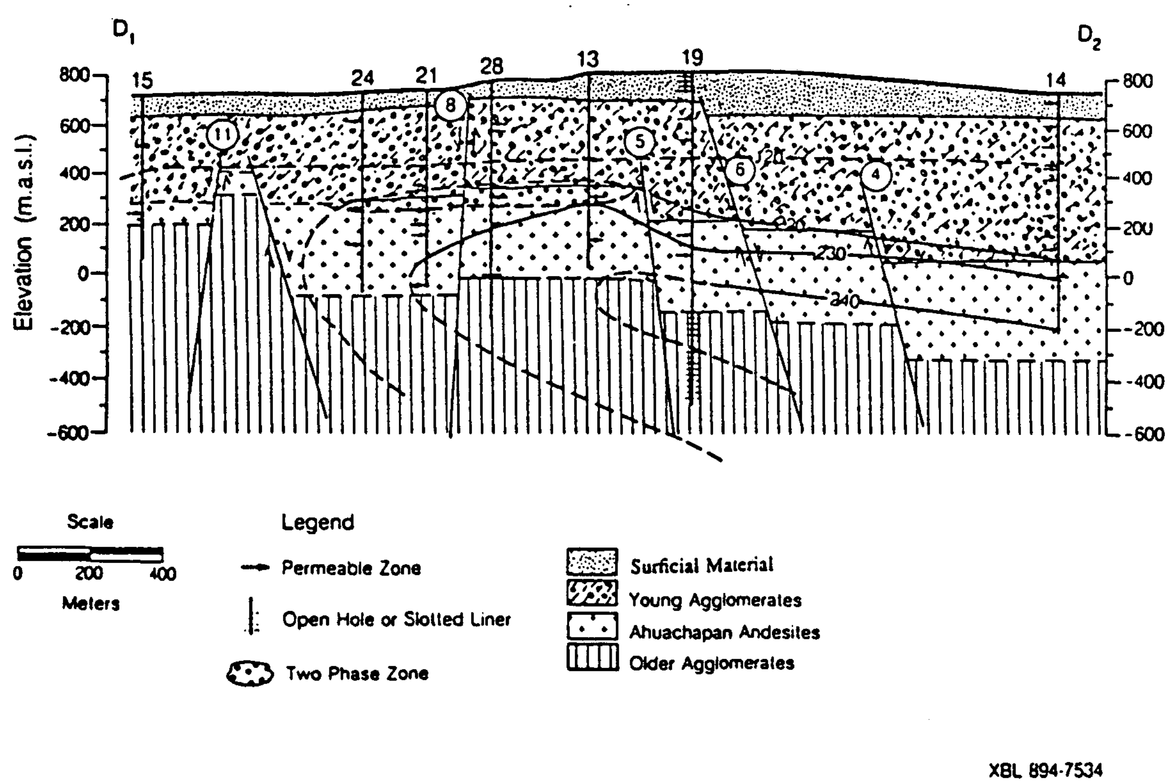

Figure 7. Section $D_1 - D_2$: cross-section through wells AH-15 to AH-14 showing lithology, faults, and isotherms.

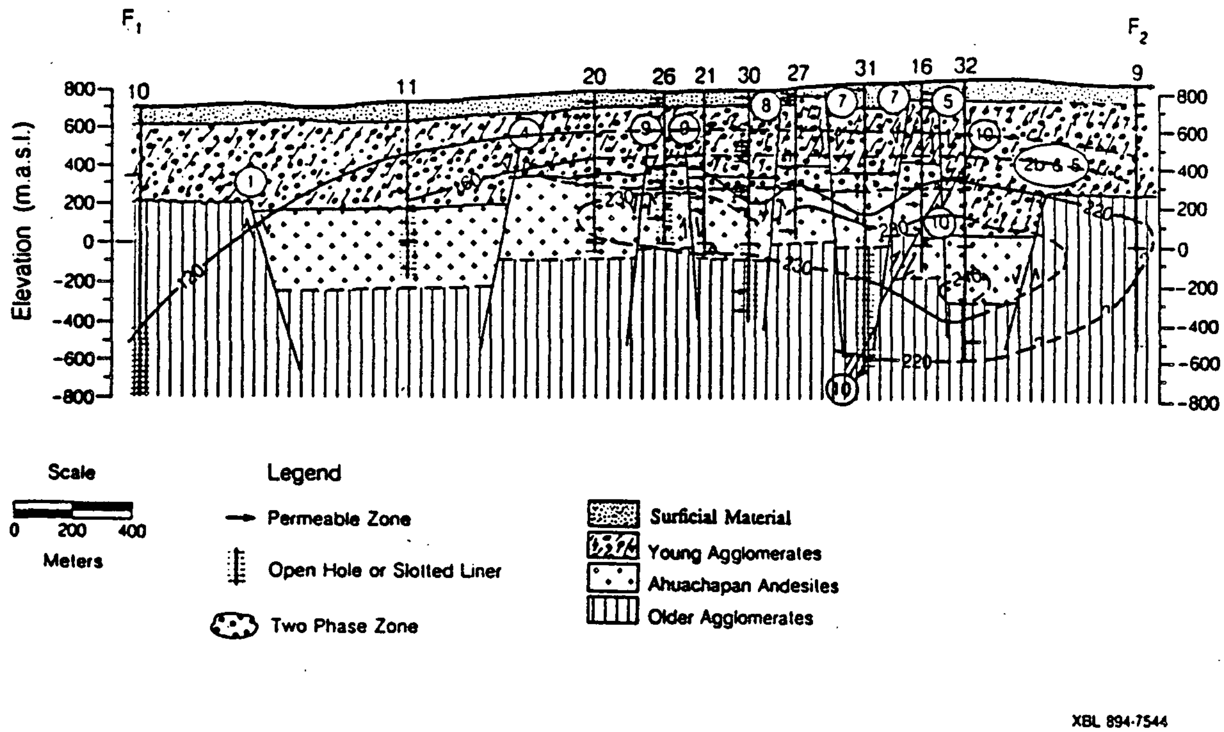

Figure 8. Section $F_1 - F_2$: cross-section through wells AH-10 to AH-9 showing lithology, faults, and isotherms.

THE AHUACHAPAN–CHIPILAPA GEOTHERMAL SYSTEM

In the vicinity of Ahuachapan, geothermal surface manifestations are spread over more than 100 km^2 (Fig. 9). These manifestations can be divided into high temperature fumaroles and steaming grounds on the northern slopes of the volcanoes located in the southern part of the area, and hot (40-100 °C) springs on the plain north of Ahuachapan.

The major fumaroles are: Cuyanausul on the northern slopes of Cerro Cuyanausul, east of Laguna Verde (outside the area shown in Fig. 9); El Sauce on the northern slopes of Laguna Verde; Agua Shuca and Playon de Ahuachapan near the wellfield; and La Labor in the Chipilapa region. Chemical analyses of gas samples from Ahuachapan and Chipilapa show similar gas composition indicating a common geothermal source fluid (Sigvaldason and Cuellar, 1970). A marked increase in hydrogen content in fumarole steam toward the southeast suggests that the geothermal upflow zone is located in the area of nearby volcanoes, probably the Laguna Verde volcano. Data from Ahuachapan and Chipilapa wells suggest that the source fluid is highly saline (more than 8000 ppm Cl) and that the upflow temperatures are above 250 °C (Aunzo et al., this volume).

The relationship between Ahuachapan and Chipilapa has been disputed over the years. Early drilling showed identical fluid chemistry and similar reservoir temperatures (Sigvaldason and Cuellar, 1970). Later, a resistivity survey of the area indicated a high-resistivity body (barrier) that separated the two fields. Recent resistivity studies, however, do not show this barrier. The previous interpretation is believed to be in error because of incorrect elevations used in the data analyses (James Fink, personal communication, 1988). The data seem therefore to indicate that the two fields are connected and fed by the same geothermal source. The ultimate proof of this connection would be pressure interference between the wells drilled in the two areas. The simple reservoir model used to match the drawdown history of Ahuachapan (Aunzo et al., 1989) predicts a drawdown in Chipilapa of a few bars due to fluid extraction in Ahuachapan that began in 1968. However, as the wells in Chipilapa are plugged at shallow depth this cannot be confirmed.

The hot springs on the plain north of Ahuachapán are at elevations below 580 masl, generally producing fluids from the Regional Saturated Aquifer (Sigvaldason and Cuellar, 1970; Cuellar et al. 1981). The maximum elevation of these springs matches with the pressure potential of the Regional Saturated Aquifer in Ahuachapán where 600-660 masl water levels are found. An exception to this is the main hot spring area, El Salitre, about 7 km north of Ahuachapán where more than 1000 L/s of 68-70 °C water used to be discharged. The fluid of these springs was, prior to exploitation at Ahuachapán, higher in dissolved solids (especially chloride) than that of the Regional Saturated Aquifer. The original chemistry of El Salitre has been explained to be due to mixing of the fluid from the Regional Saturated Aquifer with 10-20 percent of geothermal fluids with considerable steam heating (Glover, 1970; Sigvaldason and Cuellar, 1970).

The hydrologic model discussed above is summarized in the simplified illustrations shown in Figure 9. It is thought that an upflow of saline, high temperature (above 250 °C) fluid occurs underneath the volcanoes (probably Laguna Verde), southeast of Ahuachapan. From the upflow zone, fluid channels toward the north. A fraction of it flows toward the northwest and enters Ahuachapan near the southeast corner of the wellfield, as suggested by the shape of isotherms and increasing temperatures in AH-18 (Steingrimsson et al., this volume). Another fraction flows toward the east to Chipilapa, however the main stream mixes with fluids from the Saturated Aquifer and is discharged through several hot springs at the El Salitre area.

SUMMARY

Our present understanding of Ahuachapan suggests that the field is only an outflow of a deeper and much larger system and that the reservoir extends much farther to the east and southeast (Fig. 9). The main characteristics of the system are:

1) The Ahuachapan-Chipilapa system is recharged by an upflow zone southeast of the Ahuachapan wellfield, probably beneath the Laguna Verde volcanic complex. The temperature of this upwelling fluid is believed to be 250 °C or higher, as suggested by geochemical temperatures of the discharged fluid (Truesdell et al., this volume).

2) Most of the upwelling fluids flow to the north with the main outflow for this system being in the El Salitre springs area, located about 7 km north of the wellfield. The discharge is a mixture of geothermal and Regional Saturated Aquifer fluids, the mixing believed to occur in the vicinity of the springs rather than close to the geothermal field.

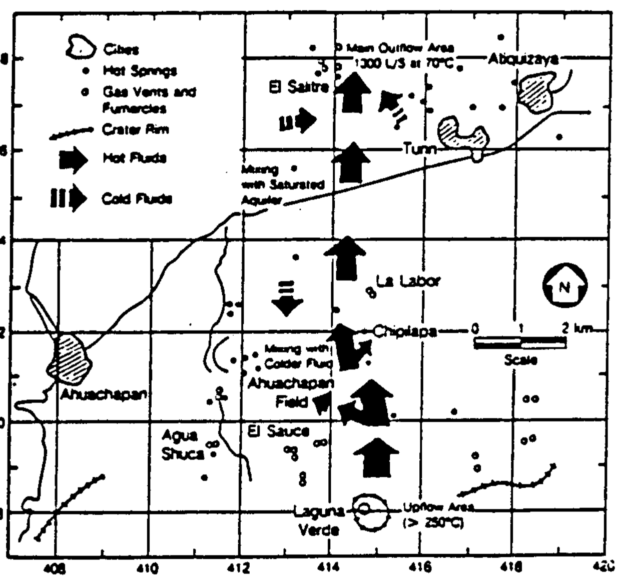

Figure 9. Fluid flow in the Ahuachapan/Chipilapa geothermal system.

3) Colder fluids recharge the Ahuachapán reservoir as evidenced by variations in chloride concentrations in the field. The cold water inflow is either laterally from the north or vertically downwards from the Regional Saturated Aquifer, which overlies the main reservoir and has a higher pressure potential.

4) The main reservoir rocks are the Ahuachapan Andesites and the underlying Older Agglomerates. Most of the produced fluids come from the andesites, although the permeability of the Older Agglomerates is significant, as evidenced by several feed zones encountered in this unit.

5) Faults limit the extent of the Ahuachapan reservoir toward the north and the west. The temperature reversal in well AH-32 also suggests that the extent of the field is limited toward the south.

6) The Ahuachapan and Chipilapa fields seem to communicate at depth and to be outflow zones of a large geothermal system.

ACKNOWLEDGEMENTS

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