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MODELING STUDIES OF THE AHUACHAPAN GEOTHERMAL FIELD, EL SALVADOR

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ABSTRACT

Modeling studies of Ahuachapan include analyses of interference test data, modeling of the fieldwide pressure decline and the development of a three-dimensional natural state model of the field. The main objective of this work is to obtain reasonable estimates for the transmissivity and storativity of the reservoir and to investigate fluid and heat flow patterns in the system.

The analyses of the interference test data and the long term pressure decline data indicate that the average reservoir transmissivity is about 30 Dm and the storativity about 3.5×10^{-6} m/Pa. The natural state modeling supports an overall average transmissivity of 25-35 Dm and indicates that the system is recharged with 255 °C hot water at a rate of about 225 kg/s. The total thermal throughflow for the Ahuachapan system is estimated to be about 250 MW_t.

INTRODUCTION

The Ahuachapan geothermal field in El Salvador has been producing electrical power since 1975. A total of 32 wells have been drilled in the area. The installed plant capacity is 95 MWe, but because of limited replacement well drilling and significant reservoir pressure drawdown a total of about 45 MWe is currently being generated.
Lawrence Berkeley Laboratory (LBL), in cooperation with Los Alamos National Laboratory (LANL) and Comision Ejecutiva Hidroelectrica del Rio Lempa (CEL), is performing reservoir evaluation studies of Ahuachapan. The main objective of this work is to evaluate the available data and conduct mathematical modeling studies aimed towards increasing the steam production and the power generation of the field. Three other papers in this volume summarize related work, including a hydrogeological model of Ahuachapan (Laky et al., 1989), geochemical analysis (Truesdell et al., 1989), and evaluation of exploitation effects (Steingrimsson et al., 1989). Some of their important findings in relation to the modeling studies are summarized below.

Hydrogeology

Four major Lithologic units are present at Ahuachapan. From top to bottom, they are the Elluvials (EL), Young Agglomerates (YA), Ahuachapan Andesites (AA) and Older Agglomerates (OA). The Elluvials are composed of colluvium and a series of altered pyroclastics and lavas. The Young Agglomerates, found below the EL, are composed of pyroclastics and andesites ranging in thickness from 300 to 800 m. The bottom of this unit is highly hydrothermally altered, forming a permeability barrier between the YA and the underlying Ahuachapan Andesites, a highly fractured unit that presents the most permeable horizons. The thickness of the AA ranges from 200 to 600m. The underlying Older Agglomerates are a combination of dense breccias and andesites, with low matrix permeability but some fracturing. Three aquifers identified in the field appear to coincide with the different lithological units. These aquifers are the Shallow Aquifer (found in EL), the Saturated Aquifer (found in YA) and the Saline Aquifer, the geothermal reservoir, (found in AA and OA). The geologic structure of the Ahuachapan field appears to be dominated by seven major and four minor faults. These faults control the heat and fluid recharge and the flow within the reservoir (Laky et. al., this volume).

Geochemistry

Analyses of the Ahuachapan well discharges yield valuable data on the initial reservoir condition and processes. The chloride distribution, with a range from 6100 ppm to 8600 ppm, shows increasing chloride from east to west. The geochemical temperatures show the same trends and range from 233 °C to 262 °C. This suggests mixing of cooler, low-salinity fluid in the east; these cooler fluids may recharge the field from the north or downward from the overlying Saturated Aquifer in the eastern part of the wellfield (Truesdell et al., this volume).

Initial Temperature and Pressure Distribution

The pre-exploitaton pressure distribution in the reservoir was near-uniform with values in the range of 32-36 barg at 200 masl. The overlying Saturated Aquifer has a pressure potential about 4-8 bars higher than the geothermal reservoir.

Temperatures exceeding 240 °C are found in the AA and temperature inversions are observed in most wells when entering the OA. All productive wells show similar profiles, with the top of the convective gradient coinciding with the top of the AA. Increasing temperatures are observed toward the southeast, where the highest reservoir temperature (245 °C) has been measured. This suggests hot fluid recharge from the southeast into the field.

Fluid Movement

It is believed that upflow of saline, high temperature (above 250 °C) fluids occurs underneath the nearby volcanic complex (probably Laguna Verde), southeast of Ahuachapan. Only a small fraction (approximately 10%) of the upwelling fluids feed the production area at Ahuachapan. Some of the fluids feed the nearby Chipilapa field, but the majority discharges 10 km to the north at El Salitre Springs. Faults restrict fluid flow to the north and west of the Ahuachapan field (See Figure 7 in Laky et al., this volume).

INTERFERENCE TESTING

Several interference tests have been conducted at Ahuachapan. One such test was carried out during the period from May 6 to August 19, 1982, to obtain data for determining the reservoir transmissivity and storativity.

During the test period the produced fluids were reinjected into wells AH-2, AH-8, and AH-29. Well AH-25 was used as an observation well; its pressure response is shown in Figure 1. Because most of the Ahuachapan wells were flowing for an adequately long time prior to the test, the wellfield pressures were in a state of quasi-equilibrium. Thus, those wells with no changes in flow rates during the test were not considered in the analysis. Table 1 gives the flow rates of the producers and injectors that affected the pressure response in AH-25 during the test period.

In the analysis the computer model VARFLOW, developed at the Lawrence Berkeley Laboratory (EG&G and LBL, 1982), was used. The program calculates pressures at each observation point by superimposing the pressure transients, calculated using the Theis solution, of all producers/injectors. The program can handle variable flowrates, an anisotropic medium and a single linear hydrologic boundary. The reservoir transmissivity and the storativity were varied until a reasonable match to observed pressures at well AH-25 was obtained. The best match between the observed and computed pressure is shown in Figure 1. For this calculation, a reservoir

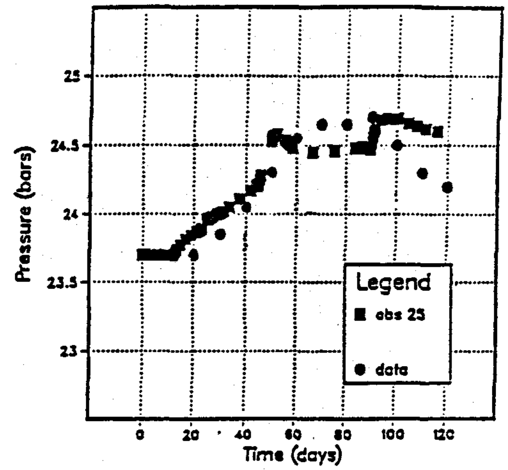

Figure 1. Match between observed and computed pressures at well AH-25 for the May-August 1982 interference test.

transmissivity of 25 Dm and a storativity of 2.5×10^{-6} m/Pa were used.

If one assumes an effective reservoir thickness of 300 m and a porosity of 10%, a total compressibility of about 1×10^{-7} Pa^{-1} can be computed from the storativity. This compressibility value is about two orders of magnitude higher than that of water at 240 °C and about two orders of magnitude lower than two-phase compressibility at 240 °C, which is reasonable given the partial two-phase conditions of the reservoir.

PRESSURE DRAWDOWN HISTORY MATCH

Pressures in Ahuachapan wells were fairly uniform prior to exploitation; production has caused significant drawdown (approximately 15 bars). Drawdown has been monitored by annual pressure surveys in all wells accessible to logging, and by daily pressure measurement at 200 masl in well AH-25.

The pressure history of Ahuachapan has been simulated using simplified models of the field. Grant (1980) did modeling studies in an attempt to match the 1975-1978 pressure changes resulting from fluid extraction. The results did coarsely match the observed pressure history, and both a high storativity coefficient and permeability were necessary to achieve reasonable matches.

In the present study, a simple model was used to match the pressure history of Ahuachapan. The main objective of this work was to obtain coarse estimates of the average reservoir transmissivity and storativity, to be used as initial input parameters for the natural state model. The model assumes an isothermal, horizontal, homogeneous, fully-saturated porous medium reservoir of constant thickness and of infinite areal extent. The system is closed above and below by impermeable boundaries and all wells were assumed to fully penetrate the reservoir. The data were analyzed using the VARFLOW code.

Table 1

Ahuachapan Flow Rates of Reinjection (R) and Producing (P) Wells in (kg/sec) 1982 Interference Test									
Date	AH-2 R	AH-4 P	AH-8 R	AH-20 P	AH-21 P	AH-22 P	AH-23 P	AH-24 P	AH-26 P
May 6	-19.8	45.1	-33.9	37.8	72.9	56.6	31.3	37.5	23.1
May 15	-19.8	45.1	0.0	37.8	72.9	56.6	31.3	37.5	23.1
May 17	-19.8	45.1	0.0	0.0	72.9	56.6	31.3	37.5	23.1
May 26	-19.8	45.1	0.0	0.0	0.0	56.6	31.3	37.5	23.1
June 1	-28.3	50.8	0.0	0.0	0.0	57.7	49.0	35.9	22.5
June 3	-28.3	50.8	0.0	0.0	0.0	57.7	49.0	0.0	22.5
June 19	-28.3	50.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
June 25	-28.3	50.8	0.0	0.0	0.0	57.7	49.0	0.0	22.5
July 1	-42.2	63.2	0.0	0.0	0.0	58.5	49.8	0.0	21.5
Aug. 1	-53.4	74.2	0.0	0.0	0.0	57.7	50.1	0.0	40.0
Aug. 2	-53.4	74.2	0.0	0.0	82.5	57.7	50.1	40.0	40.0
Aug. 3	0.0	74.2	0.0	0.0	82.5	57.7	50.1	40.0	40.0
Aug. 29	0.0	74.2	0.0	0.0	82.5	57.7	50.1	40.0	40.0

Figure 2 shows the best match of the pressure history in observation well AH-25, obtained for a medium with a transmissivity of 35 Dm and a storativity of 3.5×10^{-6} m/Pa. The model was assumed to have an impermeable N-S boundary near well AH-15, as suggested by field data. The calculated drawdown matches reasonably well the observed pressures, especially for the period up to 1969-1983. The disagreement in later years could be explained by a change in field production pattern. Other possible causes are the effects of a two-phase zone in the reservoir, and the fact that a model using a uniform permeability value is not likely to match well the behavior of this complex heterogeneous fractured system. However, the reservoir parameters obtained are consistent with those inferred from the interference test analysis.

In order to estimate the effects of reinjection that occurred from 1976 to 1982 on the pressure drawdown at Ahuachapan, the pressure history was simulated without considering any reinjection. The results are shown in Figure 3 for well AH-25. The figure shows that reinjection provided significant pressure support, with about 4 bars less pressure drawdown at the end of the reinjection period than if no injection had occurred. The figure also shows that with continued production the effects of the reinjection period became gradually smaller.

NATURAL STATE MODEL

The simulation work was carried out using the numerical model MULKOM (Pruess, 1983) with the following objectives:

1. to verify the conceptual model of the system.
2. to quantify the natural mass and heat flow in the reservoir.
3. to better understand the hydrology of the field.
4. to obtain a coarse estimate of the permeability structure of the field.
5. to obtain proper initial conditions for the exploitation modeling.

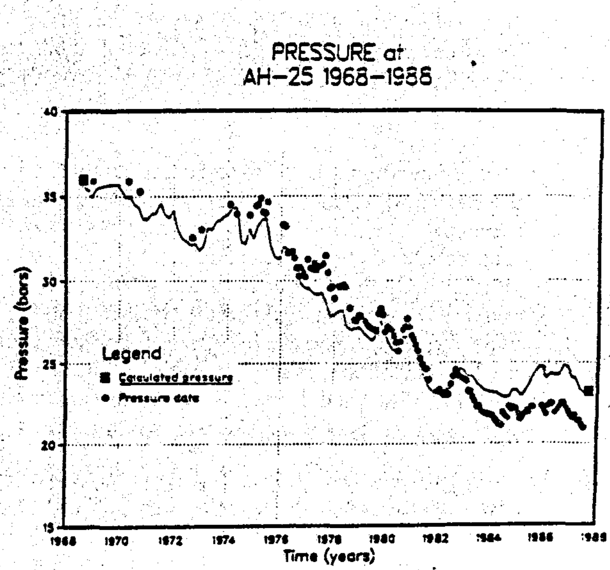

Figure 2. Pressure history match for well AH-25.

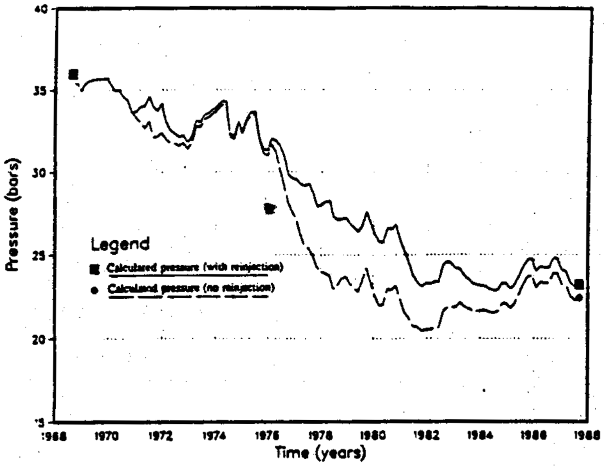

Figure 3. Comparison of pressure decline with or without reinjection.

Approach

The natural state model of Ahuachapan should represent all important features of the conceptual hydrogeological model of the field as defined by Laky et al. (this volume):

1. Hot fluid recharge into the production site occurs southeast of well AH-18. The temperature of the recharge fluids must exceed 250 °C. (See Figure 7 in Laky et al., this volume).
2. The bulk of the hot fluids flow towards the north, with only small fractions of the total flow recharging the Ahuachapan and the nearby Chipilapa reservoirs. The main outflow for the system is at El Salitre, some 7 km north of the Ahuachapan field.
3. The Ahuachapan Andesite unit is highly permeable and serves as the main conduit for lateral fluid flow.
4. The reservoir is bounded by low permeability barriers in the west (close to well AH-15) and in the north (towards well AH-10).
5. Relatively cold, low-salinity waters from the north recharge the system in the eastern part of the field.
6. Reservoir fluids are also discharged at various surface manifestations in the Ahuachapan/Chipilapa area.

The computational mesh used in this study consists of a three-dimensional, three layer grid containing 46 elements per layer, covering an area of some 50 km^2. The grid includes the inferred upflow zone, Ahuachapan, Chipilapa, and the outflow area of El Salitre. The thicknesses of the layers were determined based on lithologic and feed zone data. The top of the model is at 350 masl, which approximately coincides with the top of the AA unit. The model extends down to -600 masl. The areal dimensions of the grid are shown in Figure 4.

Few data are available regarding the fluid and heat flow at surface manifestations except for the El Salitre area, which had an estimated flow of 1300 l/s (≈ 1300 kg/s) at 70 °C, with an unknown amount of mixing between geothermal and colder waters (Sigvaldason, et al., 1970). The total energy output from the other surface manifestations was coarsely estimated based on visual observations.

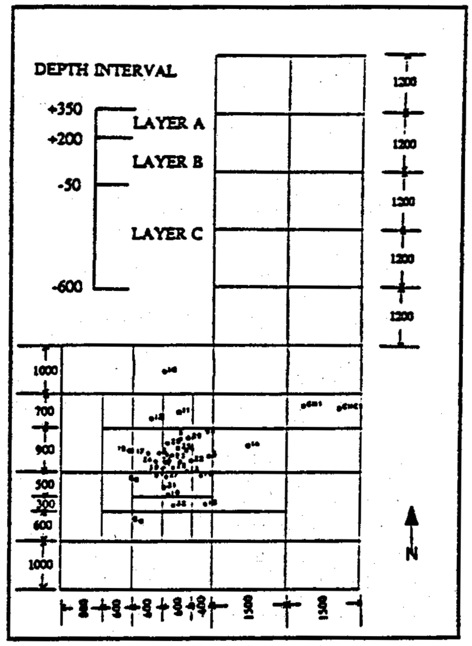

Figure 4. Grid blocks and well locations.

In the model, the surface springs are represented by pressure dependent sinks that were designed so that proper spring outflows would be simulated when the correct pressure distribution was obtained. This feature of the model will be useful in the exploitation simulations to evaluate the spring outputs as a function of reservoir pressure. The conductive heat losses to the surface are computed using an analytical algorithm developed by Vinsome and Westerfeld (1980).

In the simulations, we used a procedure similar to that employed for the Krafla geothermal field (Bodvarsson, et. al., 1984). The adjustable parameters during the modeling iterations were the flowrate and temperature of the upflow zone, spring flowrates and the global permeability distribution. The measured temperatures and pressures in the field were the main constraining parameters. A process of trial and error was carried out until a set of parameters was found that gave reasonable matches with the three-dimensional temperature and pressure distributions. The procedure employed was as follows:

1. Assign sources and sinks to the appropriate nodes,
2. Assign thermodynamic conditions to the cold and hot recharge fluids,
3. Assign rock properties and the permeability distribution,
4. Perform simulation until steady-state thermodynamic conditions are reached,

5. Evaluate the results and return to step 1 if computed temperature and pressure distributions do not fit those observed.

Best Model

A natural state model was developed that reproduces reasonably well the pre-exploitation temperature and pressure in the field. The matches between observed and simulated temperatures and pressures are shown in Figures 5-9. The model, however did not reproduce well the temperatures observed in well CH-1, especially in the lower two layers (Figure 9). The temperature profile used for comparison with the simulated results was obtained in 1969. This is the only log available that penetrates to this depth, and may not show the stabilized temperature conditions in this well.

The simulated results show somewhat colder temperatures than those observed for well AH-15 (Figure 7), which is due to the fact that the well is not in the center of the gridblock, but farther to the east. As temperatures are believed to decrease rapidly west of well AH-15, the temperature profile of this gridblock seems reasonable.

The slight difference between the simulated and observed pressures (simulated pressure are slightly higher; Figure 5) is due to the pressure drawdown caused by well testing during the field development phase (1972-1973). A considerable pressure decline was observed during that period. Although the pressure recovered during the last one and a half years prior to exploitation, the 1974-1975 data (initial pressures) indicate about 1-2 bar lower pressures than in 1968.

The results from the best model indicate that a total flow of 225 kg/s of 255 °C water recharges the system southeast of the wellfield (in the area of the Laguna Verde volcanic complex). The total thermal throughflow for the entire system is estimated to be 250 MW_t. About 60 MW_t are lost through the surface manifestations in the Ahuachapan and Chipilapa areas. Conductive heat losses to the surface are estimated to be about 20 MW_t with the remainder exiting the system by fluid discharge at El Salitre Springs.

Lithology and Permeability Distribution

Four rock types are used in the best model to represent the different lithologic units found in Ahuachapan area (see Figure 10). The material properties used are given in Table 2 and are partly based on data from Larios (1985). Description of these rock types are given below,

Rock Type 1 corresponds to the Young Agglomerates the caprock of geothermal system. The Saturated Aquifer is found in this unit.

Rock Type 2 represents the Ahuachapan Andesites, the main geothermal reservoir.

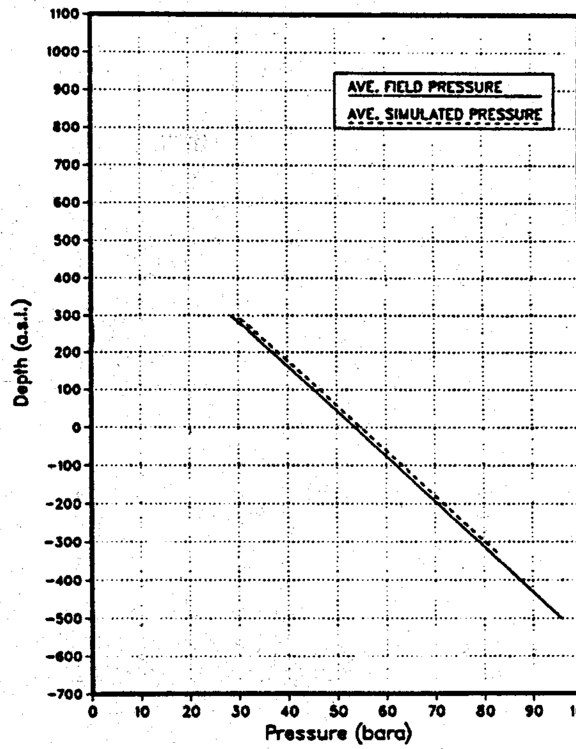

Figure 5. Match between observed and computed pressures for the best model.

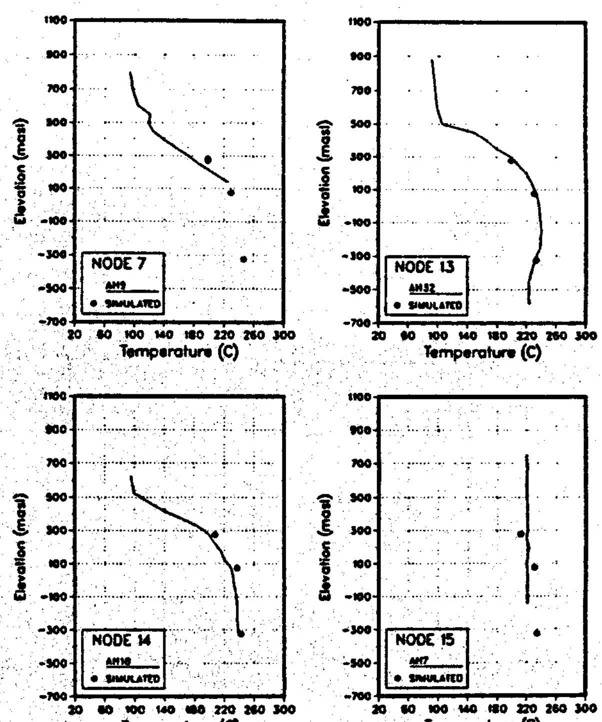

Figure 6. Match between observed and computed temperature profiles for wells AH-9, AH-32, AH-18 and AH-7.

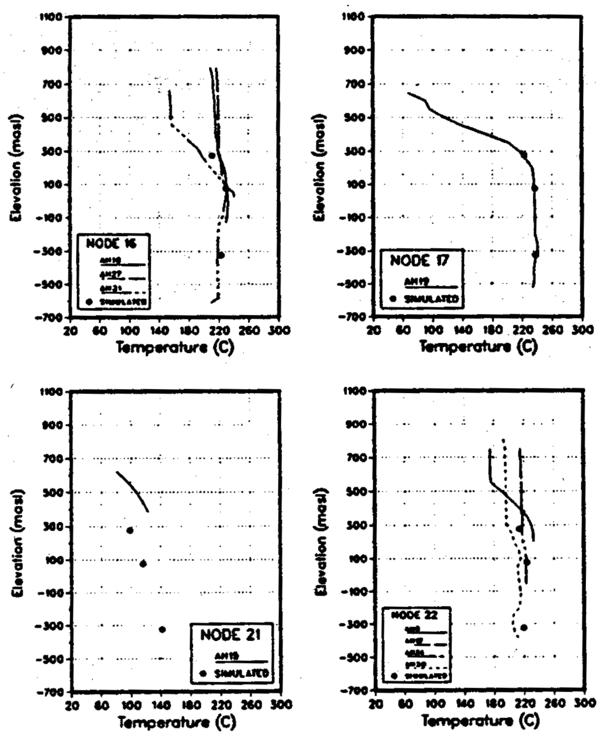

Figure 7. Match between observed and computed temperature profiles for the best model (other wells).

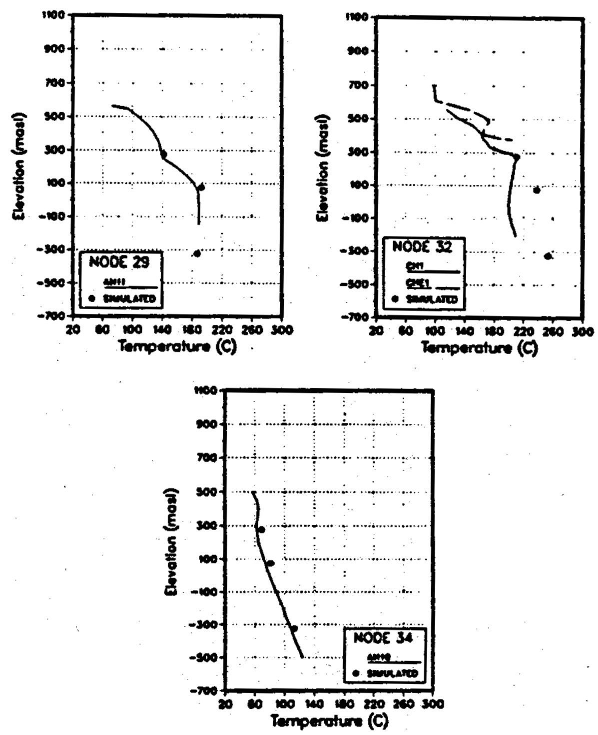

Figure 9. Match between observed and computed temperature profiles for the best model (other wells).

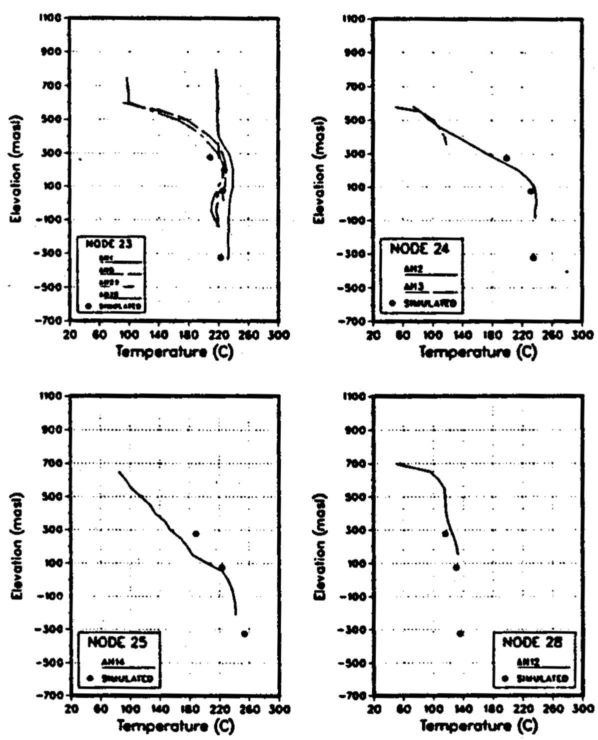

Figure 8. Match between observed and computed temperature profiles for the best model (other wells).

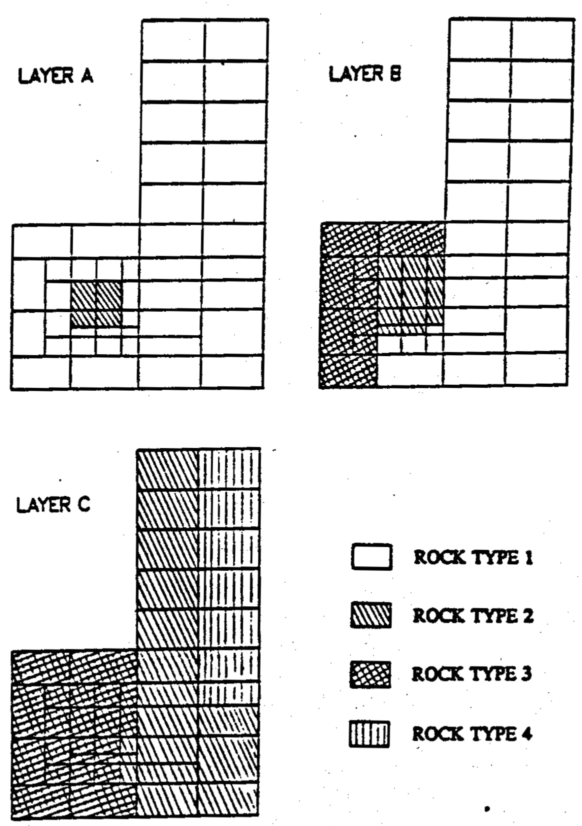

Figure 10. Distribution of rock types for the different layers in the natural state model.

Table 2

Rock Properties Used in the Natural State Model				
	Rock Type 1	Rock Type 2	Rock type 3	Rock Type 4
Density, kg/m^3	2680	2890	2800	2650
Porosity	0.10	0.10	0.05	0.10
Heat Conductivity W/m- °C	2.3	2.3	2.3	2.3
Permeability, md horizontal vertical	 10 0.2	 80 16	 20 4	 20 2
Heat Capacity J/kg- °C	1000	1000	1000	1000

Rock Type 3 represents the Older Agglomerates. In previous studies this unit was considered impermeable, but we believe that this rock unit has a significant permeability, although much lower than the overlying Ahuachapan Andesites. Several wells (e.g. AH-28 and 29) encountered permeable zones in this unit.

Rock Type 4 was used only in Layer C (Figure 10) and corresponds to an agglomerate unit, similar to the YA unit but with higher permeability. This material type was necessary to simulate the inferred high flow from the upflow zone toward El Salitre Springs.

The permeability was used as one of the adjustable parameter in the iteration procedure discussed earlier. Table 2 shows the final permeability values used in the best model; other assumed rock properties are also given. The model results indicate a horizontal permeability for the AA unit (Rock Type 2) of 80 md. Given an average thickness of this unit between 300-400 m, a transmissivity of 24-32 Dm is obtained, which agrees well with the value of 25 Dm obtained from the interference test analysis and 35 Dm estimated from the production history. The low vertical permeability of the YA (0.2 md) agrees well with the assumption that the YA unit acts as a caprock to the system. The low permeability barriers to the north and west were modeled using very low interface permeabilities between appropriate gridblocks.

Sources and Sinks

The locations of sources and sinks in the mesh are shown in Figure 11. The estimated flowrates for the surface manifestation are given in Table 3. The computed flowrate value feeding El Salitre Springs, given in Table 3 (170 kg/s) does not consider any mixing with local groundwater. Assuming local mixing to occur with a 40 °C water at shallower depths, the total flowrate of a 70 °C fluid to that area would be approximately 1290 kg/s, which agrees well with the estimate by Sigvaldason et al. (1970).

Small heat sinks were specified in the blocks with wells AH-32, AH-18, AH-31 and AH-19 in order to match the observed temperature inversions. The strengths of these sinks were 3, 6, 1.5 and 3.75 W/m^2, respectively.

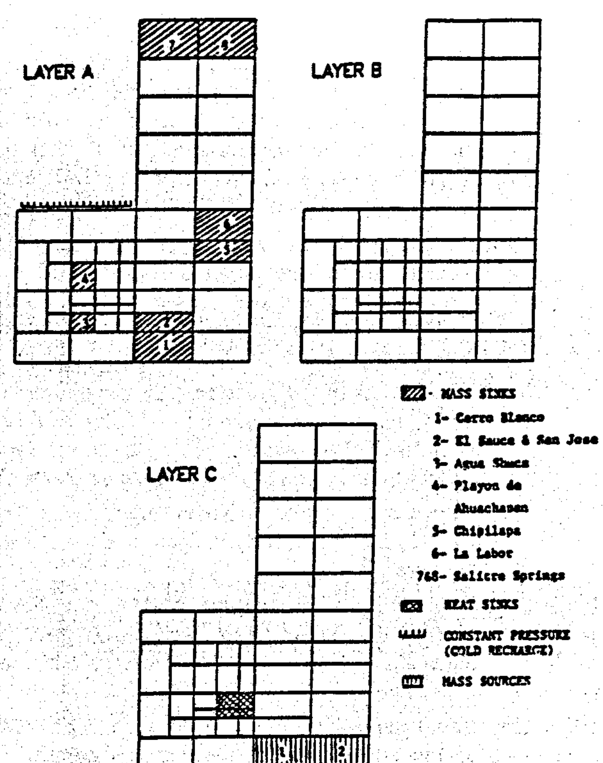

Figure 11. Location of specified sources and sinks in the natural state model.

Table 3

Flow Rates and Heat Outputs of the Different Surface Manifestations		
	Flow (kg/s)	MW_t
Cerro Blanco	5.0	5.1
El Sauce & San Jose	3.4	3.4
Playon de Ahuachapan	20.0	19.0
Agua Shuca	2.2	1.9
Chipilapa	3.5	3.2
La Labor	29.0	28.0
El Salitre	170.0	169.0

Only the outputs associated with geothermal fluids are given (see text).

A source of 60 °C fluid was specified north of AH-10. This was found necessary to match the temperature profile of well AH-10. The cold recharge was modeled using a constant pressure boundary of 42 bars in the uppermost layer (see Figure 11). The pressure at the boundary was specified so that the pressures in the adjacent blocks would be about 5 bars higher than in the rest of the wellfield, which is the observed pressure difference.

CONCLUSIONS

Various modeling studies have been conducted on the Ahuachapan field data including the analysis of interference test data, analysis of the average reservoir drawdown history and the development of a natural state model. The main conclusions of these studies are as follows:

(1) The analysis of the interference test data yields an average transmissivity of about 25 Dm and a storativity of 2.5×10^{-6} m/Pa. This storativity value is consistent with the presence of a two-phase zone in the system.

(2) The analysis of the pressure drawdown data (1969-1988) yields a transmissivity of 35 Dm and a storativity of 3.5×10^{-6} m/Pa. both of these values agree well with the results of the interference test analysis.

(3) Reinjection at Ahuachapan during the period 1976-1982 significantly helped maintain reservoir pressures.

(4) A natural state model of Ahuachapan has been developed that agrees well with the three-dimensional temperature and pressure conditions in the reservoir.

(5) Based upon the model, the horizontal permeability of the Ahuachapan Andesites is estimated to be about 80 md, yielding a transmissivity of about 30 Dm for this unit. This transmissivity is consistent with the results of the interference test analysis and the analysis of the pressure drawdown history. The vertical permeability of the Andesites is estimated to be about 16 md.

(6) The permeability of the Older Agglomerates is estimated to be 20 md horizontally and 4 md vertically.

(7) The total recharge to the Ahuachapan/Chipilapa geothermal systems is estimated to be 225 kg/s of 250 °C water, yielding a total thermal throughflow of 250 MW_t. Most of these fluids discharge in El Salitre Springs (170 kg/s), but significant energy is lost through surface springs in the Ahuachapan/Chipilapa areas (60 MW_t) and through conduction to the ground surface (20 MW_t).

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REFERENCES

Bodvarsson, G. S., Pruess, K., Stefansson, V. and Eliasson, E. T. (1984). "The Krafla Geothermal Field, Iceland. 2. The Natural State of the System," *Water Resources Research, 20*, 11, 1531-1544.

EG&G Idaho, Inc. and Lawrence Berkeley Laboratory (1982). "Low-to-Moderate Temperature Hydrothermal Reservoir Engineering Handbook" Report IDO-10099.

Grant, M. (1980). "Simple Modeling of Production and Reinjection at Ahuachapan," DSIR report, New Zealand, February 1980.

Larios, D. (1985). "Estudio de la Permeabilidad, Porosidad y Densidad de las Rocas del Campo Geotermico de Ahuachapan," CEL report, El Salvador, February 1985.

Laky, C., Lippmann, M. J., Bodvarsson, G. S., Retana, M. and Cuellar, G. (1989). "A Hydrologic Model of Ahuachapan Geothermal Field, El Salvador," this volume.

Pruess, K. (1983). "Development of the General Purpose Simulator MULKOM," 1982 Earth Sciences Division Annual Report, Lawrence Berkeley Laboratory report LBL-15500, Berkeley, CA.

Sigvaldason, G.E. and Cuellar, G. (1970). "Geochemistry of the Ahuachapan Thermal Area, El Salvador," UN Symposium on the Development and Utilization of Geothermal Resources, Pisa, Italy, Vol. 2, pp. 1392-1399.

Steingrimsson, B., Bodvarsson, G. S., Cuellar, G. and Escobar, C. (1989). "Changes in Thermodynamic Conditions of the Ahuachapan Reservoir Due to Production and Injection," this volume.

Truesdell, A., Aunzo, Z., Bodvarsson, G. S., Alonso, J. and Campos, A. (1989). "The Use of Ahuachapan Fluid Chemistry to Indicate Initial Conditions and Reservoir Processes During Exploitation," this volume.

Vinsome, P. K. W., and Westerfeld, J. (1980). "A Simple Method for Predicting Cap and Base Rock Heat Losses in Thermal Reservoir Simulations," *Journal of Canadian Petroleum Technology,* July-September.