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CHANGES IN THERMODYNAMIC CONDITIONS OF THE AHUACHAPAN RESERVOIR DUE TO PRODUCTION AND INJECTION

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ABSTRACT

Since large-scale exploitation of the Ahuachapán reservoir began in 1975 with the commencement of the first 30 MW_e unit, large changes in the reservoir thermodynamic condition have occurred. Drawdowns up to 15 bars have developed in the production field and significant temperature changes have been observed. In most cases temperatures have declined due to boiling in the reservoir stimulated by the pressure drawdown; cooling due to reinjection of spent geothermal fluids has also been observed. There are indications of a cold fluid recharge to the reservoir from the west and north. Increasing temperatures in the southeast corner of the wellfield show that significant recharge of hot fluids to the wellfield comes from the southeast; they also indicate that the recharge rate has increased with time as the pressure declines in the reservoir.

INTRODUCTION

The Ahuachapán field has been under development and exploitation for more than 20 years. The first production well was drilled in 1968 and presently a total of 32 wells are distributed over a 6 km^2 area, as shown in Figure 1. However, the productive wellfield extends over less than 1 km^2 (Vides-Ramos, 1985). The wells are completed with a cemented casing to about 500 m depth; total depths of the wells vary between 590 and 1600 m.

Exploitation of the Ahuachapán reservoir started in June 1975, when the first 30 MW_e generator went on-line. A second 30 MW_e unit commenced in July 1976, and a third one (35 MW_e) in November 1980. The power plant has never been operated at full capacity due to the lack of sufficient steam. Presently, the total fluid production rate is about 500 kg/s, which is sufficient to generate about 45 MW_e of electrical power.

Ahuachapán was the first geothermal field which utilized large scale reinjection of the waste water (Einarsson et al., 1975). Injection experiments were conducted in 1971, and a reinjection program was initiated in August 1975, shortly after exploitation started. Reinjection stopped in November 1982, and since then the waste water has been gravity-flowed to the Pacific Ocean along a 75 km long concrete channel.

The objective of this paper is to examine the pressure and temperature changes as well as changes in fluid chemistry that have occurred during exploitation of the field. Of primary interest is the evaluation of the temperature decline in producing wells in terms of boiling, reinjection returns and natural recharge.

MASS EXTRACTION HISTORY

Since August 1968, production and reinjection rates for all wells in Ahuachapán have been regularly measured and are available as monthly averages (Vides-Ramos, 1985). The cumulative extraction history of the field is shown in Figure 2. During the development phase (1968-1975), a total of 24 Mtons of fluids were produced from the reservoir, with only 2 Mtons reinjected during the 1971 injection tests. Fluid production increased drastically when the first two generators went on-line and has averaged 17 Mtons/year since 1976. The rate of reinjection has varied considerably. In early 1976 as much as 50% of the produced fluids were reinjected, but on the average some 25-30% of the extracted fluids were injected into the reservoir, until November 1982 when reinjection was stopped. A total of 38 Mtons of waste

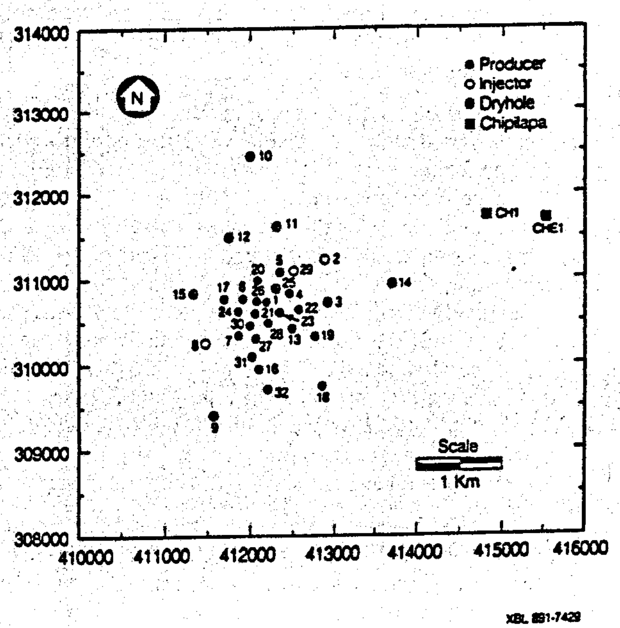

Figure 1. Map of the Ahuachapán wellfield.

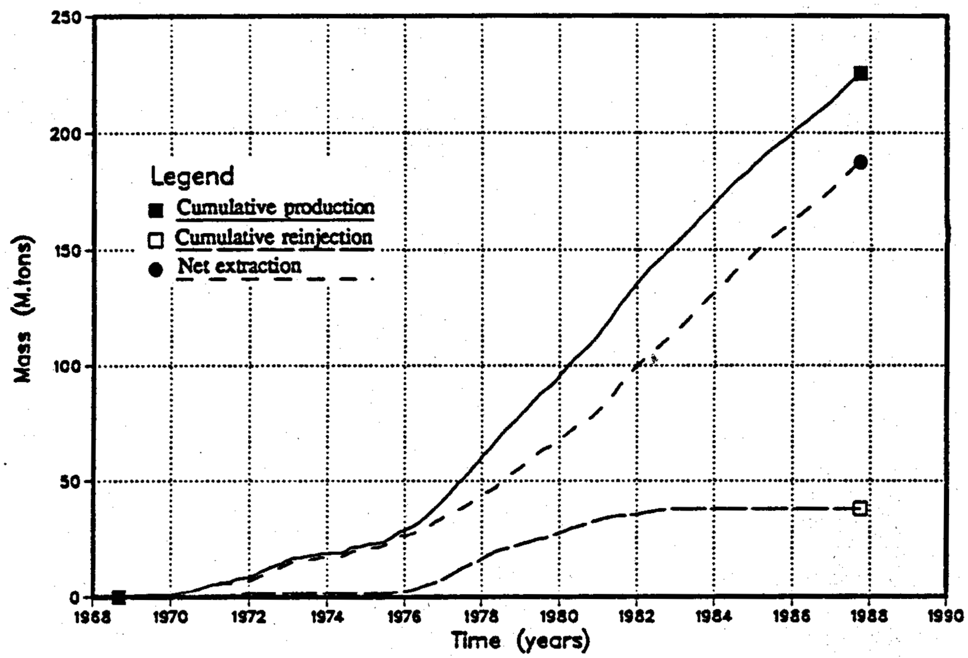

Figure 2. Cumulative fluid production and injection, 1968-1988.

water have been reinjected. In comparison, by the end of September 1988 the net fluid extraction from the field had reached 187 Mtons.

PRESSURE DRAWDOWN

Changes in reservoir pressures have been monitored during the exploitation years by running annual surveys in all wells accessible to logging. Also, daily pressure measurements at 200 masl (approximately 500 m depth) in well AH-25 are available since 1977; this well is located close to the center of the production field (Figure 1). The initial (pre-exploitation) pressures in the Ahuachapán wellfield were fairly uniform corresponding to 36 bar-g at the monitoring elevation of 200 masl (Laky et al., this volume).

Exploitation has caused a significant pressure drawdown in the production area. Figures 3 and 4 show pressure maps for the years 1978 and 1986. Both figures show a near-uniform pressure low engulfing the entire production area. In 1978 the pressures ranged between 28-30 bar-g compared with the initial 36 bar-g; by 1986 the pressures in the wellfield had declined to 20-22 bar-g. Relatively high 1978 pressures in wells AH-8, AH-29, AH-17 and AH-2 are due to reinjection into these wells. Peripheral wells AH-11, AH-14, AH-16 and AH-18 show significant drawdowns indicating natural fluid recharge from the north, east and south. Wells AH-10 and AH-15 are not in pressure communication with the geothermal reservoir and have not shown measurable drawdown.

The AH-25 pressure data have been supplemented with some 1968-1977 average well pressures at 200 masl and converted into drawdown by assuming an initial reservoir pressure of 36 bar-g. These drawdown data are plotted in

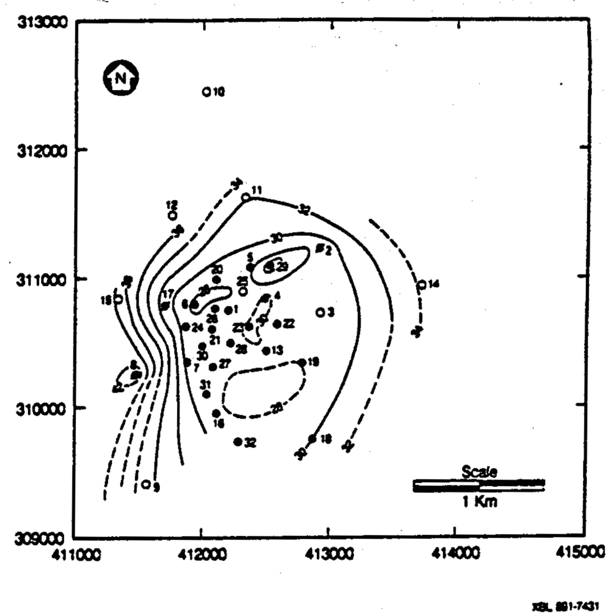

Figure 3. 1978 pressure contours in bar-g at 200 masl.

Figure 5 together with the monthly net extraction rates. The figure illustrates the close relation between the net extraction rate and pressure drawdown. The few data points from the early years show that the fluid production during well testing resulted in a significant drawdown in 1972, but as the production testing was minimal during the next few years, the field had almost recovered to initial pressures when exploitation started in 1975. Figure 5 shows that the pressure drawdown tends to stabilize during long periods of relatively constant net extraction rate, thus reaching a quasi-steady state. This pressure stabilization and the fast pressure recovery in 1973-1975 indicates that the current production wellfield is only a small part of a much larger system and that recharge into the production area is significant (see Aunzo et al., this volume).

TEMPERATURE CHANGES

Significant reservoir temperature changes have been observed at Ahuachapán due to exploitation. The most dramatic change is a gradual 10-15 °C cooling within the Ahuachapán Andesites in the main production area during the 1975-1986 exploitation period (Figure 6). Some temperature changes are also observed deeper in the reservoir and on the periphery of the wellfield. Careful analysis of the available data shows that there are several processes responsible for the temperature changes including boiling, reinjection returns and natural recharge. In the following sections the observed reservoir temperature changes are discussed in terms of these different processes.

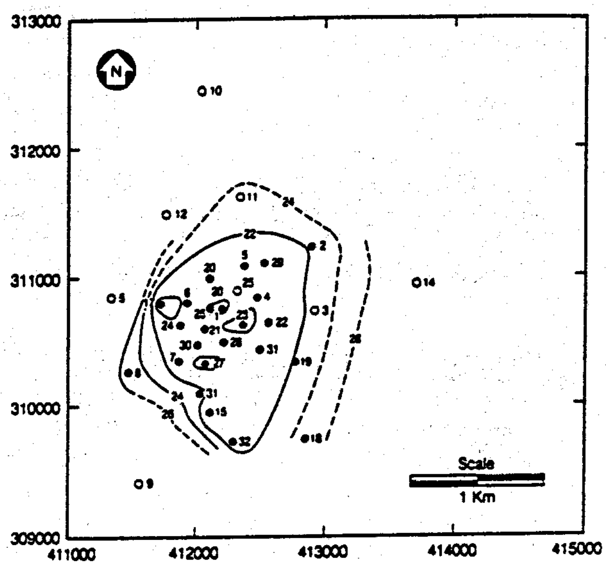

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Figure 4. 1986 pressure contours in bar-g at 200 masl.

Temperature changes due to boiling

The upper part of the reservoir was boiling prior to exploitation (Laky et al., this volume). The pressure drawdown in the field has caused the two phase region in the main production area to expand and the boiling zone to cool following the saturation curve. The boiling level, initially found at an elevation of about 300 masl, is currently (1988) at about 250 masl. The cooling of the boiling zone is on the order of 10-15 °C. It can be easily demonstrated that this cooling is primarily caused by boiling either by comparing the temperature and the pressure distribution in the field, or by plotting for each well the temperature and pressure in the two-phase region at different times and comparing the plot with the corresponding saturation values. Example of such a plot is shown in Figure 7.

Temperature changes in the liquid region of the reservoir in the Ahuachapán Andesites

The two phase region resides in the upper region of the Ahuachapán Andesites. The underlying liquid-

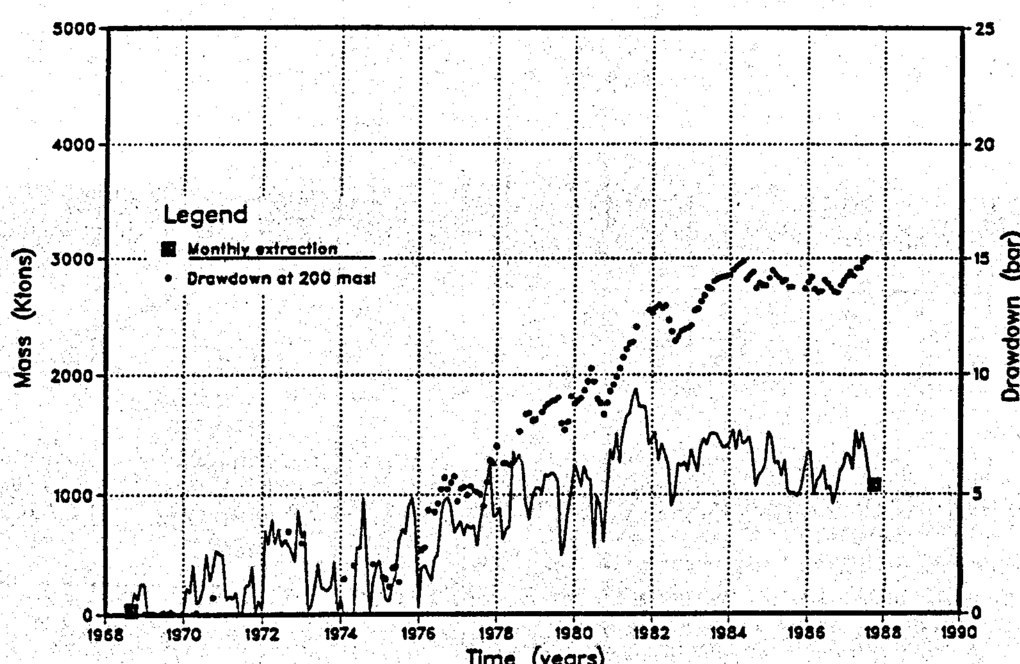

Figure 5. Monthly net extraction rates and the pressure drawdown.

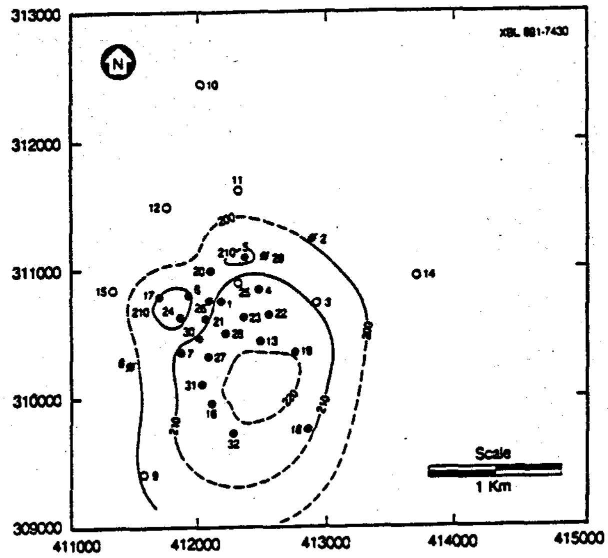

Figure 6. 1986 temperature contour map (in °C) at 200 masl.

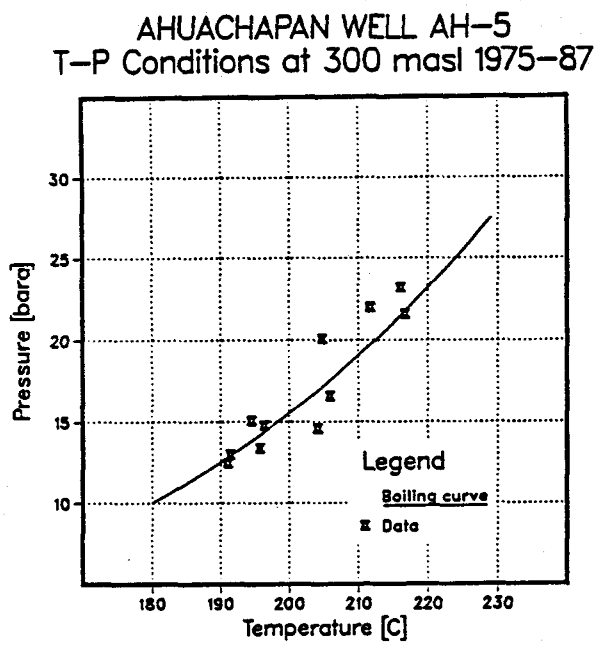

Figure 7. Plot of temperature versus pressure for AH-5 (1975-1987).

dominated zone also experienced considerable cooling during the exploitation years, except in the southwest corner of the wellfield. Early temperature logs show boiling-point-to-depth curves through the two-phase region of the reservoir and a near-isothermal interval below the boiling level to the bottom of the Andesites. These general reservoir characteristics have not changed in the production field. However, the boiling level has fallen some 50 m, as mentioned earlier, and the liquid zone has cooled with time. The best example of this behavior is well AH-21 (Figure 8) but similar behavior is observed in most of the other production wells, with the exception of wells AH-7 and AH-31.

In order to investigate the cooling of the single-phase region of the Andesites, the temperature and the pressure histories of several wells were analyzed. Examples of these plots are shown in Figure 9. In all cases the temperature decline correlates with the pressure drawdown in the reservoir. Such a consistent correlation is highly unusual in a single-phase region. Plots of temperature versus pressure (Figure 10) show that the cooling progresses parallel to the saturation curve indicating that the cooling of the single phase region in the reservoir is actually controlled by boiling. It is believed that the cause of this is recharge of a two-phase mixture of steam and water. This recharge occurs at or above 200 masl, but after entering the field the two phases segregate due to density effects, with liquid occupying the lower portion of the Andesites and steam accumulating in the upper part.

Temperature changes attributed to reinjection

Temperature data have been examined in order to determine reservoir cooling caused by the 1975-1982 reinjection program. The data indicate thermal recovery in few

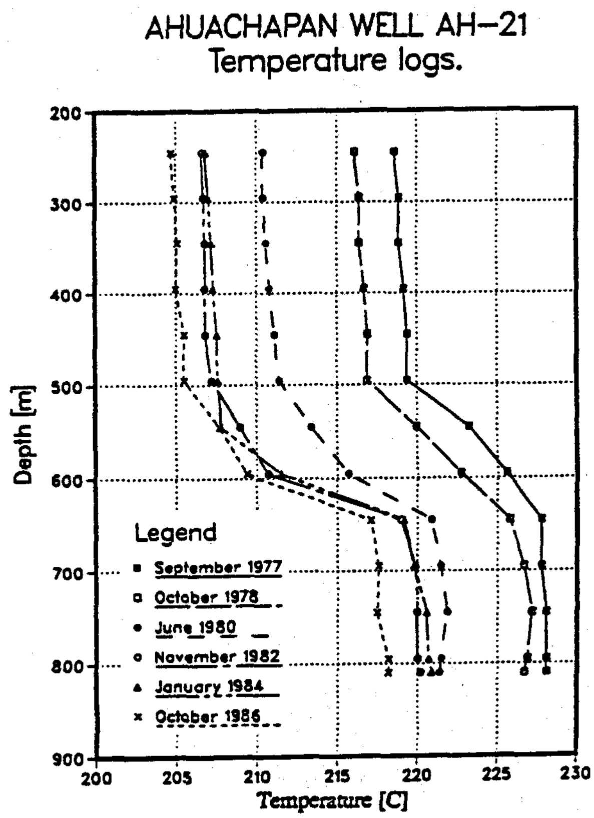

Figure 8. Selected temperature logs for well AH-21.

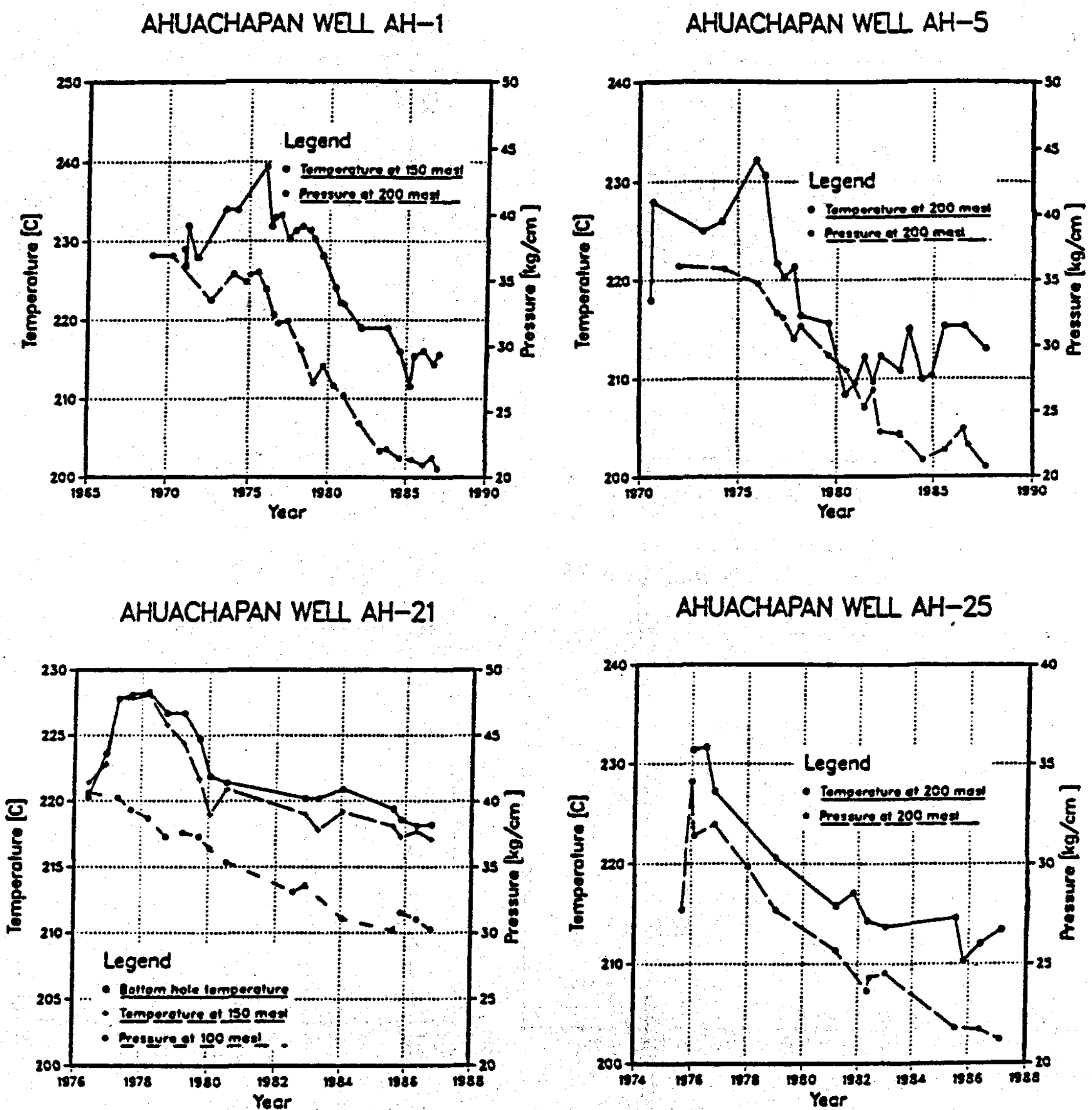

Figure 9. Selected temperature logs for wells AH-1, AH-5, AH-21 and AH-25.

wells after the reinjection was stopped in 1982. All of these wells are relatively close to an injector. Most pronounced is the cooling around injection well AH-8, but some reinjection-related cooling was also observed in the vicinity of AH-29, another injector.

Figure 11 shows temperature data at 100 masl in well AH-7, which is located near the injector AH-8. It shows gradual cooling during the reinjection period and rapid recovery after injection ceased in 1982. The cooling which occurred up to 1982 was on the order of 10-15 °C. By late 1987, the temperature had almost fully recovered. Similar temperature history is found in the vicinity of the injector AH-29 in wells AH-25 and AH-5. In general, however, one can conclude that the substantial reinjection effort did not cause large cooling effects in the producing wells.

Temperature changes due to natural recharge

The drawdown in the reservoir has stimulated natural recharge to the production area of the field. The temperature distribution in the field indicates that in the natural state the geothermal fluid recharged the wellfield from the southeast, close to well AH-18 (Laky et al., this volume). This well has shown increasing temperatures during the exploitation years, as is evident in Figure 12. The early data indicate the thermal recovery of the well after drilling was completed in 1977; the low 1985 temperatures coincide with flow testing of the well (boiling during discharge). Apart from these disturbed readings the plot shows a gradual increase in temperature since 1978. The total temperature rise is about 10 °C, reaching 245 °C in 1987, the highest reservoir temperature measured in Ahuachapán. The increasing temperatures in well AH-18 in response to exploitation support the idea

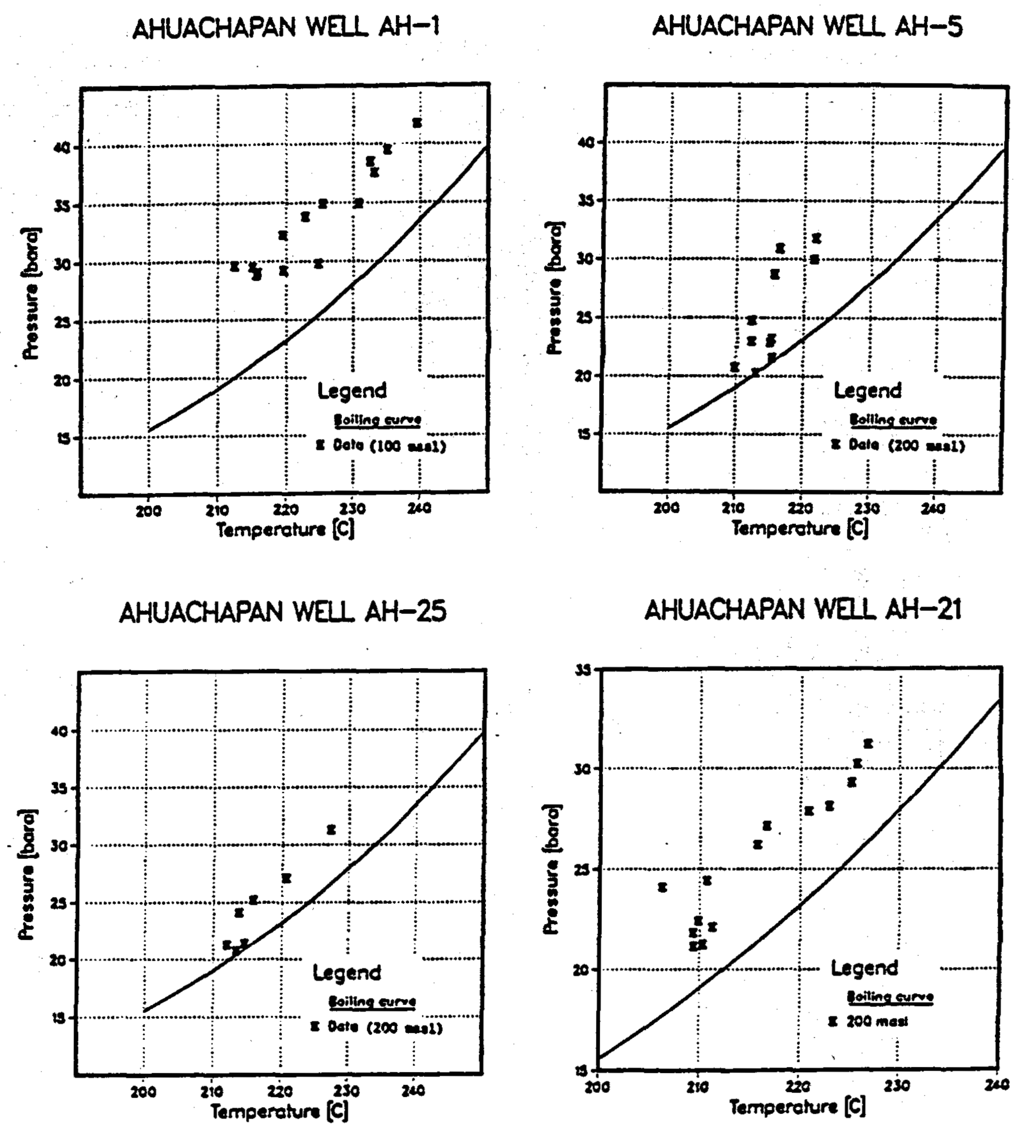

Figure 10. Temperature and pressure histories for wells AH-1, AH-5, AH-21 and AH-25.

of a natural hot fluid recharge in this part of the field and furthermore that the recharge rate has increased due to pressure decline in the reservoir.

Cold water recharge into the wellfield cannot be supported by data from peripheral wells. On the eastern margin of the field no temperature changes have been observed, while at the north and west boundaries no data are available because of obstruction in the wells at shallow depth. However, temperature data from a few wells in the production area indicate deep cold water recharge into the field from the north and west. An example of a well showing this type of cooling is AH-7. This well cooled at shallow depth (100 masl) due to reinjection, as mentioned earlier (see Figure 11). Similar cooling was observed deep in the well during the reinjection years as shown on Figure 13, but in this case little thermal recovery was measured after the reinjection ceased. The reservoir cooling can therefore not be explained by reinjection leaving cold water recharge as the only possible cause for the temperature history deep in well AH-7.

SUMMARY AND DISCUSSION

Exploitation has greatly changed the pressure and temperature conditions in the Ahuachapán reservoir. In the wellfield, pressure has declined some 15 bars and cooling of up to 15 °C has been observed.

As expected the pressure drawdown correlates well with the net extraction rate, with quasi-steady pressure conditions reached after periods of near-constant rates. This suggests that natural recharge is very significant at Ahuachapán and that the system is much larger than the current wellfield.

The temperature history of Ahuachapán is complicated and has been influenced by several factors, including:

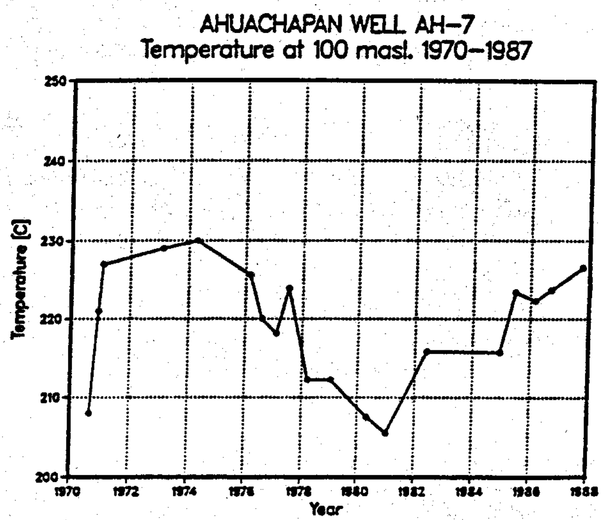

Figure 11. 1970-1987 temperature history of well AH-7 (100 masl).

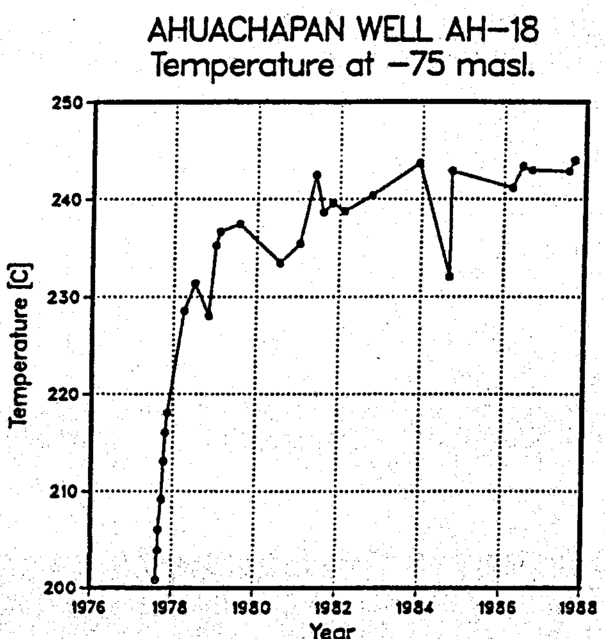

Figure 12. 1977-1988 temperature history of well AH-18 (-75 masl).

(1) Gradual cooling of the upper part of the reservoir due to boiling resulting from pressure decline.

(2) Progressive cooling of the liquid region of the reservoir in the Ahuachapán Andesite at the main production area. This cooling is due to recharge of boiling (two-phase) fluid to the production area.

(3) Temporal cooling in the vicinity of injectors during the reinjection period. This cooling, however, did not cause significant detrimental temperature decline in producing wells.

(4) Cooling in the northern and the western part of the field due to increasing cold water recharge in response to reservoir drawdown.

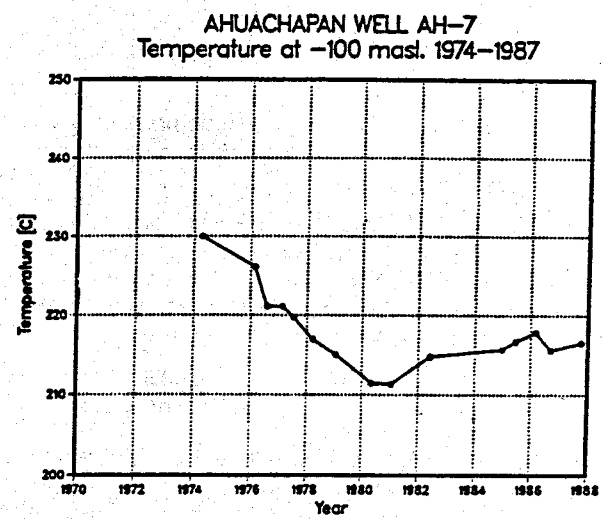

Figure 13. 1974-1987 temperature history of well AH-7 (-100 masl).

(5) Heating-up in the southeastern part of the field due to increasing geothermal (hot) fluid recharge to the production area.

The temperature history to the conceptual model of the field are presented by Laky et al. (this volume). The following statements are made with reference to Figure 2 in Laky et al., which shows major faults and flow directions. The geothermal fluid recharge enters the field from southeast and feeds the main production area through two separate "channels". The main recharge is through Fault #6 where the fluid undergoes boiling before it enters the production area. This boiling zone is believed to be in the vicinity of AH-19, may be at the intersection of Faults #5 and #6 where the Andesites are found at relatively shallow depth. The second recharge channel (Fault #10 and Fault #2a or #7) feeds the area around wells AH-7 and AH-31. Cold water seeps deep into the reservoir from the north through Fault #4 and maybe into the western portion of the field through Fault #8, but the main inflow of cold water occurs through the top of the reservoir probably through fault #6.

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REFERENCES

Aunzo, Z., Bodvarsson, G. S., Laky, C., Lippmann, M. J., Steingrimsson, B., Truesdell, A. H. and Witherspoon, P. A., (1989a). "The Ahuachapán geothermal field, El Salvador - Reservoir analysis," Lawrence Berkeley Laboratory report LBL-26612, Berkeley, CA.

Aunzo, Z., Steingrimsson, B., Bodvarsson, G. S., Escobar, C., Quintanilla, A. (1989b). "Modeling studies of the Ahuachapán geothermal field, El Salvador," Proc. 14th Workshop on Geothermal Reservoir Engineering, Stanford, CA, Jan 24-26, 1989.

EG&G Idaho, Inc. and Lawrence Berkeley Laboratory (1982). "Low-to-moderate temperature hydrothermal reservoir engineering handbook," Report IDO-10099.

Einarsson, S., Vides, R. A. and Cuellar, G. (1975). "Disposal of geothermal waste water by reinjection," Second United Nations Symposium on the Development and Use of Geothermal Resources, U.S. Government Printing Office, Vol. 2, pp. 1349-1363.

Grant, M. A., (1980). "Simple modeling of production and reinjection at Ahuachapán," DSIR Report, New Zealand, February 1980.

Laky, C., Lippmann, M. J., Bodvarsson, G. S., Retana, M. and Cuellar, G. (1989). "Hydrogeologic model of the Ahuachapán geothermal field, El Salvador," Proc. 14th Workshop on Geothermal Reservoir Engineering, Stanford, CA, Jan. 24-26, 1989.

Truesdell, A. H., Aunzo, Z., Bodvarsson, G. S., Alonso, J. and Campos, A., (1989). "The use of Ahuachapán fluid chemistry to indicate natural state conditions and reservoir processes during exploitation," Proc. 14th Workshop on Geothermal Reservoir Engineering, Stanford, CA, Jan. 24-26, 1989.

Vides-Ramos, A. (1975). "Ahuachapán, El Salvador field management," Trans. Geothermal Resources Council, International Volume, pp. 397-404.