GL00631

Geothermal Systems: Principles and Case Histories
Edited by L. Rybach and L. J. P. Muffler

12. *Extraction–Reinjection at Ahuachapán Geothermal Field, El Salvador*

GUSTAVO CUÉLLAR, MARIO CHOUSSY, AND DAVID ESCOBAR

Comision Ejecutiva Hidroelectrica del Rio Lempa, El Salvador

12.1. Introduction

In order to increase the production of electric energy in El Salvador, a program of geothermal studies was started in 1965. This program led to the development of the Ahuachapán Geothermal Field, where the first of two 30 MWe medium-pressure units was commissioned in May 1975 and the second in June 1976. During 1977, these two units provided 32·3 per cent of the total electric energy generated in El Salvador. This statistic has greatly increased the interest and confidence in the use of underground steam as a source of energy. At the present time, a third 35 MWe unit is being installed at Ahuachapán and is expected to be in operation in January of 1980.

Several new geothermal areas in El Salvador are presently under investigation (figure 12.1), and recent drilling has proved the existence of extensive fractured zones with temperatures up to 300°C.

This chapter presents pressure, temperature, and chemical data from the Ahuachapán Geothermal Field in the production stage. Future efforts to better understand the reservoir characteristics will include a tracer study and the development of a mathematical model.

12.2. Geological Setting

The general geological structure of El Salvador has been interpreted as a major structural trough cutting approximately East–West across the southern part of the country. This trough has been largely filled by Quaternary cones that compose the main volcanic chain of the country (Figure 12.1). Structurally, El Salvador can thus be divided in to three units: (1) a tilted block bordering the Pacific Ocean and dipping towards it, (2) a median valley of variable width, and (3) an uplifted northern zone composed of a number of complex fault blocks. These simple features assumed by Williams and Meyer-Abich (1955), although probably true in general terms, are in fact more complex than suggested by this model. In particular, the form of the median valley is not a simple parallel-sided rift. The uplifted southern and northern sides are a series of blocks which have been faulted and tilted to give the present-day structure.

The Ahuachapán Geothermal Field is associated with the south flank of the central Salvadorean median trough and the northwest sector of the Cerro Laguna Verde volcanic group. This extrusive complex developed during Quaternary time near the Pliocene

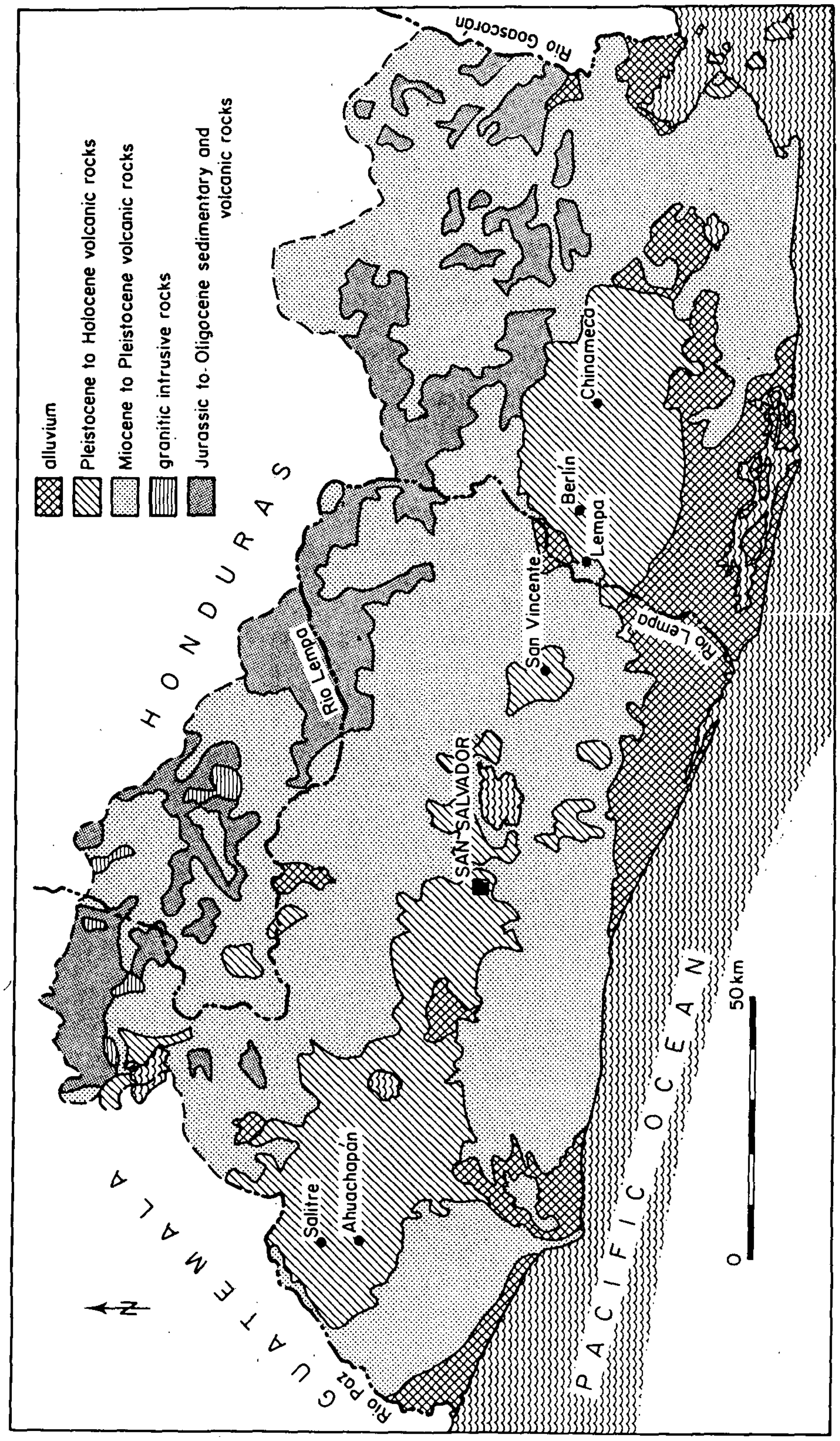

Figure 12.1. Geologic map of El Salvador (adapted from Wiesemann, 1973). Dots indicate geothermal areas under investigation

tectonic block of Tacuba-Apaneca, the regional faults of which have controlled first the sinking of the graben and subsequently the eruption of volcanic products.

The Ahuachapán Field lies in the southern part of a subelliptical basin that extends north and northwest, reflecting the subsidence of the graben.

Both the regional and the local structure are characterized by faults and fractures oriented along three main directions. An E–W system, approximately the trend of the main graben, consists of a series of step faults which limit the field to the north. To the W, the field is bounded by a second system of faults which strike NE. Finally, the most recent system of faulting and fracturing has a NNW trend and is associated with superficial hydrothermal activity. This youngest faulting probably has an important function in that it renders permeable the reservoir formations of the Ahuachapán Geothermal Field.

The stratigraphic sequence of the Ahuachapán area is described as follows (Figure 12.2):

- Laguna Verde volcanic complex: andesitic lava flows and some pyroclastics (Holocene). Thickness up to 200 m. Not shown on Figure 12.2.
- Tuff and lava: Tuffs prevail in the upper part and lava intercalactions in the lower part (Pleistocene). Thickness up to 500 m.
- Young agglomerate: Volcanic agglomerate with occasional lava intercalations (Pleistocene). Thickness up to 400 m. The unit is essentially impermeable and forms the caprock of the geothermal reservoir.
- Ahuachapán andesites: Lavas with pyroclastic intercalations (Pliocene–Pleistocene). Thickness up to 300 m. The Ahuachapán andesites constitute the reservoir formation and typically have a secondary permeability caused in part by columnar jointing related to cooling, in part by the contact surfaces of the different formations, but mainly by tectonic fracturing. In Figure 12.2, permeable zones are indicated at the top of the Ahuachapán andesites. Structure contours on the top of the Ahuachapán andesites are shown in Figure 12.3.
- Old agglomerate: Agglomerate with breccia intercalations in the lower part. Thickness in excess of 400 m.

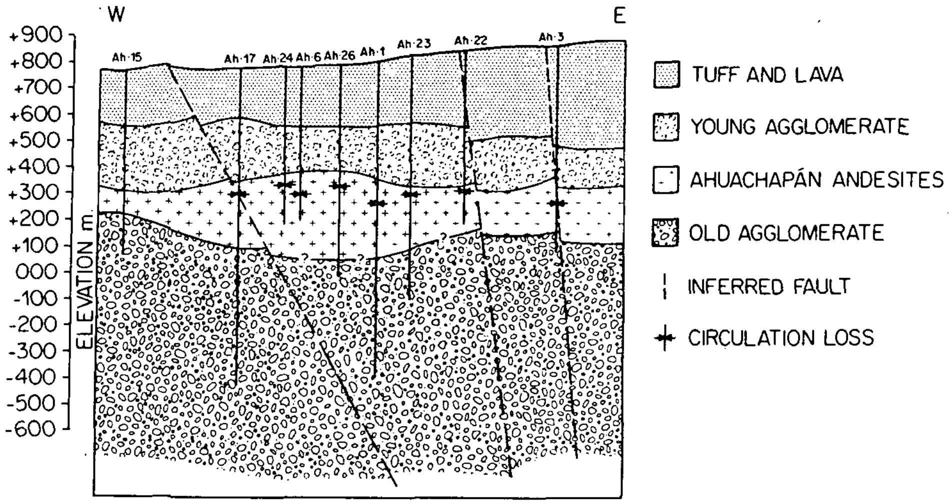

Figure 12.2. Geological cross section of Ahuachapán geothermal field. Elevation is relative to sea level

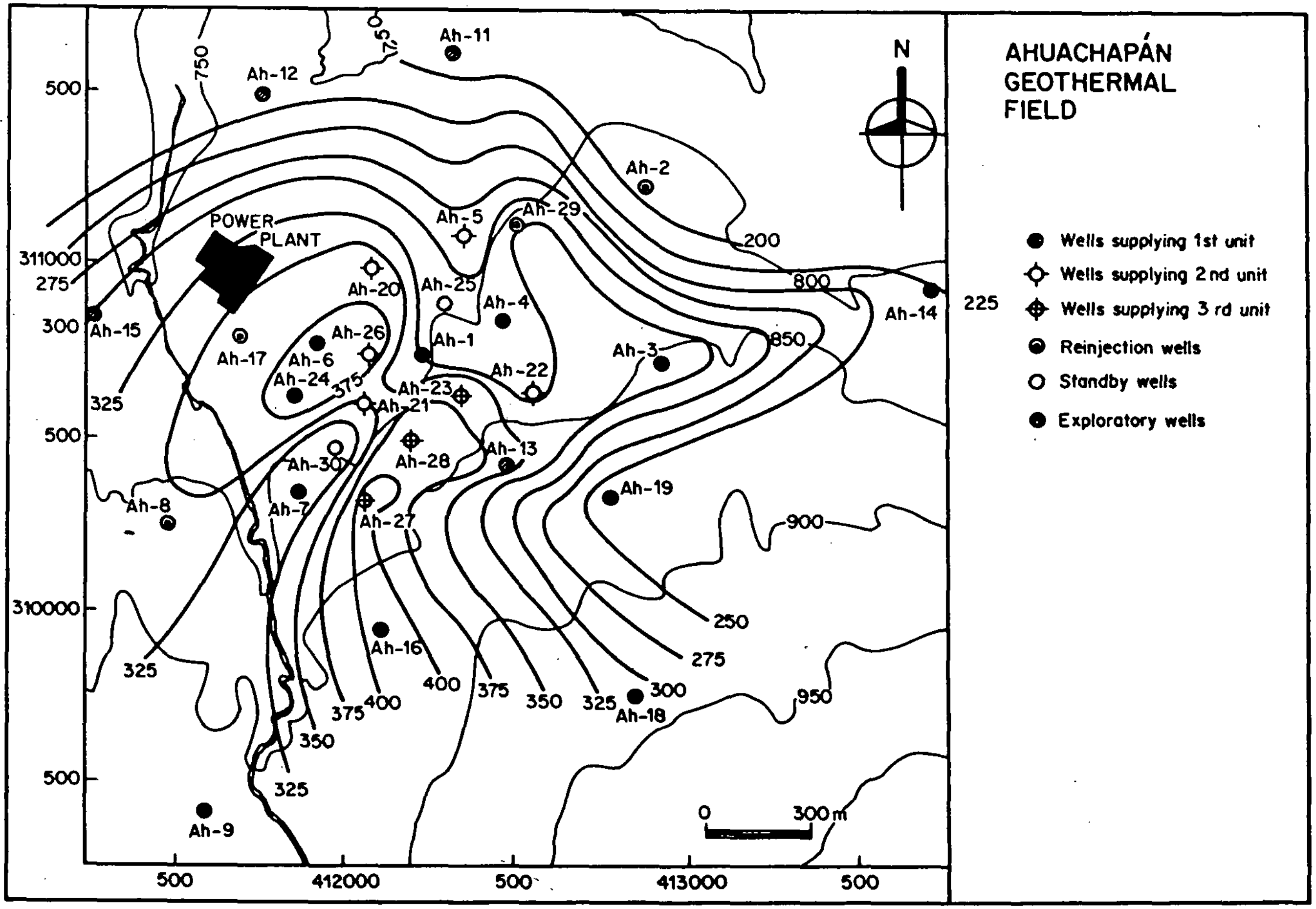

Figure 12.3. Map showing wells in the Ahuachapán geothermal field and structural contours (heavy lines, in meters above sea level) on the top of the Ahuachapán andesites. Light lines are topographic contours in meters above sea level

12.3. Hydrogeology

In the region around Ahuachapán, there are three aquifers, here termed the shallow aquifer, the saturated aquifer, and the saline aquifer. The saline aquifer is the deepest and constitutes the geothermal reservoir of the Ahuachapán field. The shallow aquifer appears to be distinct, whereas there is some communication between the saturated aquifer and the saline aquifer.

12.3.1. *Shallow Aquifer*

The shallow aquifer consists of tuffs, pumice detritus, and talus covering the lavas of the Laguna Verde complex. This unconfined aquifer is recharged by infiltrating rain water and feeds several springs located on the slopes of the Laguna Verde and Laguna de Las Ninfas volcanoes at the contact with the underlying lavas that constitute the aquiclude of this system.

The variations in flow rate are controlled by precipitation, showing very fast response. The waters are generally of calcium carbonate type, locally sulfatic, with residues below 500 mg/L. This very shallow aquifer is of interest only locally in the uphill area of the geothermal field.

12.3.2. *Saturated Aquifer*

The saturated aquifer consists of fractured lavas and pyroclastic deposits of the tuff and lava formation, while the young agglomerate, of low or no permeability, represents the impermeable basal stratum. Recharge takes place by direct infiltration, which produces a shallow free surface, tapped by several wells for domestic purposes and surfacing at several springs on the plain north of the geothermal area.

The piezometric surface in the area of the plain exhibits a concave shape that is open to the north, having a gradient (and therefore a principal flow component) in a northerly direction. The response of the piezometric level to the variations in rainfall is much slower than in the case of the shallow aquifer.

The water of the saturated aquifer is of calcium-sodium carbonate type, with residues generally below 400 mg/L. An exception to this rule is a group of springs, of which the most important one is the Salitre spring, with a flow rate of 1000 L/s and a temperature of 70°C. Water from this spring differs from the usual water of the saturated aquifer in its chemistry (sodium-chloride type) and in its much higher residues (600 to 1700 mg/L). These differences are attributed to admixture with waters that migrate upward along fractures from the underlying saline aquifer.

12.3.3. *Saline Aquifer*

The saline aquifer corresponds to the geothermal reservoir of the Ahuachapán Field and consists of the Ahuachapán andesites. The permeability of the Ahuachapán andesites is predominantly secondary, due to fractures, thus explaining the circulation losses observed during drilling. The permeability of the aquifer is therefore extremely anisotropic and variable; however, it is logical to assume that the permeability is highest along the previously mentioned principal directions of faulting and fracturing.

12.4. Characteristics of the Ahuachapán Wells

By early 1979, 29 wells had been drilled in the Ahuachapán Field, with depths between 591 and 1524 m. All the wells are located in an approximate area of 4 km^2. The zone of production, however, covers only 2 km^2, with a minimum well spacing of about 150 m. No significant interference has been detected among the wells.

The wells are distributed as follows (Figure 12.3): ten production wells provide steam for the first and second unit, three wells will provide steam for the third unit, two production wells are kept as standby, four wells are used for reinjection purposes, and there are ten exploratory wells.

Typical completions of production and reinjection wells are shown in Figure 12.4. These completions are based on a good knowledge of the geological conditions and have been standardized for the whole field.

The characteristics of the production wells are presented in Table 12.1, including depths and elevations of the top of Ahuachapán andesites. From the production characteristics it can be observed that there exists no relation between the well depths and mass discharge. The production characteristics, however, do correlate with the elevation of the top of the formation. The wells on the structural high have discharge enthalpies that correspond very closely to the enthalpy calculated from the adiabatic expansion of water at the initial reservoir temperature (230°C) and pressure. However, wells off the structural high have lower enthalpies, with the greatest deviations observed in the wells that showed, during drilling, circulation loss at relatively shallow levels within the reservoir.

The wells with higher steam percentage, Ah-6 and Ah-26, correspond exactly to the structural high of the reservoir (Figure 12.3). In both wells, 78 per cent of the produced steam fraction comes from steam in the reservoir water. However, well Ah-24, which is located in the same structural high, has a much lower enthalpy and steam content. This discrepancy is believed to be due to the sealing of the shallower fractures during the drilling of Ah-24.

12.5. Reinjection Program

The search for a better way for disposing of the hot, saline water and for maintaining the reservoir pressure at stable conditions led to a reinjection program. This program started in August 1975 when Ah-2 (a production well with low permeability) was converted to reinjection by using residual water from well Ah-4 at atmospheric pressure. Under these conditions a flow of 126 ton/h was injected into well Ah-2. In January 1976, injection tests under pressure were started between the producing well Ah-7 and the injection well Ah-8. The Ah-7 separator pressure was used as a driving force between the wells, with the water being thus kept free of any contact with the atmosphere. This process avoided silica scaling, allowed the reinjection at higher temperatures (±160°C), and increased the reinjection capacity. In April 1976, this injection system was put into full operation, and in October 1976 fluid from the system Ah-6 and Ah-21 began to be reinjected into Ah-17. It is important to point out that at the beginning Ah-17 received only water from Ah-6. However, Ah-17 showed great absorption capacity, and Ah-21 water was subsequently added to this reinjection system.

12.5.1. *Completion of the Reinjection Wells*

The reinjection wells have, at the present time, two kinds of completion:

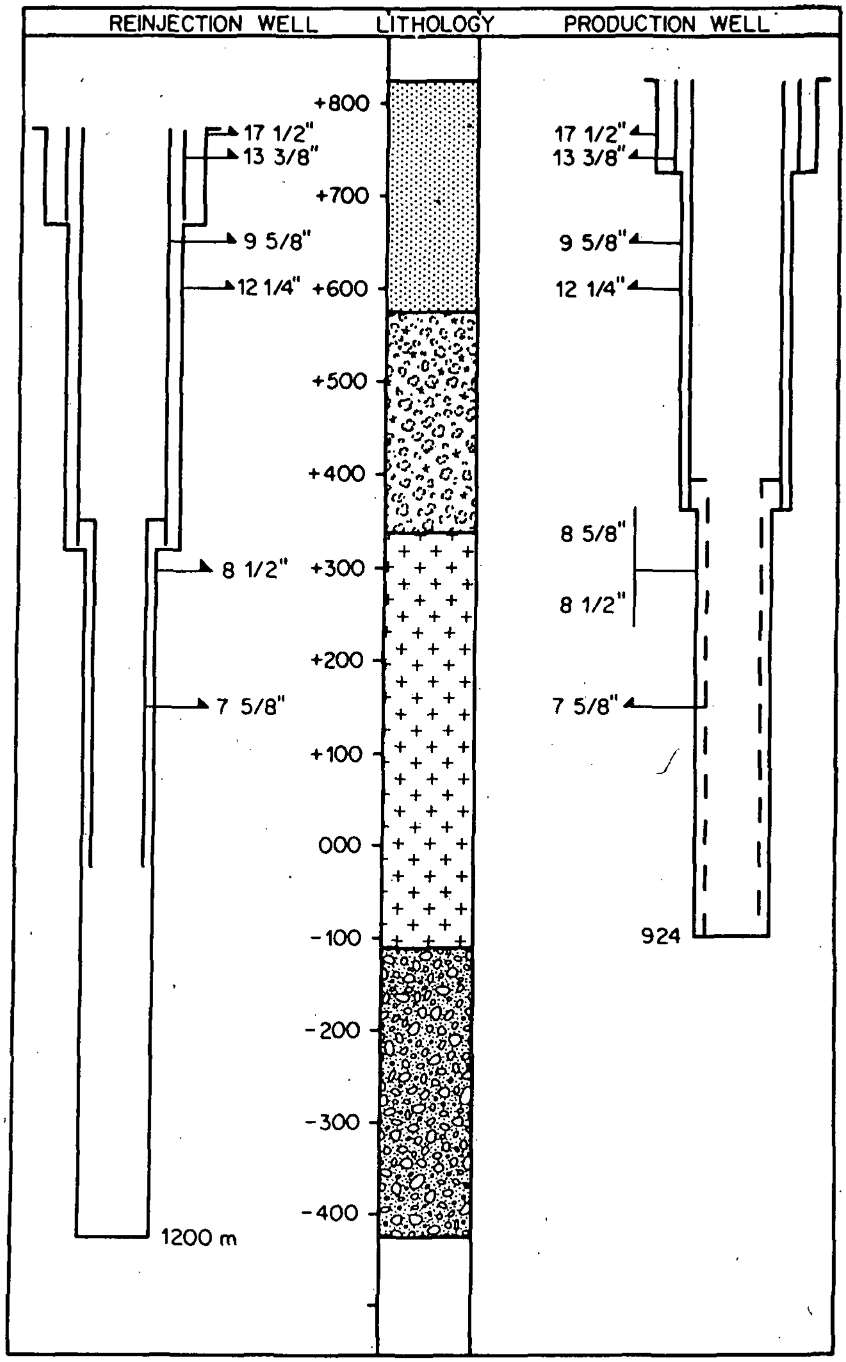

Figure 12.4. Typical completions of production and reinjection wells at Ahuachapán. Depth scale in meters relative to sea level. Stratigraphic units as in Figure 12.2.

Table 12.1. Characteristics of Ahuachapán production wells

		Mass rate (kg/s)						
Well	Separator pressure (10^2 kPa)	total (TM)	steam (SM)	water	Enthalpy (J/g)	Steam ratio SM/TM	Total depth (m)	Elevation of top of Ahuachapán andesites (m)
Ah-1	5·4	85·08	12·50	72·58	984	0·15	1205	325
Ah-4	5·9	99·46	23·33	76·13	1176	0·23	640	315
Ah-5	5·4	49·97	5·56	44·41	908	0·11	952	284
Ah-6	5·5	32·96	13·61	19·35	1536	0·41	591	383
Ah-7	5·3	44·98	7·64	37·34	1026	0·17	950	285
Ah-20	5·3	47·28	11·94	35·34	1197	0·25	600	370
Ah-21	5·6	82·22	11·94	70·28	984	0·15	849	350
Ah-22	5·4	70·68	16·34	54·34	1160	0·23	659·5	315
Ah-24	5·3	51·93	7·50	44·43	975	0·14	850	380
Ah-26	5·3	21·44	8·89	12·55	1536	0·41	804	391
Totals		586·00	119·25	466·75				

1. Wells which were designed for production purposes and recently transformed to reinjection wells (Ah-2 and Ah-8). These wells still keep the production completion (Figure 12.4), having production casing cemented down to the top of the reservoir and open hole to the bottom.
2. Wells completed with a double purpose (production-reinjection). These wells have production casing cemented down to the top of the reservoir, with uncemented casing subsequently hung down to the bottom of the Ahuachapán andesites.

Reinjection wells Ah-17 and Ah-29 (double purpose) are very close to the production wells, and the lithologic columns show a considerable reservoir thickness (400 and 325 m, respectively). However, the wells Ah-2 and Ah-8 are farther away from the production zone and show a lesser reservoir thickness (105 m and 75 m, respectively).

12.5.2. *Capacity of Reinjection Wells*

The capacity of the reinjection wells is closely related to the formation permeability and to the reinjection pressure. For example, at atmospheric pressure well Ah-2 absorbed only 126 ton/h, but, using the separation pressure of the well Ah-4, increased to 245 ton/h. The quantities of the reinjected fluids are illustrated in Table 12.2.

12.5.3. *Reinjected and Extracted Mass*

In order to have a clearer knowledge of the reservoir behavior, the extraction in the Ahuachapán Field can be divided into two periods: a development period from August 1968 to July 1975, and a production period from July 1975 to the present.

The total mass extracted and reinjected during these two periods is shown in Table 12.3. As can be seen from the table, the reinjected mass has been, up to the present time, 29·5 per cent of the total mass extracted and 39·9 per cent during the production period alone.

Table 12.2. Summary of the Ahuachapán reinjection program

Well	Date	Reinjection pressure (10^2 kPa gauge)	Mass capacity (ton/hr)	Cumulative mass capacity (ton/hr)
Ah-2	Aug. 1976	atmospheric	130	130
Ah-8	Jan. 1976	4·9	200·4	330·4
Ah-2	Mar. 1976	6·0	114.9*	445.3
Ah-29	Apr. 1976	5·1	306·4	751·7
Ah-17	Oct. 1976	5·9	167·1	918·8
Ah-17	Dec. 1977	6.1	306.1*	1224·8

* Increment with respect to its initial capacity.

Table 12.3. Fluid extracted and reinjected at Ahuachapán

	1st Period (tons)	2nd Period (tons)	Total
Extracted mass	23,317,800	48,228,933	71,546,733
Reinjected mass	1,850,060	19,218,384	21,068,444
Net mass extracted	21,467,740	29,010,549	50,478,289

12.5.4. *Reinjection Control*

Several questions arising from the reinjection program led to a study of the effects of injection on the field condition. As a part of the study, measurements of temperature and pressure in the production and non-production wells were taken. Figure 12.5 shows that there is an immediate pressure response to variations in reinjection or extraction. However, temperature variations probably are masked by other kinds of changes. In order to detect small pressure changes, a continual recording pressure gauge has been installed in well Ah-25. These data have not yet been processed.

In order to detect any change in permeability, spinner equipment has been used in the reinjection wells to detect absorption zones (Figure 12.6). Well Ah-2 has permeability in the zone between 20 and 250 m above sea level and none in the bottom. Well Ah-17 absorbs all the injected water immediately after the bottom of the hanger liner. This can be interpreted to indicate that water circulates upward through the annulus ring to the total lost circulation zone at +300 m. In the open hole at depth, the formation has a low permeability. Well Ah-29 shows permeability throughout the open hole; water may flow to the annulus, but to a lesser extent than in well Ah-17.

The paths taken by the water injected into wells Ah-17 and Ah-29 can be determined by repetitive analyses for chloride in production wells. The water injected into Ah-29 goes partly to the central field and partly to the east, whereas it appears that most of the water injected into Ah-17 goes toward the center of the field.

12.6. Effects of the Reinjection-Extraction Rate

The various changes from the original reservoir conditions are due to the different rates of reinjection and extraction used in field operation. The reservoir behavior during

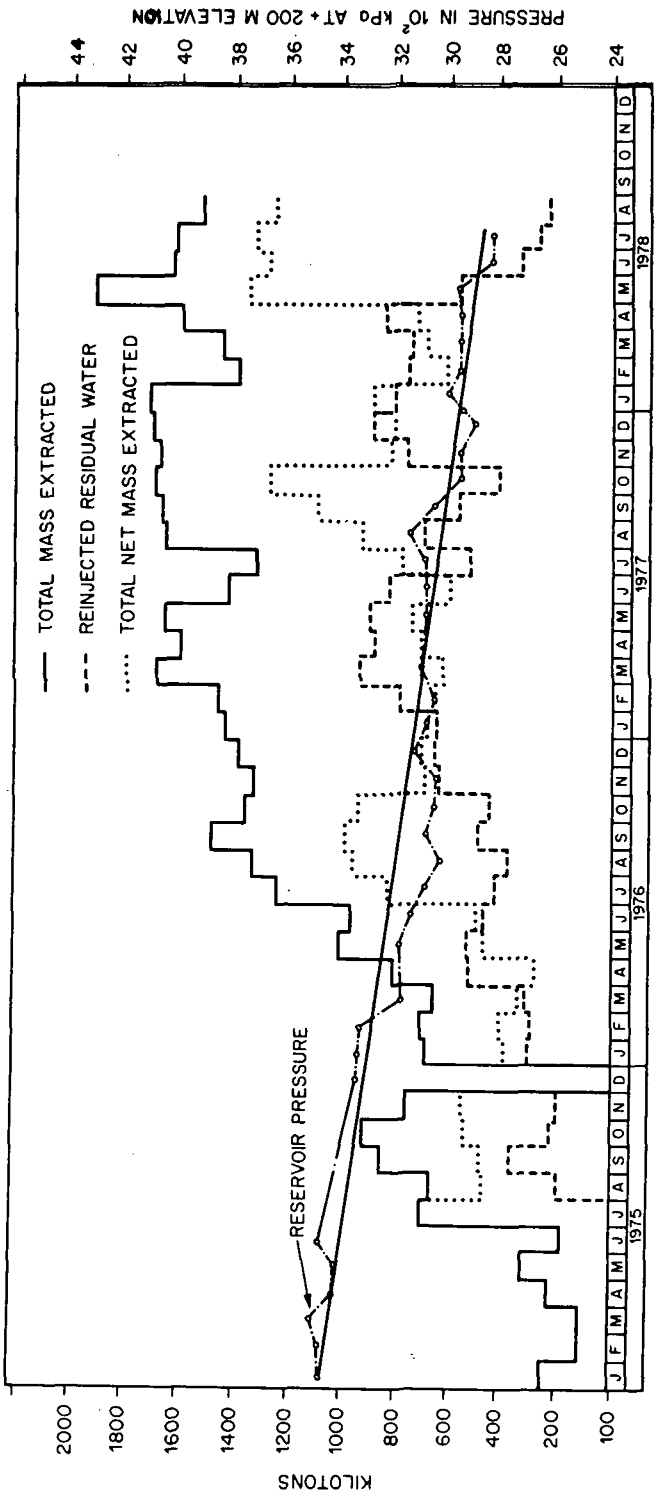

Figure 12.5. Graph showing monthly measurements of fluid production, fluid reinjection, and reservoir pressure at Ahuachapán from January 1975 to August 1978

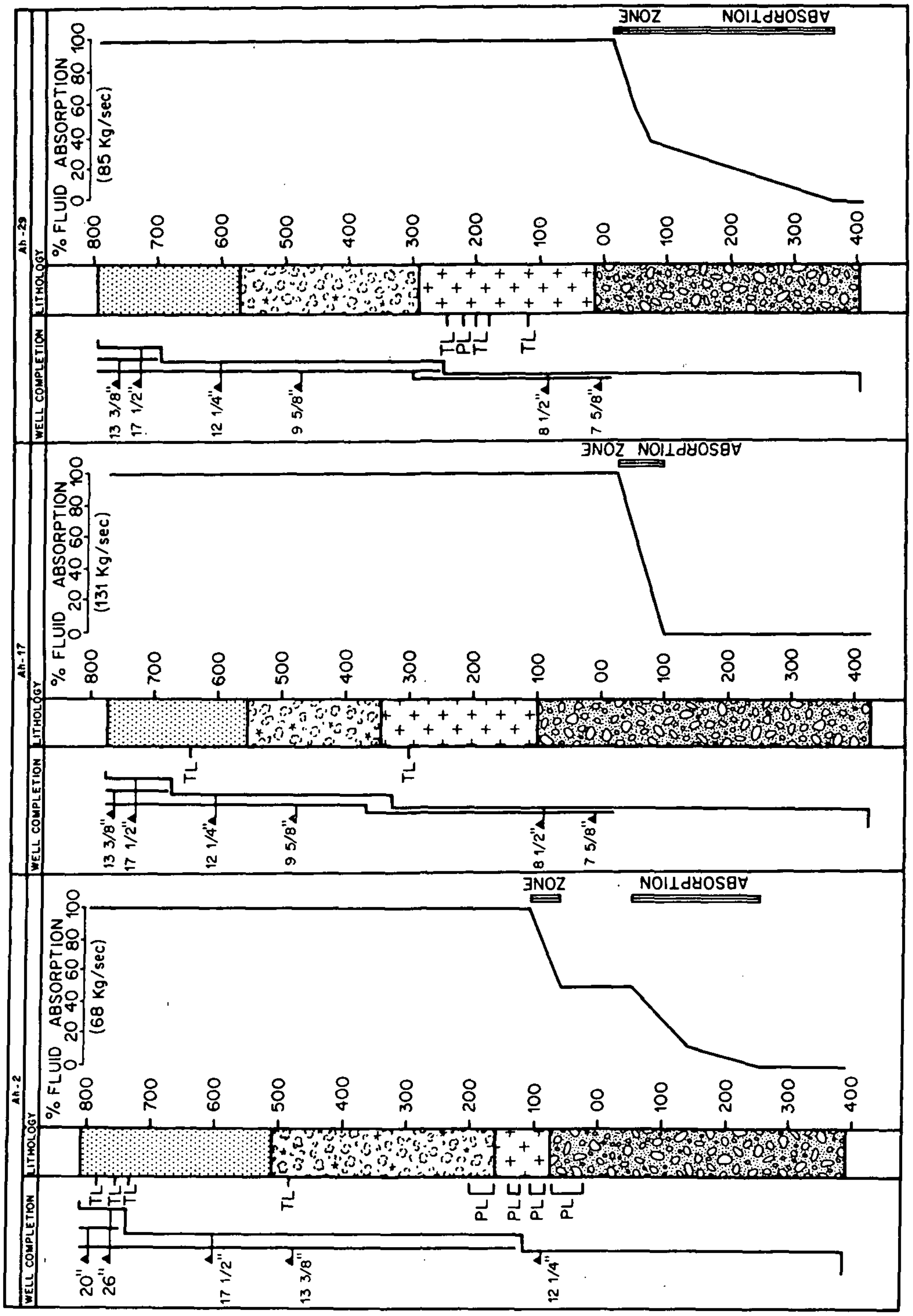

Figure 12.6. Graphs showing absorption of fluid as determined from spinner logs during injection, for wells Ah-2, Ah-17, and Ah-29. TL indicates total loss of circulation during drilling; PL indicates partial loss of circulation

production has been, according to experience in other places, typical of a water-dominated field. However, the general trend depends on the reinjection rates. In this section, we shall analyze how varying extraction-injection rates effect the pressure and temperature of discharged fluids.

12.6.1. *Pressures*

Figure 12.7 illustrates the reservoir pressure change as a function of the cumulative net mass extraction. At the beginning, the reservoir had a pressure (at 200 m above sea level) close to 3600 kPa, which is greater than the saturation pressure at the measured temperature (2960 kPa at 232°C). Subsequently, as a result of extraction, the pressure fell to new equilbrium values dependent on the extraction rate, reaching at the end of the development period in July 1975 a value of 3560 kPa. The existence of recharge is suggested by the fact that the pressure change was only 40 kPa in spite of the large amount of mass extraction. The anomalously high pressure values observed in 1971 may be due to the first injection tests.

During the production period subsequent to July 1975, the pressure decreased rapidly, reaching values close to the saturation pressure (2960 kPa). Then followed a stabilization period controlled by the reinjection effects and the developing of a steam zone in the reservoir.

Figure 12.5 presents in more detail the changes in the pressure during the production period, showing also the different extraction-reinjection rates. It can be seen clearly that

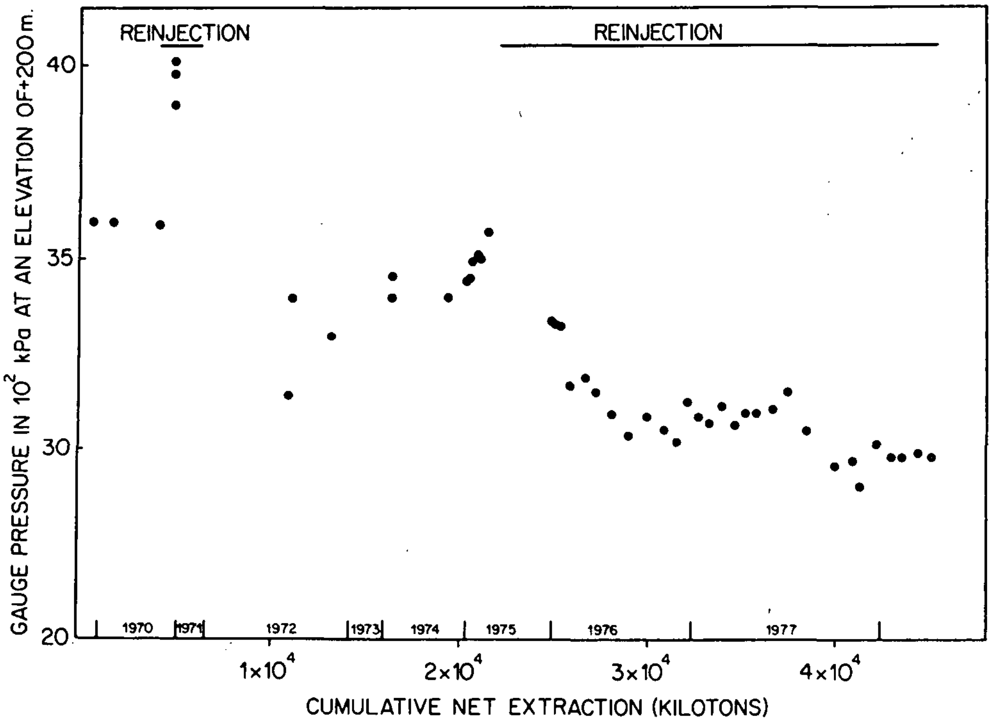

Figure 12.7. Graph showing reservoir pressure change at Ahuachapán as a function of cumulative net extraction of fluid. Note that time scale is not linear

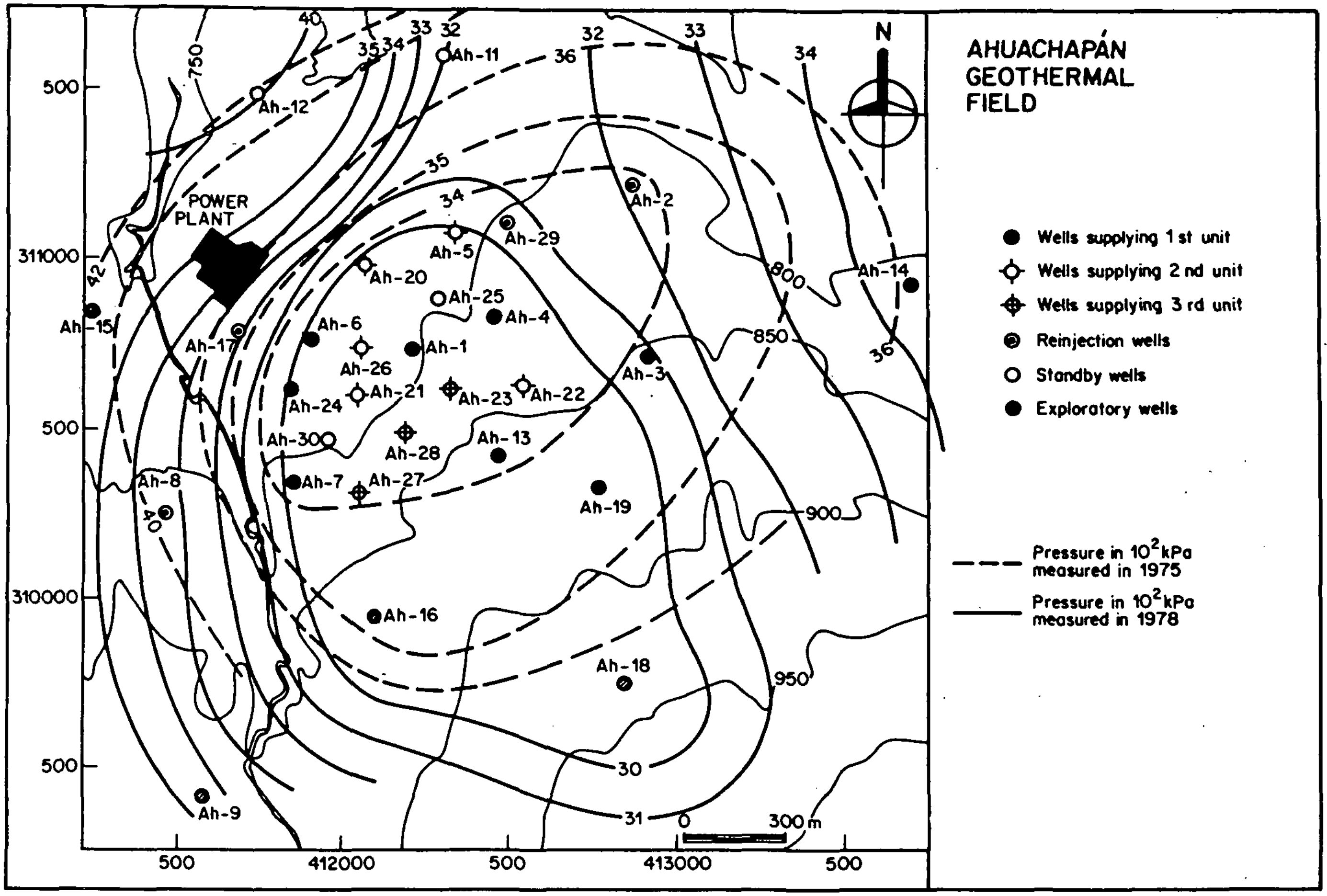

Figure 12.8. Map showing wells at Ahuachapán geothermal field and change in pressure at 200 m above sea level between 1975 (heavy dashed lines) and 1978 (heavy solid lines). Light lines are topographic contours in m above sea level

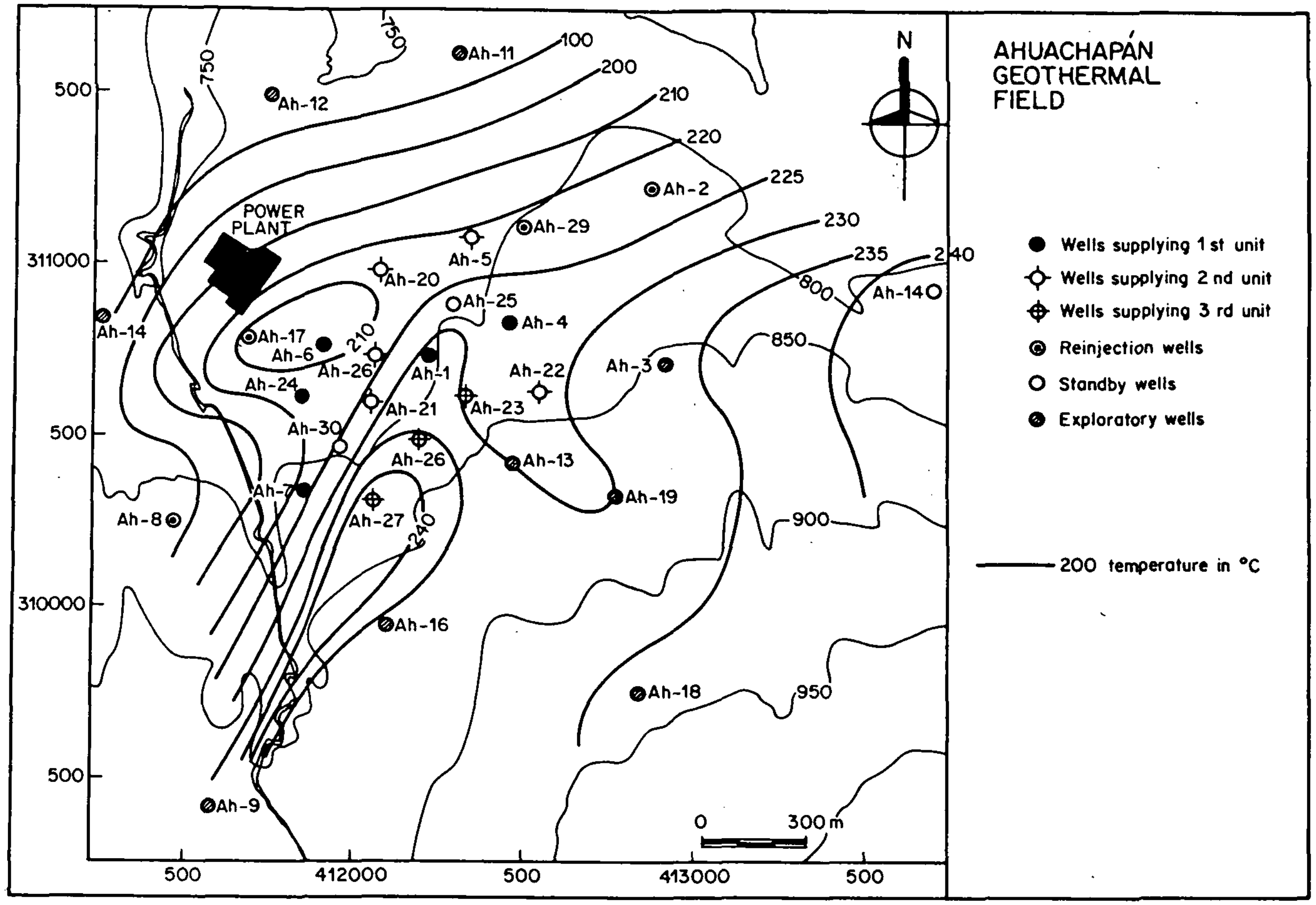

Figure 12.9. Map showing geothermal wells and reservoir temperatures (heavy lines) at Ahuachapán based on experimental quartz-water equilibria and on chemical analyses of silica in reservoir water in 1978. Light lines are topographic contours in m above sea level

pressure depends on the reinjection and extraction rates and therefore on the net mass extraction. With the starting of intensive production, the pressure decreases but tends to stabilize once the new equilibrium state is reached as a consequence of the reinjection and the development of a steam zone in the structural high of the reservoir. It seems difficult to determine which of the two effects is dominant.

The pressure distributions in the reservoir before and after intensive extraction are shown in Figure 12.8. The pressure sink is spreading toward the south, where more permeability has been found. In the east and west directions, in which the reservoir is limited, the pressure response has been minimum.

12.6.2. *Temperatures*

Reservoir temperatures have been calculated from chemical analyses for silica in reservoir water in 1975 and 1978, using the experimental equilibrium between quartz and water. In 1975 the 230°C isothermal line included all the production wells, but Figure 12.9 shows that in 1978 the same isotherm had contracted to include only production wells Ah-27, Ah-26, and Ah-1.

The distribution of reservoir temperatures (Figure 12.9) is influenced by well depth, by reinjection, and by the development of a steam zone in the structural high of the reservoir. The low-temperature zone in the region of well Ah-6 corresponds to this structural high and is near to the reinjection well, Ah-17. It is believed, however, that the predominant effect is due to boiling, since the temperature decrease in the zone occurred prior to operation of the reinjection well.

The distribution of temperatures also shows two additional things: (1) temperatures increase to the southwest, which seems to be the direction from which recharge occurs, and (2) temperatures increase towards the southeast, where the rocks have lower permeability and conductive heat transfer plays a bigger role.

12.7. Conclusions

The results of the intensive extraction of Ahuachapán can be summarized as follows:

1. The reservoir pressure has decreased below the saturation pressure corresponding to the reservoir temperature, thus causing boiling in the formation and the development of a steam zone in the structural high.
2. The temperature has reached an equilibrium state in response to the new pressure.
3. The extraction rate for total mass has decreased as a consequence of the decreasing pressure. However, this does not indicate a remarkable decrease in the amount of available steam.
4. Stabilization of the pressure appears to result both from control of the reinjection rate and from the development of a steam zone.

References

Wiesemann, G., 1973. 'Arbeiten der Bundesanstalt für Bodenforschung in der Republik El Salvador in den Jahren 1967–1971', *Münster. Forsch. Geol. Paläont.*, **31/32**, 277–285.

Williams, Howel, and Meyer-Abich, Helmut, 1955, 'Volcanism in the southern part of El Salvador, with particular reference to the collapse basins of Lakes Coatequepue and Ilopango', *Univ. Calif. Pubs. Geol. Sci.*, **32**, 1–64.

Bibliography

Baldo, L., Cozzini, M., and Carrena, E., 1977. 'Aprovechamiento del fluido geotermico del campo de Ahuachapán (El Salvador)', *Proc. Internat. Symposium on Geothermal Energy, Guatemala City, October 1976*, Rome, Istituto Italo–Latino Americano, 411–431.

Choussy, M. E., and Penate, T. S., 1977. 'Campo geotermico de Ahuachapán despues de un ano de exploitacion', *Proc. Internat. Symposium on Geothermal Energy, Guatemala City, October 1976*, Rome. Istituto Italo–Latino Americano, 527–552.

Cuéllar, Gustavo, 1976. 'Comportiamento del la silice en aguas geotermicas de desecho', *Proc. 2nd United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, May 1975*, 1337–1343 (English translation on pp. 1343–1347).

Cuéllar, Gustavo, Rentana, M. E., and Diaz, Oscar, 1978. 'Recursos geotermicos en El Salvador', *Simposio sobre Exploration*, OLADE, Quito, Equador, March 1978, 15 pp.

DiPippo, Ronald, 1978. 'The geothermal power station at Ahuachapán, El Salvador', *Geothermal Energy Magazine*, **6**, 11–22.

Retana, M. E., and A. Maltez, M., 1977. 'Estado actual de las investigaciones geotermicas en la zona oriente de El Salvador', *Proc. International Symposium on Geothermal Energy, Guatemala City, October 1976*, Rome, Istituto Italo-Latino Americano, 273–313.

Romagnoli, P., Cuéllar, G., Jimenez, M., and Ghezzi, G. (1976), 'Aspectos hidrogeologicos del camp geotermico de Ahuachapán, El Salvador', *Proc. 2nd United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, May 1875*, 563–570 (with English translation 541–574).

Sigvaldason, G. E., and Cuéllar, G., 1970. 'Geochemistry of the Ahuachapán thermal area, El Salvador, Central America', *Geothermics*, Special Issue 2, **2**, 1392–1399.

Vides, Alberto, 1976. 'Investigaciones recientes en el campo geotermico de Ahuachapán', *Proc. 2nd United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, May 1975*, 1835–1850 (with English translation, 1851–1854).