

TWENTY YEARS OF EXPLOITATION AT AHUACHAPAN GEOTHERMAL FIELD AN ASSESSMENT OF THE CHEMICAL AND PHYSICAL RESERVOIR PARAMETERS

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ABSTRACT

A general review of the chemical changes which have occurred in the reservoir of Ahuachapan geothermal field is given with emphasis on the main processes resulting from intensive mass extraction in twenty years of commercial exploitation. New data and several new geochemical interpretations have been incorporated into the chemical conceptual model. The main discovery is that two different recharge fluids are moving into the well field. The main hot fluid recharge comes from the South near the Laguna Verde volcanic complex and moves through the field mixing with cold water inflow from above mainly at the SE part. Due to the fault system, the main recharge from the upflow zone reaches the SW part as undiluted fluid, as indicated by the salinity and geothermometer temperatures that are almost the same as original values (near 9000 mg/kg and 240°C respectively). In the central and NE parts of the reservoir the fluid is strongly affected by the above recharge water. The gas results suggest a deep fluid contribution with maximum temperatures around 300 °C. The increase in gas contents developed over the years suggests an open boundary at the bottom of the reservoir. This means that magmatic fluid can ascend through fractures or the matrix of the basement rock. The reservoir processes governing fluid chemistry seems to be dilution from above or lateral inflow of relatively cold water, boiling and a high temperature fluid recharge.

INTRODUCTION

The Ahuachapan geothermal field has been monitored systematically since 1975 when continuous power generation started. Figure 1 shows well locations with the contours of reservoir temperature computed by the silica geothermometer in 1995 (Fournier and Potter, 1982). The long

chemical history of the water and gas chemistry of 14 production wells have been compiled and interpreted. Previous studies for Ahuachapan geothermal field are in Truesdell et al. 1989, Steingrímsson et al. 1991, Aunzo et al. 1991, Montalvo 1994 and D'Amore 1996.

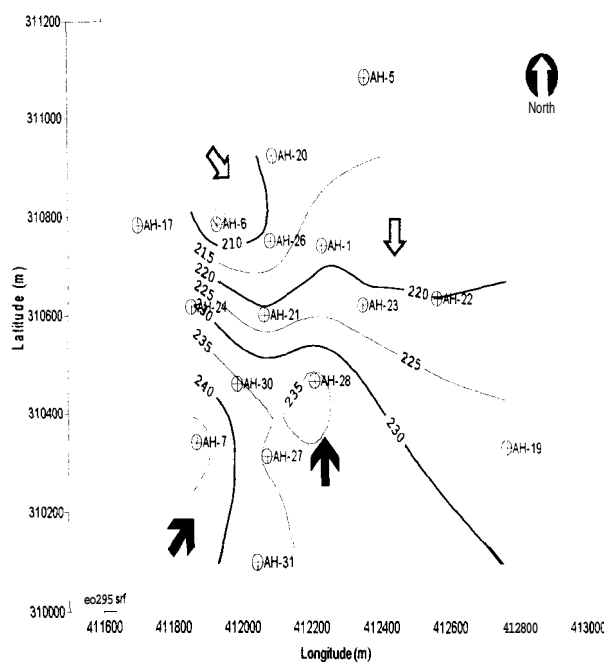


Figure 1. Silica temperature distribution in 1995

Several chemical methods and parameters have been studied in order to select the most useful guides to the changes in chemistry with time. The evolution of the concentration of conservative species such as chloride, the chloride/sulfate ratio, the enthalpy temperature, geothermometer temperatures and the chloride-enthalpy mixing model are each important as indicators of processes affecting the reservoir fluid like dilution, boiling and conductive heat transfer from the rocks. Important information related to

mineral saturation is also provided by the use of the chemical simulation code WATCH. The evaluation of steam reservoir evolution and estimation of the highest temperatures of the system are given by the Grid method (D'Amore and Truesdell, 1985) using the gas contents of wellhead in the total fluid.

This information together with monitoring of surface manifestations are useful in clarifying fluid movement changes due exploitation. Figure 2 presents a general hydrological model for the Ahuachapan-Chipilapa geothermal system modified from the natural state model of Aunzo et al. (1991).

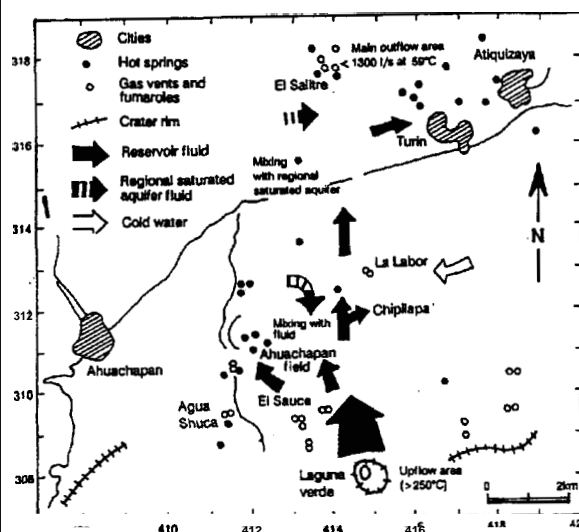


Figure 2. Hydrological flow conceptual model

CHEMICAL TIME VARIATIONS

A systematic analysis of chemical data shows a predominant dilution trend for all the production wells. In order to give a typical overview of the evolution of Ahuachapan water chemistry, two wells were identified as representatives of the different reservoir behavior observed.

Well AH-1 was chosen for its marked tendency to produce more diluted waters and for its low discharge enthalpy, and well AH-6 chosen for its tendency to produce progressively more saline fluid and for its evolution to higher enthalpy discharge.

Most of the wells show a slight enthalpy decline, and some wells have almost constant enthalpy. This is true both for measured enthalpy and for that based on geothermometer temperatures.

This dilution and decline in reservoir enthalpy characterizes wells in the northern and northeastern sectors of the wellfield. In the south and southeast,

however, stable conditions are observed and the NaKCa geothermometer indicates unchanged temperatures that could result from recharge of hot fluid. We must also take into account the strong cooling trend indicated by cationic geothermometers for some wells up to 1988 and for others up to 1991, after which the indicated temperatures started to rise. This is interpreted as showing two main sources of recharge to the wellfield. Complementary information from the evolution of gas contents, gives evidence of a contribution from fluid originating in the deepest part of the system.

The following table presents values for each well of the different parameters at initial and present reservoir conditions.

WELL	YEAR	Cl res ppm	CaSO4 mg/l00a	CO2 dt	%W	T SiO2 °C	NaKCa °C	Na/K °C	TDP1 °C	Watch °C	Tm °C
AH-1	1975	8201	414	2.65	0.04	234.1	260.2	259.0	233.5	228	240
	1994	6381	187	4.14	0.10	219.4	252.1	250.0	295	208	210
AH-6	1975	8172	403	10.53	0.09	226.9	257.2	252.9	265.5	233	235
	1995	7486	197	220.4	0.84	204.0	248.6	243.3	2367	205	205
AH-7	1975	10072	489	10.84	0.20	245.2	261.5	259.9		294	
	1994	9760	559	16.89	0.31	247.7	259.1	255.0		268	
AH-19	1984	6501	251	22.20	0.48	226.2	241.0	234.2			
	1994	6103	200	7.66	0.15	227.1	245.0	239.6		278	
AH-20	1983	6382	236	33.40	0.28	219.9	245.0	238.6	269.8	233	225
	1995	6020	175	23.15	0.33	212.0	246.3	240.5	252.7	203	200
AH-21	1977	9512	321	6.62	0.12	232.4	256.9	251.1	249.5	230	230
	1995	8362	371	17.46	0.32	221.4	261.3	261.0	254.1	223	225
AH-22	1977	6922	246	30.38	0.41	232.7	239.0	217.7			
	1995	5460	181	77.28	0.62	219.6	241.0	234.4		2374	
AH-23	1980	6887	242	41.38	0.47	224.6	245.7	238.5		234	230
	1995	5583	187	104.1	0.93	220.7	247.7	241.5	226.6	215	210
AH-24	1978	9278	583	7.38	0.11	247.3	261.6	259.8		290	
	1995	8745	432	11.92	0.24	233.0	267.7	275.7		264	
AH-26	1977	7965	288	115.6	0.65	229.7	253.9	250.2			
	1995	6203	183	132.5	0.80	210.9	246.0	242.0		234	
AH-27	1980	7650	496	40.06	0.45	241.0	262.5	262.5		245	240
	1995	6415	297	87.30	0.91	233.7	261.1	260.8		227	211
AH-29	1980	6836	339	4.95	0.08	232.0	254.8	250.7		237.8	
	1993	7268	284	15.94	0.30	235.6	255.1	256.3		255.6	
AH-31	1985	8729	480	0.88	0.02	244.3	257.0	290.8			
	1995	8195	306	9.26	0.18	236.4	265.6	271.1		216.5	

Table 1. Annual average parameters values at initial and present conditions

Note: CO₂ dt (total discharge), T SiO₂ (Fournier and Potter 1982), T NaKCa (Fournier and Truesdell, 1973), T Na/K (Truesdell, 1976), T DP (D'Amore and Panichi, 1982), WATCH (Arnorsson et al., 1982), Tm (measured temperature).

There are also wells with different features, like dry-steam producer AH-17 located in the centre of the

field (showing a behaviour similar to well AH-6), which developed silica scaling but after cleaning is operated at higher well-head pressure without any problem. Also well AH-32 located in the South part of the field and close to the upflow zone which developed calcite scale after few months of production. Due to drilling problems after cleaning, another directional well in the same site was drilled without reaching the original feed zone, so at present the well is in observation. The interpretations for these two wells are not included here because of the lack of chemical data.

Water Chemistry

Chemical species and ratios were plotted against the time using chemical data for the wells collected from the start of exploitation to present. The chloride histories of selected liquid and two-phase wells are shown on Figure 3 based on annual average values .

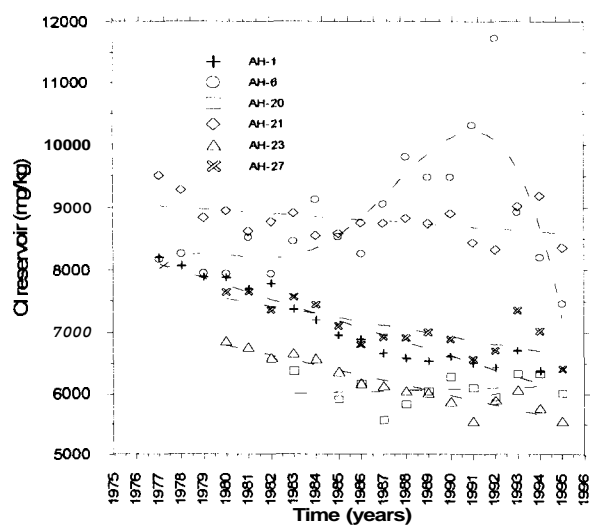


Fig. 3. Chloride reservoir for selected wells

The reservoir chloride concentration of well AH-1 fluid declined from around 8000 ppm in the early years of production to 6500 ppm for the last data. This represents a dilution of about 19%. The decline was gradual until 1987 but has shown some stabilization in the last few years. On the other hand, well AH-6 shows, some scatter but a clear trend towards increased reservoir chloride concentration up to 1992. Only in the last three years have values been observed lower than in earlier years. Such change could be related to fluctuations in the liquid mass flow rate due to the lower mass extraction in the field and lateral dilution. Well AH-21 shows a moderate decrease in chloride at the beginning, some

stabilization later and finally some scattering values in accordance with the lower variations of enthalpy and total mass flow rate in the last years. Well AH-20 shows almost constant chloride trend over the years instead of the increasing water flow rate and decreasing enthalpy values for the last years.

Figure 4 shows that dilution also affects the chemical evolution of well AH-6 in spite of the increase in measured enthalpy related to boiling (Fig. 9).

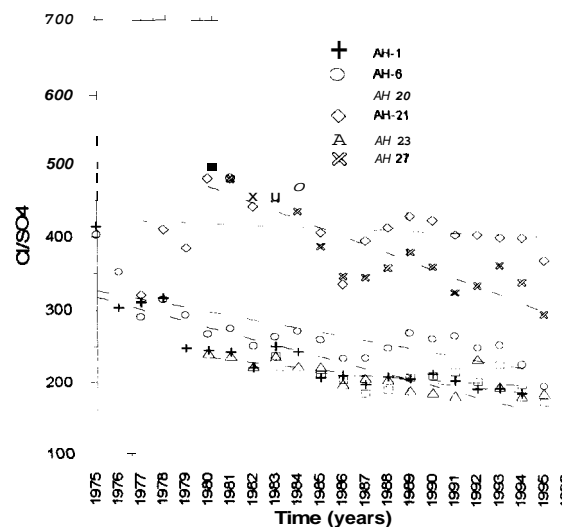


Fig. 4. Chloride-sulfate ratio evolution

Figure 4 shows the evolution of the Cl/SO₄ ratio. General decrease is observed probably due to lateral dilution and constant or increasing values of sulfate due to the deep recharge. According to Watch simulation results the anhydrite is not present in the reservoir as a primary mineral then the increase in sulfate concentration can not be due to cooling of fluid by dilution.

During exploitation a decrease of pH in one unit in average and increase of computed partial pressure of CO₂, H₂ and H₂O in almost all wells up to 8 times were observed. The only explanation of this is consistent with an inflow from beneath the productive horizon of hot acidic and gassed fluid.

The cationic geothermometers results in Figures 5 and 6 show in general a clear cooling trend up to 1985-87 and stabilization and recovery after that. This is possible related to the inflow of some deep recharge fluid in the local aquifer.

The silica geothermometer, however also shows an initial decline but followed by an abrupt increase

from around 1985-1987 to 1991 when decline started again. This may be related to boiling that increases the silica concentrations followed by renewed dilution. There is no physical evidence that quartz deposition occurred.

The average of Na/K temperatures ranges between 230-250°C and those of NaKCa between 240-255°C. The cationic geothermometers are not strongly affected by the process of dilution and the cooling of the system. In figures 5 and 6 the relative position of the observed trend seems to be related to different feed zones: a shallow one above 500 m, and a deeper horizon around 1000 m. Then the lower cationic geotemperature are in general observed for the shallow wells.

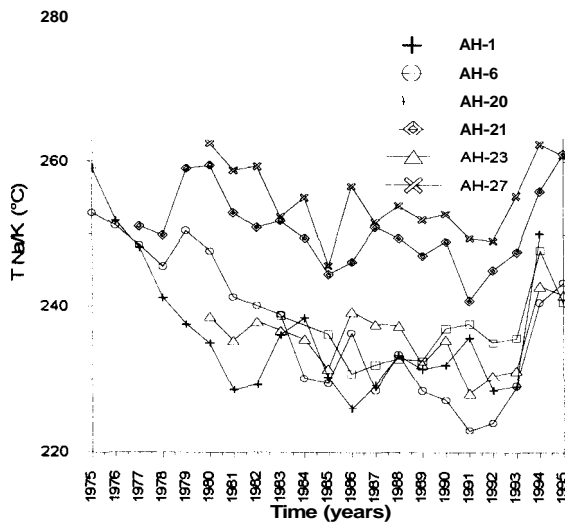


Fig. 5. Evolution of Na/K temperatures.

The enthalpy evolution of Ahuachapan production wells revealed by the comparison between the measured enthalpy and the liquid-phase enthalpy values calculated from geothermometer temperatures is summarized for all the wells in Table 2 and shown in Figures 8 and 9 for two representative wells AH-1 and AH-6 respectively.

Boiling lowers fluid temperatures within expanding boiling zones with progressively decreasing pressures as the fluid follows the two-phase liquid-vapor curve. The near-well fluid is cooled by boiling, and heat is transferred to the fluid from the reservoir rocks, probably as a result of flashing flow in fractures.

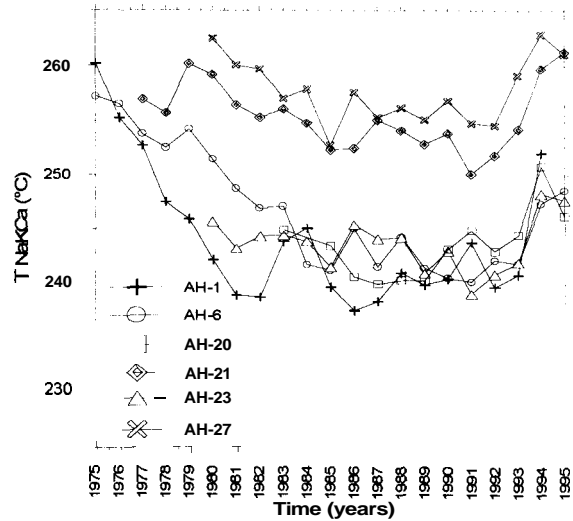


Fig. 6. Evolution of NaKCa temperatures.

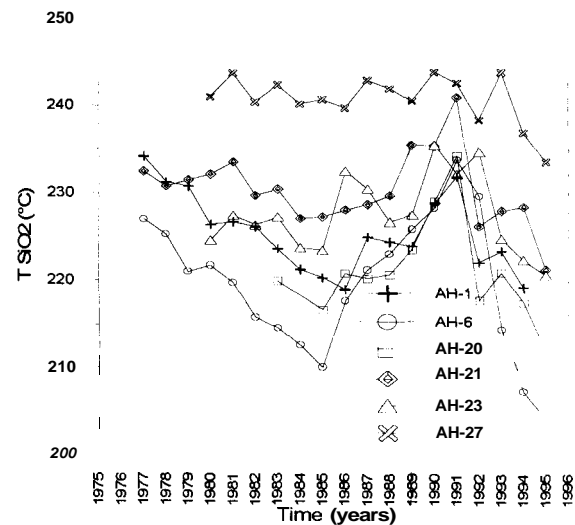


Fig. 7. Evolution of silica temperatures.

Wells	Prevalent order	Indicated process
AH-1, AH-7, AH-19, AH-21, AH-24, AH-28, AH-31	$H_{NaKCa} > H_{SiO2} > H_m$	mixture of cooler more diluted water
AH-6, AH-22, AH-23, AH-26, AH-20, AH-27	$H_m > H_{NaKCa} > H_{SiO2}$	boiling during flow to the well

Table 2. Main processes occurring in production wells. H_m (measured enthalpy); H_{NaKCa} and H_{SiO2} (geothermometer enthalpy values)

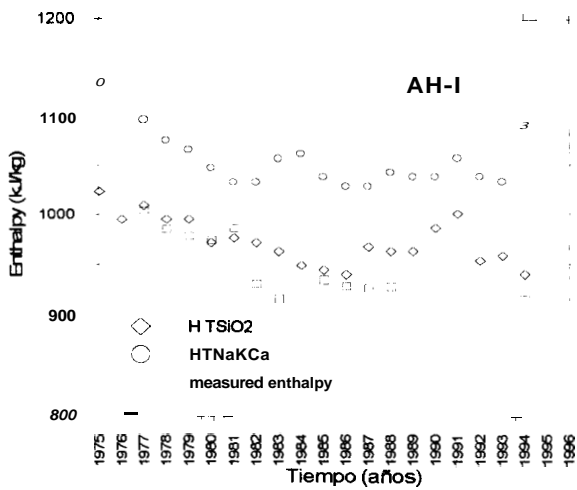


Fig. 8. Evolution of enthalpy in AH-1

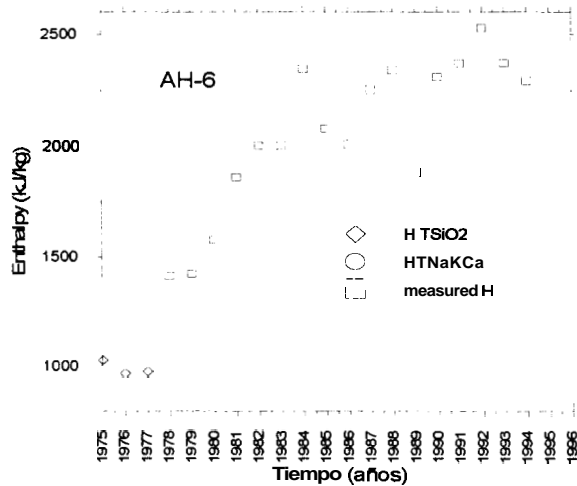


Fig. 9. Evolution of enthalpy in AH-6

Figures 10 and 11 show enthalpy-chloride relations for Ahuachapan wells. Reservoir chloride and measured discharge enthalpy for low- and moderate-enthalpy wells is shown, but for high-enthalpy wells the enthalpy calculated from NaKCa geothermometer temperatures is used. Figure 10 clearly show typical dilution for some of the low enthalpy wells, which causes a decrease in enthalpy and chloride with time because of dilution from relative cold water. A complex trend is evident for the high enthalpy wells (Fig. 11) that could be related to boiling and heat transfer combined with cooling and dilution processes.

Wells such as AH-19, AH-26, AH-28 and AH-31 show almost constant enthalpy and some decrease in reservoir chloride. Wells AH-22, AH-23 and AH-27 shows a decrease with time in chloride content and

an increase in enthalpy. On the other hand, wells AH-20, shows large decrease in enthalpy and slight in chloride.

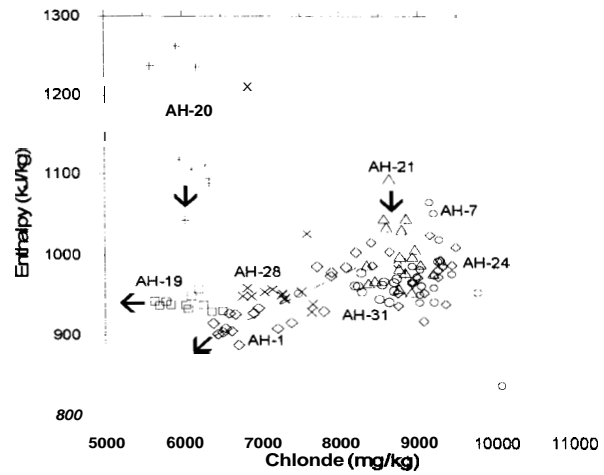


Fig. 10. Enthalpy-chloride for low enthalpy wells

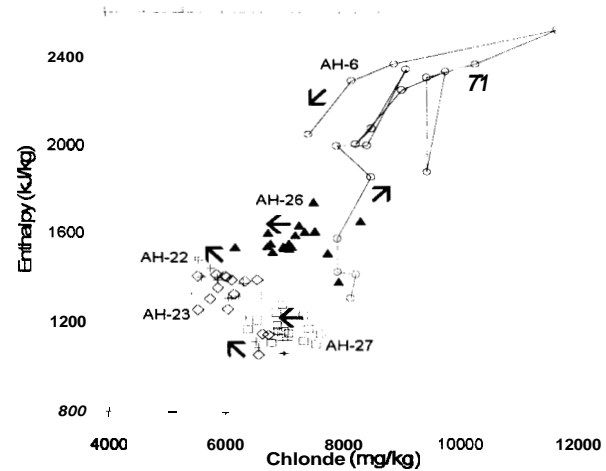


Fig. 11. Enthalpy-chloride for high-enthalpy wells

Finally wells AH-1, AH-7, AH-21 and AH-24 uniformly show a marked decrease in enthalpy and in chloride. With the methods presented here it becomes complicated to describe the origins of the different types of behavior due to boiling, dilution or other reservoir processes because of the complex behaviour that each well can show during exploitation. The present analysis can be considered as qualitative. In the vicinity of a particular well several mechanism can be assumed to explain the different tendencies described above. Boiling, heat transfer from the rock and steam addition can change the enthalpy without changing the chloride (Truesdell et al., 1988).

Gas Chemistry

Several observations can be made, considering the observed variations with time of gas compositions. Figure 12 shows the evolution of CO₂ total discharge compositions considered representative of the total gas content in the wells.

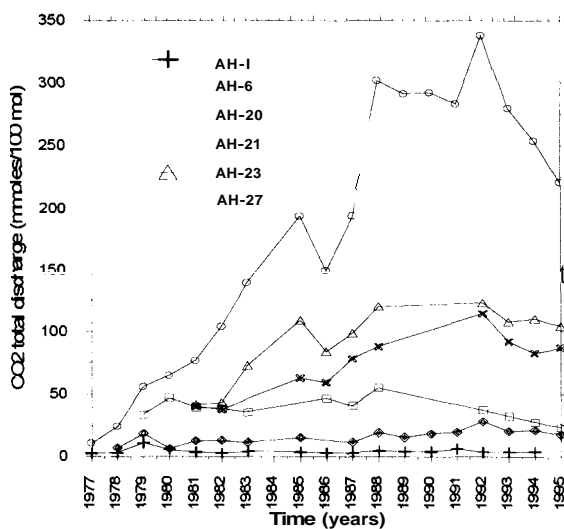


Fig. 12. CO₂ evolution for selected wells

Wells producing liquid have shown almost constant gas content through the years whereas a marked increase in gas concentration is observed in high-enthalpy wells. This increase in reservoir gas ranged in weight percent between 0.1% for well AH-1 to 0.8% for well AH-6.

On grid diagrams (D'Amore and Truesdell, 1985), all wells show a general increase of reservoir steam fraction y , from negative or zero values up to a maximum of 0.02-0.05 (for wells AH-6 and AH-17 respectively showing the highest value of enthalpy). The initial negative values are consistent with degassing of the original local reservoir water at starting conditions (as at Wairakei geothermal field), with a subsequent inflow of deep fluid rich in gas with a different composition producing the observed increase of y and T values, which with time cross the $y = 0$ line. For well AH-6, which is affected by the deep fluid, computed temperatures increase up to 290°C. This suggests that the temperature of the fluid in the deep reservoir would exceed 300°C.

The contribution of the deep fluid is shown in the temperature range for each well increasing in order:

- AH-1 between 200 and 225°C
- AH-20 between 235 and 255°C

- AH-21, AH-23 and AH-27 between 250 to 270°C
- AH-6 and AH-17 between 275 and 300°C

Figures 13 and 14 show the grid end member wells AH-1 and AH-6.

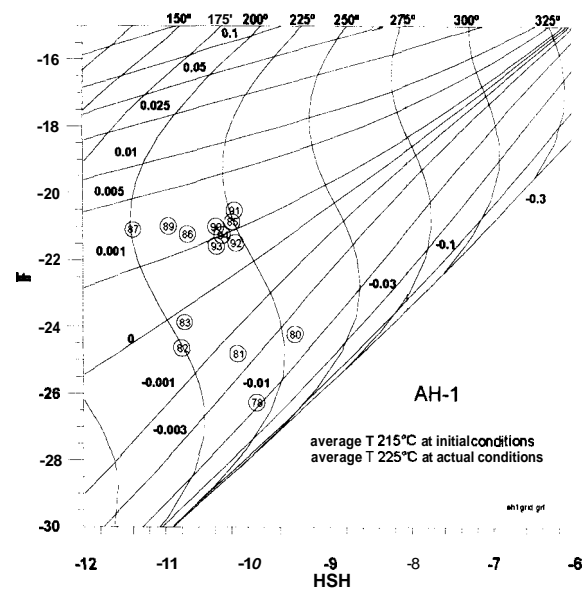


Fig. 13. Grid diagram showing the AH-1 evolution

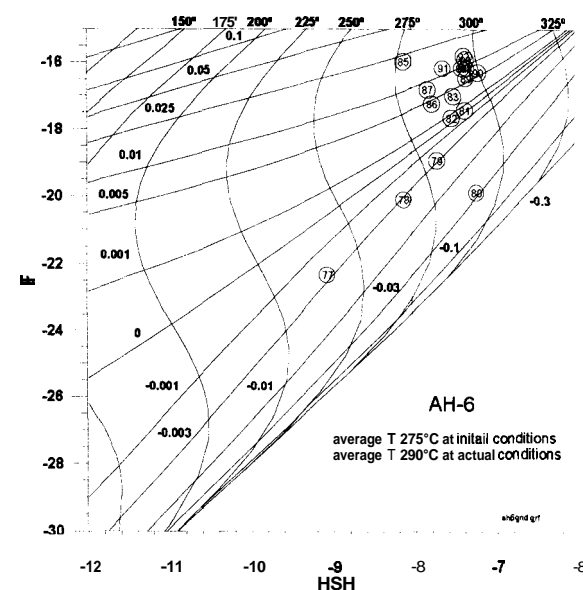


Fig. 14. Grid diagram showing the AH-6 evolution

The increase with time in reactive gas and gas partial pressure together with the computed y and the grid temperature is quite peculiar to the Ahuachapan field. Wairakei shows a strong decrease of gas content with boiling, down to very negative y values (Giggenbach, 1980). However Wairakei is

characterized by a reservoir sealed at the bottom and open to lateral recharge, whereas the Ahuachapan shallow reservoir is open to lateral and deep recharge as well as natural recharge from above. Similar behavior characterizes wells of the Palinpinon field located close to the heat source (D'Amore et al., 1993).

The relative contents of Ar-N₂-He at present conditions are reported in a triangular diagram on Figure 15. The points for selected wells and El Playon fumarole (which is located into the wellfield) are located between air saturated water and a magmatic-andesitic component (about 50%). This is inferred because of the high ratios of both N₂/Ar and N₂/He. In the diagram it is supposed a pure meteoric origin for argon. He is supposed to be originated from mantle.

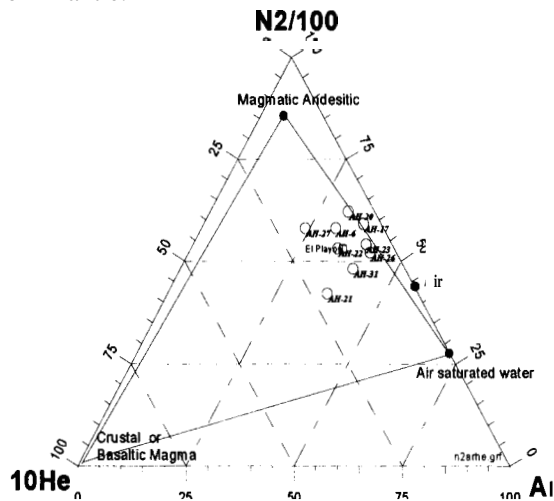


Fig. 15. N₂-Ar-He relative composition for selected wells and El Playon fumarole

Chemical parameter distribution

In order to illustrate the main changes which production wells have shown from the early exploitation period to the present, several figures can be drawn showing the areal distribution of reservoir chloride, quartz, Na/K and Na/KCa geothermometers, the measured discharge enthalpy, and the gas-steam ratio (in wt% at separator pressure). The chloride distribution has been chosen as representative of the two main recharge fluids that are consistent with the geothermometer temperatures. Fluid movement into the wellfield is shown in Figures 16 and 17 and these changes were included in the hydrological flow model on Fig. 2.

Geothermometer temperatures and chloride concentrations suggest an inflow of hot fluid in the SW part of the wellfield (upflow zone) with original temperatures from 240 up to 260°C, and 8000 to 9000 mg/kg of chloride. Moreover the dilution due to the natural recharge water from above is mainly from NE. On the other hand, the distribution of enthalpy at different periods of time clearly show a boiling zone located mainly around wells AH-6 and AH-17.

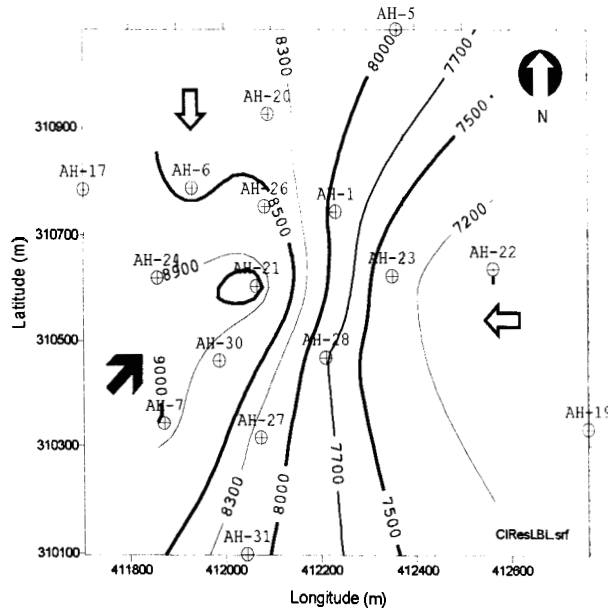


Fig. 15. Initial reservoir chloride distribution

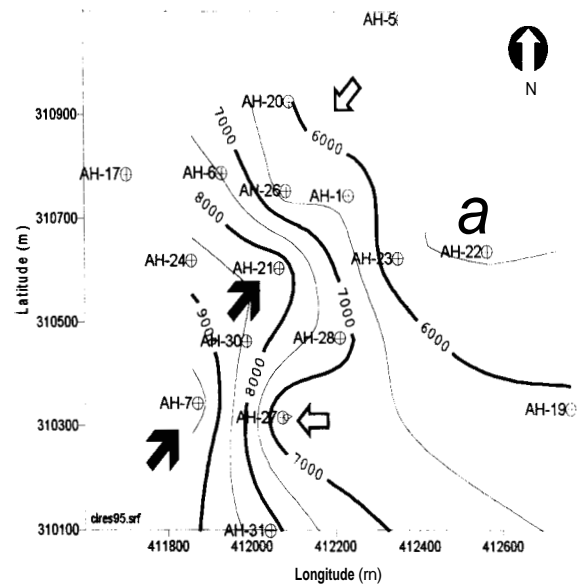


Fig. 16. Present reservoir chloride distribution

GAS-WATER-ROCK INTERACTION PROCESSES

Simulations of gas-water-rock interactions have been made using the Watch code. From observed petrography the following mineral species have been considered: calcite, pyrite, quartz, wairakite, laumontite, prehnite, zoisite, epidote, K-feldspar and low-albite. We add anhydrite to explain the SO₄ content and diopside for the Mg content. Indeed, the system is undersaturated in Mg-chloride at all temperatures, probably because the local chloride is a Mg-Fe solid solution. This may explain why the Na-K-Mg triangular diagram of Giggenbach (1988), produces unrealistic temperatures, as his method considers K-mica and pure Mg-chloride as present.

All the minerals considered (except anhydrite) have actually been observed in petrographic analysis of well cuttings. Moreover, the mineral assemblage considered here has been found in similar andesitic system like the fields in Phillipines. In the case of dilution of the reservoir water from the recharge water for Ahuachapan, all minerals are undersaturated with exception of anhydrite, quartz, laumontite, low-albite and K-feldspar. At initial conditions, epidote and prehnite are always present.

It should be stressed that the temperatures calculated by Watch, the measured temperatures and those from the weirbox SiO₂ contents are consistent among themselves and with lateral recharge of water with low or nil gas contents. Figures 18 and 19 show the cooling observed in well AH-1.

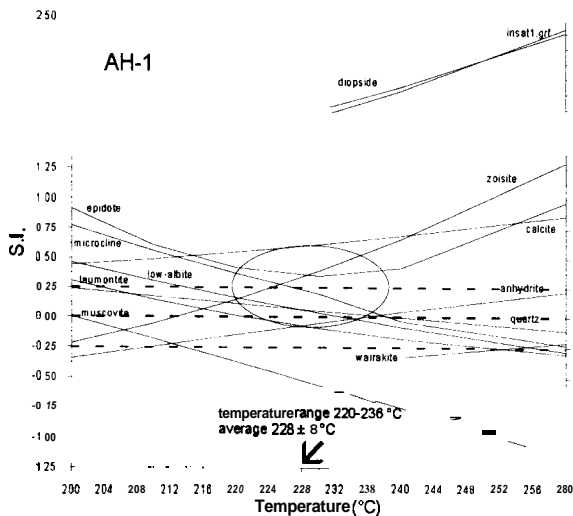


Fig. 17. Initial saturation indexes for well AH-1

The saturation indexes for selected minerals at initial conditions calculated by Watch, have also been used to show that with present conditions there is no evidence of potential scaling (e.g. calcite).

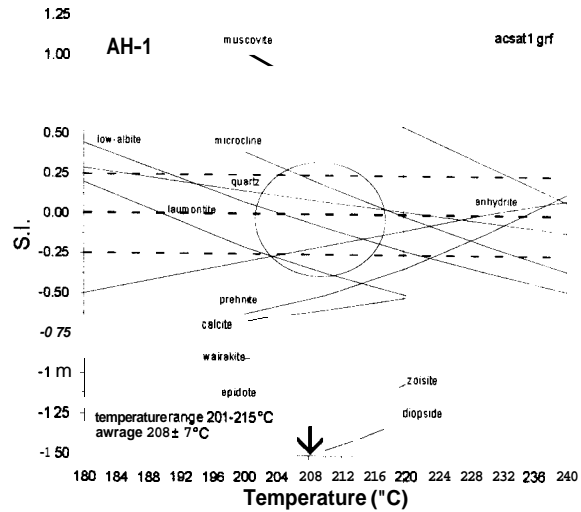


Fig. 18. Present saturation indexes for well AH-1

CONCLUDING REMARKS

- The field is mainly recharged by two fluids: a hot deep fluid rich in gas and sulfates with low pH, and natural recharge flowing from above. The cold water recharge, after interaction with rock, becomes a fluid with a moderate salinity and temperature (around 1000 ppm and 160°C; Montalvo, 1994).
- The dominant reservoir processes of the Ahuachapan field due to exploitation without reinjection are dilution from the cold water recharge from NE and boiling, but the inflow of deep fluid also influences the chemistry and thermodynamic equilibrium for some wells.
- The temperatures generated from S.I. values are consistent with measured values both at starting and present production conditions showing a general dilution and cooling in the shallow original production zone.
- The hot fluid recharge in the SW part of the wellfield has produced reservoir waters with salinity and temperature similar to initial values.
- Considering gas composition the temperature of the deep fluid would exceed 300 °C.
- Scaling potential estimates show undersaturation for almost all minerals considered, so there is no evidence of scaling risk under present conditions.

Figure 20 summarizes the different fluids that move into the Ahuachapan reservoir: a) the inflow of the old water from the saturated regional aquifer as the main source for the dilution and cooling processes; b) the recharge of deep fluid entering the reservoir laterally (main upflow) is responsible for the increment of the fluid temperature for the last 4-5 years regarding the cationic geothermometers; and c) the gassy fluid originated probably from the deepest part of the exploited reservoir that present the highest temperature of the system.

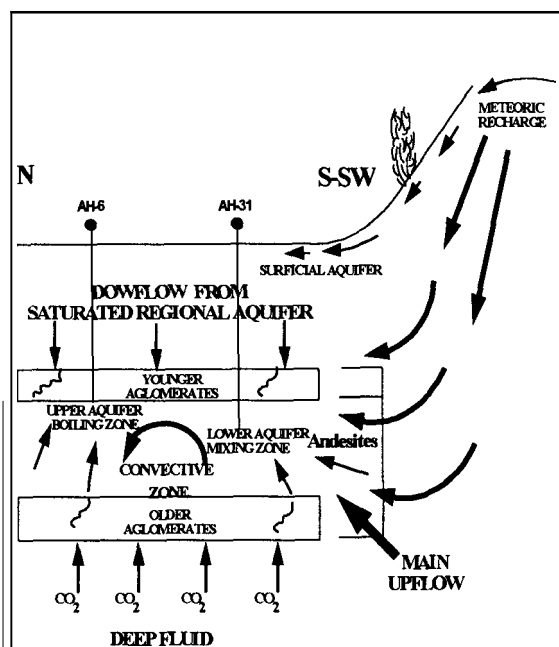


Fig. 20. Schematic representation of the different fluids moving into the Ahuachapan geothermal reservoir

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