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HETEROGENEITY OF THE LIQUID PHASE, AND VAPOR SEPARATION IN LOS AZUFRES (MEXICO) GEOTHERMAL RESERVOIR

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ABSTRACT

Data of chemical and isotopic composition of fluids from Los Azufres geothermal wells is interpreted in order to characterize the composition of the liquid phase, and to define the relation between this phase and fluids from steam-producing wells.

Chemical and specific enthalpy data show that most wells considered are fed a mixture of steam and liquid. Thus, flashing occurs in the formation. This poses a problem on the interpretation of isotopic data, because the composition of the feeding mixture need not be representative of the composition of the liquid phase in the reservoir. Two extreme alternatives for the interpretation of isotopic data are considered. In the first alternative the composition of the total discharge is considered to be the same as that of the liquid in the reservoir. In the second alternative the feeding fluid is considered to be a mixture of the liquid phase in the reservoir and the calculated fraction of steam. In addition, this steam is assumed to separate from a much larger mass of that liquid phase at the downhole temperature. The contribution of steam is then substracted from the total discharge to yield the composition of the liquid phase. Using data for silica concentration in total discharge and separated water, the chloride concentration in the reservoir liquid is calculated. This result is used to calculate the fraction of steam in the feeding mixture of each well. The isotopic data is then corrected as proposed for the second alternative, to yield the composition of the liquid phase. Comparison of the corrected and uncorrected isotopic valuesshows that the correction has an important effect only when the steam mass fraction in the feeding mixture is large (> 20%). The correction tends to reduce the dispersion of data points in a δ D vs δ^{18}O diagram. Points representing composition of liquid phase show an approximately linear distribution, suggesting a process of mixing of two fluids. Available data appears to rule out the possibility of mixture with local meteoric or shallow ground waters. Some spatial correlations of composition are noted. The composition of fluids produced by two steam wells corresponds to steam separated from a much larger mass of liquid. Temporal variations in the composition of fluid produced by steam well A-6 suggests that this well might be fed with steam from more than one section in the reservoir.

INTRODUCTION

The chemical and isotopic composition of hydrothermal fluids constitute one of the early important sources of information, which could be used to begin the characterization of a geothermal reservoir. It is particularly important to assemble as complete a set of data as possible from the pre - and early explotation stages, since this would provide valuable information on the natural state of the system. This in turn would make it possible to monitor the changes occurring in the reservoir as exploitation begins and proceeds.

Giggenbach and Quijano (1981) have assembled a set of data of isotopic and chemical composition of fluids from geothermal wells in Los Azufres field, as well as from hydrothermal springs and fumaroles of the area. They have interpreted the evidence in a study of the regional hydrology of the Cuitzeo - Los Azufres area. One of the major findings of this study is the clear difference between the isotopic composition of local meteoric and shallow underground waters, and the composition of the geothermal fluids. The authors have concluded that the reservoir fluid consists of paleowaters, and postulate a relation between the Los Azufres aquifer and thermal springs in the Cuitzeo - Araro area, some 30 kilometers north.

The explored area in Los Azufres field covers an extension of about 30 Km^2 (Fig. 1). The field is located in a mountain range, bounded on two sides by valleys. The average altitude of well heads is 2850-2900 meters above sea level; the valleys lie about 300 m to 500 m below. There are two main sections which have been selected for exploitation, based on favorable temperature and permeability conditions. In the northern section, known as the Maritaro area, one finds only wells that produce a mixture of water and steam. In the southern section, known as the Tejamaniles area, one finds steam-producing wells, interspersed with mixture - producing wells. The present contribution describes the results of a study of the hydrology of the Los Azufres reservoir. The main objective of this investigation has been to determine any possible differences among the liquid phases from the several sections of the field, and to determine the relation between the fluid emanating from steam-producing wells and the liquid phase. We have used a subset of the data included in the work of Giggenbach and Quijano (1981).

OBSERVATIONS

Table 1 shows a set of chemical and isotopic composition data for fluids produced by wells from Los Azufres. The specific enthalpy of the total discharge is also shown. Values for the ionic species and silica refer to their concentration in the liquid separated at atmospheric pressure. The boiling temperature in Los Azufres area is 92°C. The delta values for deuterium and ^{18}O refer to the composition of the total discharge. These values have been calculated from the composition of the liquid separated at atmospheric pressure, using data given by Truesdell et al (1977) for partition coefficients of deuterium and ^{18}O between the vapor and liquid phases.

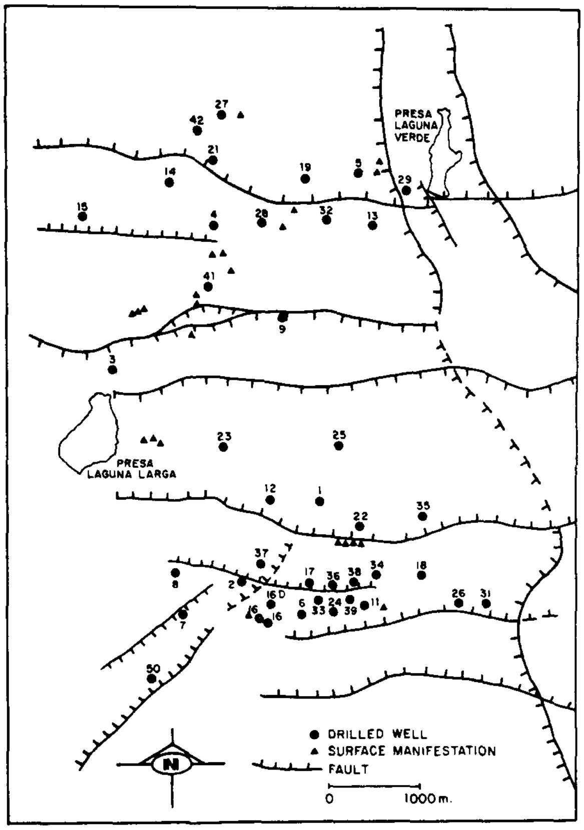

Fig. 1. Map of Los Azufres Geothermal Field.

The Table includes isotopic data for fluids from two steam-producing wells (A-6 and A-17). For some of the mixture-producing wells isotopic but not chemical data is available. Downhole temperatures obtained with Kuster type equipment are shown in Table 2. Also shown are temperatures calculated by means of a *Cationic Composition Geothermometer* (Nieva and Nieva, 1982), the Na-K-Ca geothermometer

TABLE 1.- Chemical and isotopic composition data of Los Azufres fluids.

WELL	H J/g	Na^+	K^+ ppm	Cl^-	SiO_2	^{18}O	D	DATE OF SAMPLING
A-1	1750	-	-	-	-	-3.94	-56.6	20/ 3/82
A-2	1400	-	-	-	-	-4.33	-62.6	20/ 3/82
A-4	1460	1804	499	3270		-4.44	-65.2	8/ 5/80
A-5	1885	1876	534	3320	1160	-4.03	-58.8	29/ 4/80
A-5	1671	1638	465	2870	1250	-4.06	-62.4	13/ 1/81
A-6	2660	-	-	-	-	-4.26	-53.4	8/ 5/80
A-6	2756	-	-	-	-	-4.83	-60.6	13/ 1/81
A-6	2673	-	-	-	-	-5.02	-55.7	20/ 3/82
A-7	1360	1496	250	2460	780	-4.23	-65.0	17/ 4/80
A-8	1570	1606	359	2760	1100	-4.67	-65.8	26/ 4/80
A-13	1234	1499	390	2580	1020	-2.76	-60.4	14/ 1/81
A-13	1490	-	-	-	-	-2.57	-57.2	20/ 3/82
A-16D	1230	-	-	-	-	-3.72	-58.9	20/ 3/82
A-17	2673	-	-	-	-	-5.06	-58.8	20/ 3/82
A-19	2452	1689	475	3060	1050	-5.21	-62.4	13/ 1/81

H = specific enthalpy

(Fournier and Truesdell, 1973) and the revised silica geothermometer (Fournier and Potter II, 1982). In all cases there is good agreement among the values calculated with the different geothermometers. The measured values, on the other hand, seem to be consistently below the calculated values. Furthermore, the measured values would appear to be low also from a consideration of the specific enthalpies of total discharge. Given these observations and the general agreement among the geothermometers, only the latter have been considered in selecting a value of downhole temperature for each well. The selected values are shown in Table 2.

TABLE 2.- Measured and calculated downhole temperatures for Los Azufres wells.

WELL	T MEAS. °C	*T CCG °C	°T Na-K-Ca °C	&T SiO_2 °C	DATE OF SAMPLING
A-1	292	304	-	-	
A-2	280	304	290	285	14/ 4/80
A-4	298	308	314	-	8/ 5/80
A-5	270	311	318	308	13/ 1/81
A-7	249	251	254	262	17/ 4/80
A-8	275	282	286	295	26/ 4/80
A-13	265	300	300	287	14/ 1/81
A-13	265	292	297	280	9/ 2/83
A-16D	260	261	265	255	9/ 2/83
A-18	250	284	290	266	2/ 3/82
A-19	271	310	312	290	13/ 1/81

*CCG = Cationic Composition Geothermometer (Nieva and Nieva, 1982).

°Na-K-Ca Geothermometer (Fournier and Truesdell, 1973).

&SiO_2 = Revised and expanded silica (quartz) Geothermometer (Fournier and Potter, 1982).

In most cases listed in Table 1, the specific enthalpy of the total discharge is considerably in excess of the specific enthalpy of liquid water at the downhole temperature. This implies that phase separation occurs in the formation, so that the wellbore is fed a mixture of steam and liquid. This poses a problem on the interpretation of the isotopic composition of total discharge. This problem arises from the fact that, if phase separation occurs in the formation, there is no certainty that the isotopic composition of the total mixture entering the well is representative of the undisturbed liquid phase in the reservoir. The problem is particularly complex because only part of the steam present in the feeding mixture might represent an excess, the rest of it originating from local boiling (see Truesdell et al, these Proceedings, and Nieva et al, 1982, for a discussion of this problem). In view of the unavailability of the necessary information for the estimation of excess steam, it is decided to consider two extreme alternatives and to compare the final conclusions. The first extreme position is to consider the isotopic composition of the total discharge as identical to that of the liquid phase in the reservoir. The other alternative is to consider as excess all the steam present in the mixture. In this case, it is also to be assumed that the steam has separated from a much larger mass of the reservoir liquid at the downhole temperature. Using partition coefficients for deuterium and ^{18}O, calculated at that temperature, one can correct the isotopic composition of the total discharge in order to obtain the composition of the liquid phase, according to the following expressions:

$$\delta_x^{lp} = (\delta_x^{td} - \Theta) / \Phi \qquad (1)$$

$$\Theta = 1000\ f\ (1 - \alpha) / \alpha \qquad (2)$$

$$\Phi = 1 - f + (f/\alpha) \qquad (3)$$

where f is the fraction of excess steam in the mixture; α is the atomic ratio of ^{18}O over ^{16}O in the steam, divided by the corresponding ratio in the liquid phase, at the downhole temperature. The superscripts lp and td refer to liquid phase and total discharge, respectively. The symbol x stands for ^{18}O or D. In cases where a steam deficit is estimated, the composition of the liquid phase is calculated from:

$$\delta_x^{lp} = (\delta_x^{td} + \Theta) / \Phi \qquad (4)$$

The fraction of steam in the feeding mixture is calculated from the silica concentration in the total discharge and that in the liquid separated at atmospheric pressure. From the latter concentration, and the assumption that the flow inside the borehole occurs adiabatically, one can calculate the downhole temperature (Fournier and Potter II, 1982). In so doing one also obtains the equilibrium concentration of silica in the liquid phase at the calculated downhole temperature. Considering this value and the silica concentration in the total discharge, one obtains the fraction of steam in the feeding mixture by a simple mass balance calculation. Data and results for this calculation are presented in Table 3, for the cases where silica concentrations are available. In all cases except one, the results indicate the presence of a substantial fraction of steam in the feeding mixture; in the case of well A-19 the steam constituted the larger part (80% in weight). For well A-13 a small steam deficit is calculated; given the errors in enthalpy measurements and silica determination, this result probably means that the well was being fed only liquid.

TABLE 3.- Percent steam in feeding mixture calculated from silica concentration. Chloride concentration in the total discharge, and calculated concentration in liquid phase in the reservoir.

WELL	H J/g	T °C (SiO$_2$)	SiO$_2$ ppm			% VAPOR
			s.w.	t.d.	eq.	
A-5	1885	308	1250	427	703	39
A-5	1671	300	1160	505	673	25
A-7	1360	262	780	446	519	14
A-8	1570	295	1100	528	653	19
A-13	1234	287	1020	640	623	-3
A-19	2452	290	1050	97	635	85

H = specific enthalpy of total discharge.
s.w. = Water separated at atmospheric pressure.
t.d. = Total discharge.
e.q. = Equilibrium concentration of silica at estimated downhole temperature.

The values of steam fraction calculated above, and the chloride concentration in the separated water, could be used to estimate the chloride concentration in the liquid phase of the reservoir.

Results of these calculations are shown in Table 4. The general agreement between the several calculated values is clear. Two of the six values deviate noticeably from the rest. Since these values correspond to the cases where the steam fraction was largest, and thus are more likely to result from overcorrections, they were not taken into account for the estimation of an average value of chloride concentration in the reservoir. The value obtained is 1650 ppm.

TABLE 4.- Chloride concentration in total discharge and calculated concentration in the liquid phase of the reservoir.

WELL	CHLORIDE (ppm)	
	total discharge	liquid phase in reservoir
A-5	1134	1868
A-5	1250	1667
A-7	1407	1638
A-8	1325	1638
A-13	1619	1575
A-19	284	1856

Inverting the mass balance calculation referred to in the last paragraph, it is possible to calculate the fraction of steam in the feeding mixture from the chloride concentration in the total discharge, and the average concentration in the liquid phase of the reservoir. Table 5 shows the results obtained for samples listed in Table 1. In a few cases of mixture-producing wells where chemical analysis data are not available, the fraction of steam was calculated by means of an enthalpy balance calculation.

TABLE 5.- Percent steam in feeding mixture calculated from chloride concentration in total discharge. Calculated isotopic composition of liquid phase.

WELL	% STEAM	^{18}O	D	DATE OF SAMPLING
A-1	°29	-3.67	-57.5	20/ 3/82
A-2	° 8	-4.25	-62.9	20/ 3/82
A-4	-4	-4.48	-65.1	8/ 5/80
A-5	31	-3.77	-59.6	29/ 4/80
A-5	24	-3.86	-63.7	13/ 1/81
A-7	15	-4.00	-65.5	17/ 4/80
A-8	20	-4.45	-66.5	26/ 4/80
A-13	2	-2.74	-60.4	20/ 3/82
A-13	°10	-2.47	-57.5	20/ 3/82
A-19	83	-4.53	-64.6	13/ 1/81
A-16D	4	-3.66	-59.1	20/ 3/82

°Chloride concentration not available; calculated from specific enthalpy of total discharge.

DISCUSSION

The uncorrected values of isotopic composition of total discharge are plotted in Fig. 2. It is evident that there is considerable dispersion of the compositions corresponding to mixture-producing wells (represented by circles). The values corresponding to fluids produced by steam wells (represented by triangles) tend to be in the upper left section of the distribution, as would be expected from the values of partition coefficients of the isotopic species

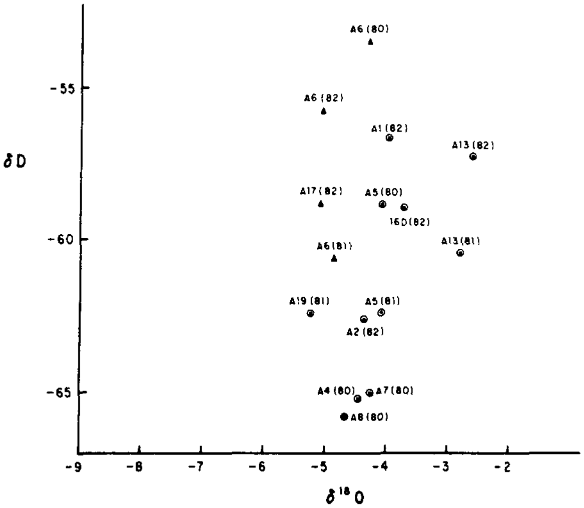

Fig. 2. Isotopic Composition of total discharge from Los Azufres wells. Circles and triangles represent fluids from mixture-producing and steam wells, respectively.

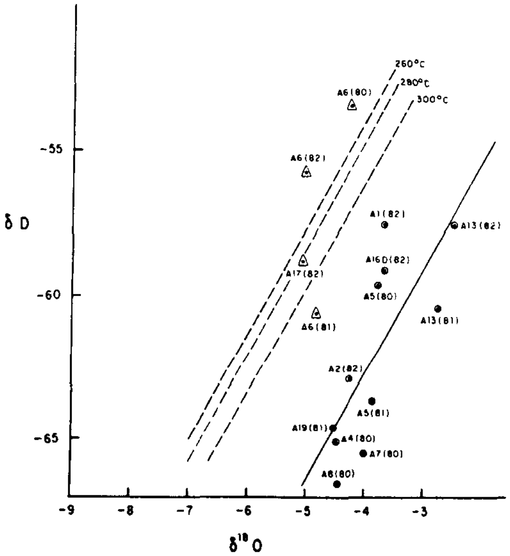

Fig. 3. Isotopic compositions of total discharge after correcting those corresponding to mixture-producing wells, in the manner described in the text. Symbols as for Fig. 2.

between steam and liquid at temperatures above 250 °C.

Fig. 3 presents a plot of the isotopic values, corrected as proposed under the second alternative. Superposition of Figs. 2 and 3 shows that the correction has a substantial effect only for those cases where 20% or more of the feeding mixture was constituted by steam, as is the case of wells A-19, A-5 (sample of 1980) and A-1. The correction tends to reduce the dispersion of the data points corresponding to liquid phase. I also increases the systematic difference between the compositions of liquid and steam phases. The data points for liquid phase show an aproximately linear distribution; the solid line corresponds to a least-squares fit with a correlation coefficient of 0.75.

The uncertainties in the measurement of δD and $\delta^{18}O$ are estimated as $\pm$ 0.5 and $\pm$ 0.05, respectively. The observed differences in isotopic composition of liquid phase are much larger than these error margins, and thus indicate a degree of heterogeneity in the aquifer. As reported by Giggenbach and Quijano (1981), the isotopic compositions of local shallow waters and the geothermal fluids are very different, ruling out the possibility of a direct origin of the latter from local meteoric precipitation. The approximately linear distribution in Fig. 3 suggests the possibility of mixture of two fluids in the aquifer. Extrapolation of the best-fit line gives an intercept with the meteoric line (Craig,1961) corresponding to an isotopic composition very different than that of any of the analysed local waters. Although there is a considerable scatter in the points along the adjusted line, it can be concluded that available evidence does not support the possibility of mixing of the geothermal fluid with local ground waters.

The wellheads of A-7 and A-8 are on different sides of a fault (see Fig. 1); however, well A-7 is very close to the fault and on the side of inclination of the fault plane, so that it probably intersects it. This is consistent with the two wells being fed by fluid of similar composition. The feeding zone of A-2 is on the other side of the fault, and this well receives fluid of a somewhat different composition. Well A-16D is relatively close to A-2, but separated by an inferred fault. The feeding fluid of A-16D is clearly different than that of the other three wells mentioned above.

The northern and southern sections of the field which have been chosen for exploitation are separated by a zone of high resistivity (Romero and Palma, 1983), and of relatively minor hydrothermal alteration at the surface and shallow levels. Thus, the two sections might appear to be unrelated. However, the available information from deep wells in the middle section show that there is a continuity of hydrothermal alteration at great depth (> 1800 m), which joins the northern and southern sections. This suggests that there is a deep aquifer which spans the entire area of the field (Cathelineau et al, this Proceedings). Well A-4, A-19, A-5 and A-13 are distributed along the Maritaro fault. The fluid feeding well A-4 is similar to that which feeds wells A-7 and A-8 in the southern part of the field. Well A-13, which is on the same side of the Maritaro fault than A-4, receives a fluid of very different composition. However, it should be noted that the feeding zones of these two wells are at very different depths. The slotted liner sections of A-4 and A-13 are at approximately 900-1300 meters and 1650-1850 meters above sea level, respectively. The slotted liner section of A-5, on the other side of the Maritaro fault, is at an intermediate depth (approximately 1400-1800 meters above sea level). The composition of the fluid feeding this well is also intermediate, but closer to that of A-13. Data for well A-19 can not be used to support or disprove this suspected correlation of composition with depth, because its slotted liner section spans most of the depth range involved (1200-1850 meters above sea level). Clearly, information from more wells located in this area is needed, in order to investigate the possibility of the existence of two aquifers at different depths.

The compositions of steam phases separated at 300°C, 280°C and 260°C from liquid phases with compositions falling in the solid line of Fig. 3, have been calculated. The results fall in the broken lines shown in the same Figure. These calculations assume that the mass of the separated steam is negligible compared to that of the remaining liquid. If this is not so, than the composition of the separated steam will fall in the space bounded by the broken and solid lines, the closer to the latter the higher the fraction of separated steam. The points corresponding to the 1980 and 1982 samples from well A-6 seem to fall just out of the allowable range. However, taking into account the error margin in the determination of deuterium, and the scatter of the linear distribution of liquid phase compositions, these two points might fall in the extreme of the range. The other two points corresponding to samples from steam wells also fall near the extreme of the range, close to the broken lines. This implies that wells A-6 and A-17 are fed by steam separated from a much larger mass of liquid. The large variations with time shown by the composition of fluid produced by A-6, suggests that this well might receive steam from more than one section of the aquifer, at different times.

CONCLUSIONS

The chemical and specific enthalpy data show that there is phase separation in the feeding zones of most of the wells considered. The isotopic composition data shows no evidence of mixing of the geothermal fluid with local meteoric and shallow ground waters. These inferences are consistent with a situation in which the aquifer has no local recharge, although it may have lateral recharge from the low-lying surrounding valley. Under these circumstances, it would be expected that the system be underpressurized and flashing would occur in zones with a high degree of fracturing, as well as in zones of intake of producing wells.

The origin of the heterogeneity of the liquid phase in the reservoir remains obscure. The approximately linear distribution of isotopic compositions suggests a process of mixing of two fluids. Clearly, data from more of the wells in the field is needed in order to draw firmer conclusions in this regard. In particular, it is necessary to investigate the possible correlation of isotopic composition with depth in the northern section of the field.

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