

CHEMICAL AND ISOTOPIC EVIDENCE OF STEAM UPFLOW
AND
PARTIAL CONDENSATION IN LOS AZUFRES RESERVOIR

NIEVA*, D., VERMA*, M., SANTOYO*, E., BARRAGAN*, R.M., PORTUGAL*, E.,
ORTIZ†, J. AND QUIJANO†, J.L.

*Instituto de Investigaciones Eléctricas
Apartado Postal 475
Cuernavaca, Mor., México 62000

†Comisión Federal de Electricidad
Ave. de las Camelinas 3527, 7° piso
Morelia, Mich., México

ABSTRACT

Data of chemical and isotopic composition of fluids from Los Azufres wells, collected over a two year period, provide evidence of a process of upward flow and partial condensation of steam in the reservoir, which explains part of the previously reported heterogeneity in isotopic composition of the liquid phase (Nieva et al, 1983).

For the southern part of the field, a direct correlation is found between chloride and oxygen-18 concentrations, and an inverse correlation between these parameters and deuterium and carbon dioxide concentrations in the liquid phase of the reservoir. Chloride ion concentrations increase gradually from ca 600 ppm in the production zones of shallow wells to ca 1900 ppm in the case of deep wells. This observations agree with predictions based on the well-known model for vapor dominated systems of White et al (1971).

For the northern part of the field the same correlations are observed, except for the deuterium concentration which in this case correlates directly with oxygen-18. It is concluded that the same process of steam upflow occurs in the northern section but that some other process - perhaps a mixture with other hydrothermal fluid - is also occurring.

INTRODUCTION

The primary geology (Camacho, 1976; Gutiérrez-Negrín and Aumento, 1982; Cathelineau et al, 1987), alteration mineralogy (Cathelineau et al, 1985; Cathelineau and Nieva, 1985) and some features of the hydrological structure of the Los Azufres field (Iglesias et al, 1985; Nieva et al, 1986) have been discussed elsewhere.

A previous analysis of chemical and isotopic composition data from Los Azufres fluids, led to the detection of a significant heterogeneity in the composition of the reservoir fluids produced by various wells (Nieva et al, 1983). This was interpreted as resulting from the mixture of more than one hydrothermal fluid, but no solid conclusions as to their origins could be drawn, except for supporting the assertion that there exists no substantial mixture

with local meteoric water (Giggenbach and Quijano, 1981). A more detailed interpretation was impeded by uncertainties concerning well flow conditions (hence about specific enthalpies of the total discharges) at the time of sampling, and also because of the occurrence of phase separation in the formation, leading to uncertainties in the relation between the compositions of the well discharge and the reservoir fluid.

Giggenbach (1980) and D'Amore and Celati (1983) have devised methods to calculate the fractional molar contribution of reservoir steam in the total discharge from a well. This parameter has come to be known as the "y value" (Giggenbach, 1980), steam fraction (D'Amore and Celati, 1983), or steam excess (Nieva et al, 1982; Truesdell et al, 1984). Heretofore this parameter shall be referred to as steam excess, and shall be expressed in units of mole percentage. The original procedure of Giggenbach (1980) has been modified, so as to make it applicable to the case of well fluids with high contents of non-condensable gases (Nieva et al, 1985). Knowledge of the total discharge composition and of the steam excess, allows for the calculation of both the reservoir liquid and steam phases.

This contribution presents an analysis of chemical and isotopic composition data from Los Azufres well fluids, collected over a period of about two years. The sampling program was designed so as to include as many wells as possible, some of them sampled repeatedly; extreme care was taken to select wells in appropriate and characterized flow conditions, and to enhance the reproducibility of the sampling operation and the precision of the isotopic and chemical analysis.

RESULTS

Table 1 presents steam composition data for samples collected between June, 1984 and February, 1986. Some of the wells could be sampled only once, but those which provide steam for the 5 wellhead generators were sampled several times. Included in Table 1 is the best estimate for the reservoir temperature in the production zone of each well.

The calculation of steam excess also allows

TABLE 1. COMPOSITION OF SEPARATED STEAM FROM LOS AZUFRES WELLS

WELL	T _s °C	f _s	X _g	CO ₂	MOLAR FRACTION X 1000 H ₂ O-FREE BASIS					NH ₃	T _{res} °C	DATE OF SAMPLE
					H ₂ S	H ₂	CH ₄	N ₂				
A- 5	182	0.71	8.6	971.	20.0	4.7	0.67	3.5	0.6	300	24 485	
A- 5	180	0.71	10.8	976.	16.8	3.0	1.1	2.8	0.4	300	25 685	
A- 5	180	0.70	19.8	988.	7.1	1.8	0.35	1.8	0.9	300	12 985	
A- 5	179	0.72	9.3	975.	17.6	2.9	0.49	2.4	1.9	300	25 286	
A- 5	165	0.73	8.2	970.	19.5	3.5	0.90	3.9	2.2	300	13 586	
A- 5	179	0.72	8.3	984.	9.3	2.7	0.59	2.5	0.9	300	24 986	
A- 6	192	1.	31.7	989.	5.9	0.9	0.49	3.7	0.3	259	24 485	
A- 6	191	1.	28.1	979.	9.3	1.6	1.3	4.5	4.3	259	26 685	
A- 6	177	1.	41.5	984.	4.5	0.8	0.49	6.8	3.0	259	11 985	
A- 6	179	1.	36.3	983.	5.9	0.9	0.66	7.0	2.2	259	91085	
A- 6	180	1.	29.2	977.	6.8	1.1	0.82	7.9	6.6	259	27 286	
A- 6	180	1.	35.2	981.	5.9	1.1	1.00	7.5	3.3	259	14 586	
A- 6	179	1.	38.7	981.	5.4	1.1	0.76	10.2	1.6	259	24 986	
A- 9	148	0.49	2.1	920.	62.3	7.4	0.38	1.1	8.7	330	9 884	
A-13	172	0.56	5.1	961.	30.0	5.1	0.36	2.0	1.2	300	24 485	
A-13	172	0.58	6.4	969.	22.0	4.1	1.1	1.9	2.2	300	25 685	
A-13	172	0.58	13.9	986.	9.3	2.3	0.29	1.3	1.4	300	12 985	
A-13	174	0.58	5.9	971.	22.8	3.5	0.48	1.9	0.5	300	101085	
A-13	163	0.59	6.3	965.	26.8	5.5	0.32	1.3	1.2	300	26 286	
A-13	177	0.58	5.1	959.	26.3	7.4	1.1	2.7	3.4	300	13 586	
A-16AD	176	0.75	12.0	981.	9.8	3.8	0.14	4.2	1.5	280	7 684	
A-16AD	177	0.75	8.9	877.	9.4	2.4	0.19	109.8	0.9	280	8 585	
A-16AD	180	0.75	39.7	917.	3.1	0.6	0.10	75.8	3.7	280	10 985	
A-16AD	180	0.75	9.8	886.	9.4	1.0	0.19	98.9	4.2	280	91085	
A-16AD	182	0.75	8.1	877.	9.9	8.6	0.08	101.5	3.4	280	26 286	
A-16AD	183	0.75	14.9	811.	7.1	17.7	0.74	160.9	2.7	280	14 586	
A-17	172	1.	21.5	983.	11.6	3.2	0.28	1.8	0.6	264	6 684	
A-17	176	1.	14.2	993.	1.3	1.6	0.11	1.0	2.6	264	10 884	
A-17	179	1.	20.9	979.	10.9	2.6	0.30	6.3	0.5	264	23 485	
A-17	175	1.	20.0	982.	10.0	1.9	0.60	3.2	2.6	264	26 685	
A-17	102	1.	66.6	977.	9.0	2.7	0.26	7.5	3.2	264	11 985	
A-17	180	1.	27.2	983.	6.8	1.8	0.28	5.5	2.4	264	91085	
A-17	180	1.	15.9	977.	11.0	1.0	0.08	2.1	8.5	264	27 286	
A-17	207	1.	15.0	973.	12.8	2.6	0.48	6.9	4.1	264	14 586	
A-17	213	1.	16.9	977.	10.1	2.3	0.35	7.5	2.8	264	24 986	
A-18	156	0.66	32.3	990.	5.9	1.0	0.09	2.0	0.8	280	8 684	
A-18	127	0.69	35.0	986.	5.3	0.8	0.47	3.7	3.4	280	11 985	
A-18	158	0.66	28.2	986.	6.7	0.9	0.42	3.1	3.1	280	26 286	
A-19	138	0.40	1.1	866.	95.8	18.3	0.24	4.1	16.1	310	9 884	
A-19	145	0.39	1.9	926.	63.8	2.9	0.95	1.7	4.4	310	25 685	
A-19	165	0.35	5.5	980.	15.1	2.4	0.04	1.5	1.5	310	25 286	
A-19	165	0.36	2.6	961.	26.4	6.2	0.80	3.7	2.3	310	13 586	
A-22	190	0.43	4.7	963.	24.5	8.5	0.14	2.0	1.5	310	11 684	
A-22	197	0.42	8.2	979.	15.3	3.7	0.03	0.6	2.0	310	9 884	
A-22	169	0.46	4.7	963.	19.5	6.8	0.44	3.2	6.9	310	91085	
A-26	177	0.34	18.3	982.	8.6	1.4	0.99	3.2	3.8	292	26 685	
A-28	169	0.36	0.9	873.	83.4	25.0	0.40	2.7	15.6	310	9 884	
A-28	165	0.37	2.2	928.	48.4	11.1	3.0	4.0	6.0	310	27 685	
A-28	182	0.34	10.8	986.	9.3	2.2	0.09	0.4	2.7	310	12 985	
A-28	177	0.35	1.8	941.	38.2	13.1	0.09	1.5	6.4	310	25 286	
A-28	177	0.35	1.7	937.	27.1	23.9	1.2	6.1	5.2	310	13 586	
A-32	161	0.85	8.8	967.	26.7	4.2	0.33	1.3	0.9	300	8 585	
A-33	206	0.84	27.6	987.	7.6	2.0	0.61	2.4	0.8	260	11 684	
A-34	197	0.83	45.3	989.	5.6	2.4	0.88	2.2	0.4	265	8 684	
A-35	192	0.82	14.9	975.	12.5	6.7	0.58	4.1	0.9	280	11 684	
A-36	150	0.67	14.4	981.	11.3	4.2	0.10	2.9	0.9	270	7 684	
A-36	148	0.65	17.3	984.	9.7	2.2	0.23	2.3	1.4	270	8 884	
A-37	201	1.	3.2	949.	15.5	23.5	1.1	7.7	3.8	263	14 586	
A-38	205	0.82	23.1	984.	7.3	3.8	0.44	3.7	0.5	262	7 684	
A-38	205	0.82	24.4	985.	7.5	3.1	0.46	3.7	0.4	262	7 684	
A-38	182	0.88	18.4	988.	8.2	0.9	0.26	2.5	0.5	262	8 585	
A-38	142	0.87	17.5	976.	8.5	1.5	0.34	3.2	10.8	262	27 286	
A-46	184	0.31	11.3	969.	24.9	3.7	1.0	0.9	1.0	270	1 785	
A-46	185	0.31	9.3	977.	10.8	2.9	0.15	5.8	3.0	270	101085	

T_s = steam separation temperature; f_s = steam weight fraction in total discharge;X_g = millimoles of non-condensable gas per mol of H₂O in steam; T_{res} = reservoir temperature

for the calculation of carbon dioxide (and other volatile species) concentration in the reservoir liquid phase (Nieva et al, 1985). Table 2 shows the calculated values for well A-17. This well is chosen for detailed analysis because of the very high value of steam excess calculated for the sample of September, 1985, which is one of a set of anomalies believed to be precursors of the September, 19 and September 21, 1985 earthquakes (Santoyo et al, 1986). Table 2 includes the isotopic composition of the total discharge, and the calculated composition of the reservoir liquid phase. This data allows for several checks on the internal consistency of the steam excess concept and calculation procedure. One of this checks is the observed (and expected) linear correlation between steam excess and carbon dioxide concentration in the total discharge (plot not shown). The concentration of oxygen-18 would be expected to correlate inversely with the steam excess, since this species partitions preferentially into the liquid phase. This correlation, which provide for a second check, is shown in Figure 1. The solid line drawn in the Figure was calculated using the expected relationship given by the formula:

$$[\delta^{18}O]_{td} = [\delta^{18}O]_{res,l} + F_{se} \times \left(\frac{1-\alpha}{\alpha}\right) \left([\delta^{18}O]_{res,l} + 1000\right) \quad (1)$$

where F_{se} is the mass fraction of the steam excess in the total discharge, $[\delta^{18}O]_{res,l}$ and $[\delta^{18}O]_{td}$ are the concentrations of oxygen-18 in the reservoir liquid phase and the total discharge, respectively. α is the partition coefficient of oxygen-18 between steam and liquid, evaluated at the downhole temperature. The value of the last parameter was calculated using data assembled by Truesdell et al (1977). Contrary to oxygen-18, deuterium is expected to increase in concentration with an increase in steam excess, because at the reservoir temperature this species partitions preferentially into the steam phase. This is indeed what is observed, with the inverse correlation being close to the calculated trend (plot not shown for lack of space).

The above correspondence between expected and observed trends, provide confidence on the use of the steam excess concept to calculate the composition of the reservoir liquid phase, from the composition of the total discharge. The procedure consists of a mass-balance calculation, which takes into account the steam/liquid partition coefficient of each species. The procedure was applied to data collected from April, 1985 to February, 1986, and the results are shown in Table 3. The parameters calculated are the concentrations in the liquid phase of the chloride ion, oxygen-18 and deuterium, as well as the molar fraction of carbon dioxide. For each parameter the Table presents the average value and average deviation.

Some of the wells were sampled only once, and the single result is provided. The Table includes carbon dioxide concentration data for samples collected before the isotopic study had begun. Also presented is the elevation of the production zone of each well, which was taken as that of the midpoint in the open liner segment.

It is evident from the results in Table 3 that the parameters which could be measured with better precision are the concentrations of chloride ion and oxygen-18. Figure 2 shows the direct correlation that exists between these two parameters. The Figure includes data from wells from both the northern and the southern sections of the field (for a map of the Los Azufres field refer to Nieva et al, 1985, or 1983). Figures 3 and 4 show the distribution of chloride ion concentration with respect to elevation for the southern and northern sections, respectively. In these Figures the vertical bars represent the length of the open liner segment in the wellbore. In spite of the large uncertainties in the elevation of the production zones, it is clear that the chloride ion concentration increases with depth.

In the northern part of the field there is a clear inverse correlation between the concentrations of chloride ion and carbon dioxide (Figure 5). For the southern section, there is a trend of increasing carbon dioxide concentration with increasing elevation of the production zone (Figure 6). This last correlation excludes the cases of wells A-18 and A-26, both of which are located in the southeast extreme of the field, and which show several chemical deviations from the general pattern; among these anomalies is the high gas content of the produced fluids, high concentration of calcium ion in the brine, etc.

DISCUSSION

The observations presented above could be summarized by the statement that, in Los Azufres, the concentration of a volatile species (such as carbon dioxide) is higher in the upper levels of the two phase zone of the reservoir, while the concentrations of the less volatile species (such as chloride ion and oxygen-18) increase with depth. The simplest and most reasonable explanation for this set of observations is the occurrence of a process of up-flow of steam; the condensation of a fraction of this steam continually dilutes the concentration of the non-volatile species, while the volatile species are continually transported to the upper levels.

The deuterium results corroborate the above model for the southern section of the field. The inverse correlation between the concentrations of deuterium and oxygen-18, which is shown in Figure 7, indicate that the concentration of deuterium (a "volatile" species at the reservoir temperature) decreases with depth. The slope of the fitted line is consistent

TABLE 2. TOTAL DISCHARGE COMPOSITION AND CALCULATED EXCESS STEAM AND COMPOSITION OF RESERVOIR LIQUID PHASE FOR WELL A-17.

DATE OF SAMPLE	STEAM EXCESS (%)	C O M P O S I T I O N					
		TOTAL DISCHARGE			RESERVOIR LIQUID PHASE		
		X _{CO₂} x1000	δ ¹⁸ O	δD	X _{CO₂} x1000	δ ¹⁸ O	δD
6 684	17.8	20.7	-	-	1.6	-	-
10 884	7.8	13.9	-	-	2.4	-	-
23 485	13.8	20.1	-4.94	-60.7	2.0	-4.75	-61.2
26 685	8.8	19.3	-4.76	-62.5	3.1	-4.64	-62.8
11 985	47.8	61.0	-5.30	-58.2	1.9	-4.63	-59.9
91085	13.5	26.1	-4.89	-63.9	2.8	-4.70	-64.4
27 286	6.0	15.3	-4.52	-64.8	3.4	-4.44	-65.0

tent with an average temperature of the ascending steam of 230°C to 245°C. The occurrence of this process of steam upflow and partial condensation is in agreement with predictions based on the model for vapor dominated systems proposed by White et al (1971).

In the northern part of the field the distribution with depth of the studied species is the same as in the southern section, except for the case of deuterium. Figure 8 shows the direct correlation between the concentrations of deuterium and oxygen-18. If the steam upflow were the only process responsible for the observed chemical and isotopic heterogeneity of the reservoir fluid, it would be necessary to postulate that the average temperature of the ascending steam is less than 220°C or higher than 375°C, which is inconsistent with measured temperatures. Thus, it is concluded that some other process is also intervening, perhaps the mixture of two hydrothermal fluids.

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TABLE 3. AVERAGE VALUES AND DEVIATIONS FOR CONCENTRATIONS OF ¹⁸O, DEUTERIUM, CHLORIDE ION AND CARBON DIOXIDE IN THE LIQUID PHASE OF THE RESERVOIR. ELEVATIONS OF PRODUCTION ZONES.

WELL	$\delta^{18}\text{O}$		δD		CHLORIDE		MOLAR FRACTION OF CO_2		ELEVATION (masl)
	AVE. VALUE	AVE. DEV.	AVE. VALUE	AVE. DEV.	(ppm)		$\times 1000$		
					AVE. VALUE	AVE. DEV.	AVE. VALUE	AVE. DEV.	
A- 5	-3.66	0.02	-64.3	1.0	641	23	4.31	0.56	1432
A- 6	-5.54	0.40	-61.0	1.2	-	-	4.95	0.55	2065
A-13	-2.45	0.08	-61.6	0.7	941	7	2.48	0.41	1710
A-16AD	-3.52	0.27	-61.4	1.0	579	19	2.03	1.20	1968
A-17	-4.67	0.09	-62.7	1.5	-	-	2.48	0.51	2210
A-18	-3.32	0.22	-64.8	1.2	1002	29	7.31	1.04	1756
A-19	-3.32	0.24	-61.7	1.3	1241	44	1.56	0.67	1160
A-22	-2.64	-	-66.7	-	1877	-	1.96	0.33	1300
A-26	-2.00	-	-62.9	-	1770	-	5.68	0.50	1665
A-28	-2.51	0.21	-61.0	1.4	1587	4	0.65	0.22	1180
A-32	-2.64	-	-57.9	-	-	-	3.38	0.50	1380
A-33	-	-	-	-	-	-	2.71	-	2150
A-34	-	-	-	-	-	-	2.92	-	2085
A-35	-	-	-	-	-	-	1.57	-	1625
A-36	-	-	-	-	-	-	1.84	0.70	1840
A-37	-	-	-	-	-	-	0.29	0.25	1875
A-38	-4.21	-	-64.1	-	-	-	2.70	1.11	2120
A-46	-	-	-	-	-	-	1.55	0.17	1827

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FIGURES

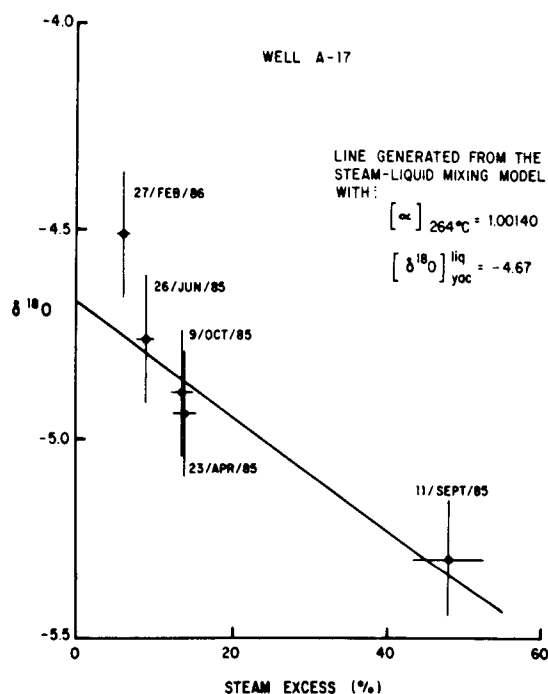


FIGURE 1. Concentration of oxygen-18 vs steam excess in total discharge. The straight line was drawn with equation 1, and the parameter values specified in the Figure.

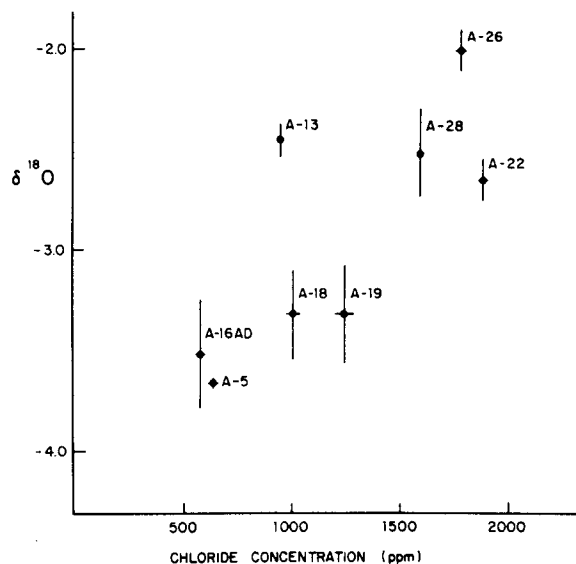


FIGURE 2. Concentration of oxygen-18 vs concentration of chloride ion. Length of error bars represents twice the average deviation from the mean for the corresponding parameter.

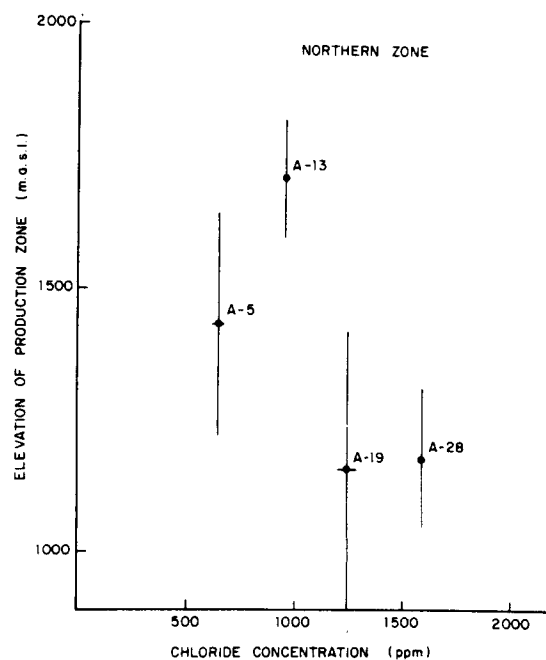


FIGURE 4. Elevation of production zone vs concentration of chloride ion in the liquid phase of the reservoir. Horizontal and vertical lines have the same meaning as in Figure 2.

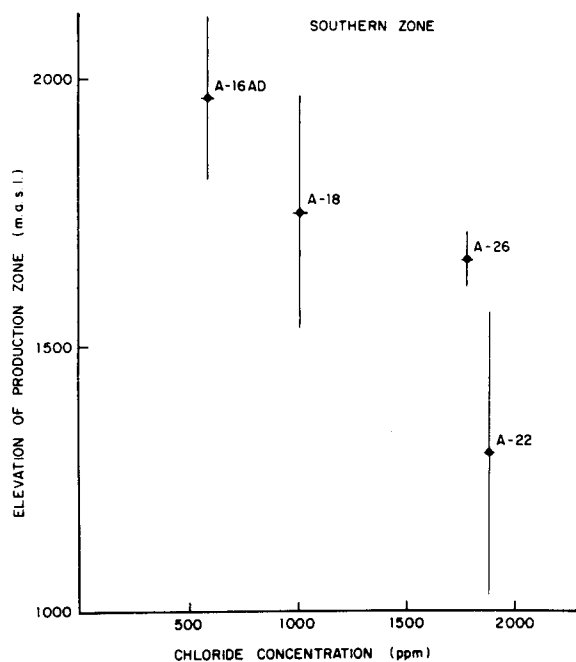


FIGURE 3. Elevation of production zone vs concentration of chloride ion in the liquid phase of the reservoir. Horizontal lines are error bars and vertical lines represent the length of the open liner segment in the wellbore.

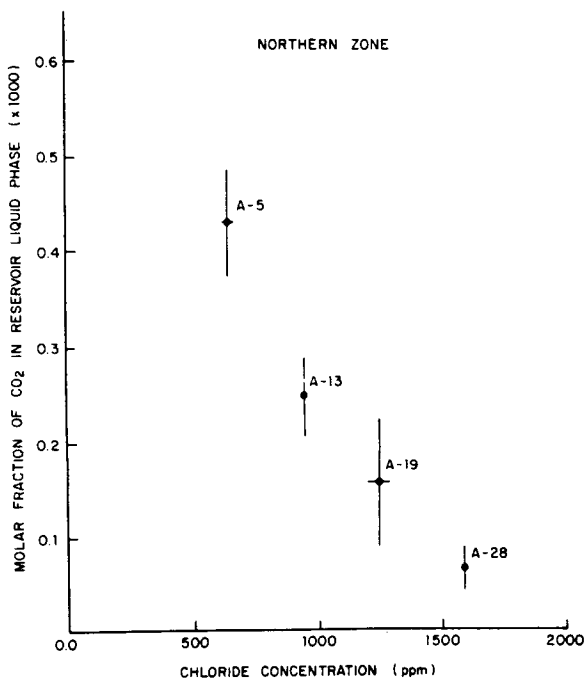


FIGURE 5. Molar fraction of carbon dioxide vs chloride ion concentration in liquid phase.

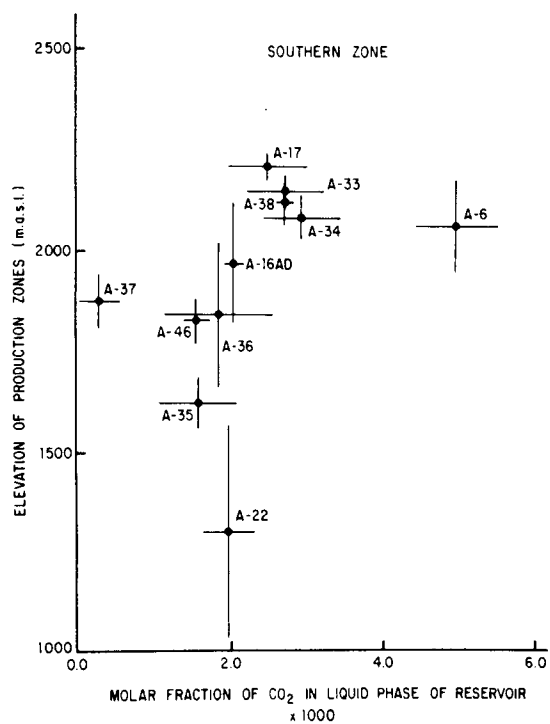


FIGURE 6. Elevation of production zone vs molar fraction of carbon dioxide in liquid phase.

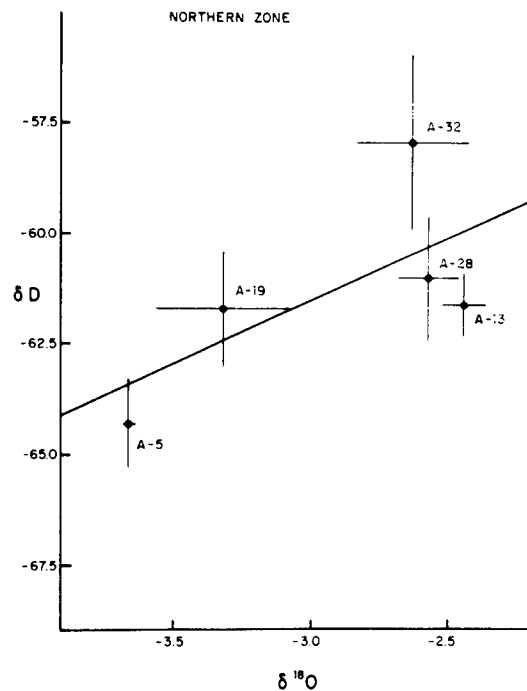


FIGURE 8. Concentration of deuterium vs concentration of oxygen-18 in reservoir liquid phase.

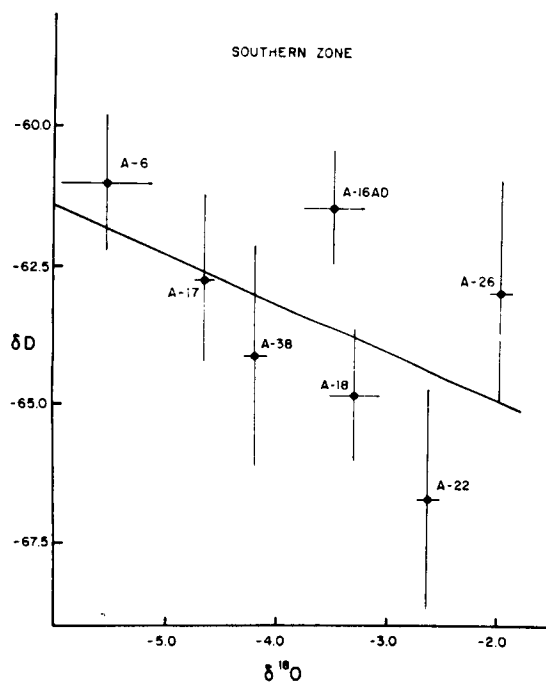


FIGURE 7. Concentration of deuterium vs concentration of oxygen-18 in reservoir liquid phase.