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Gas geochemistry in modeling geothermal reservoirs

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RESUMEN

Se presentan los modelos geoquímicos para los yacimientos geotérmicos de Los Azufres y Los Humeros. En ambos casos la fase gaseosa tuvo un papel importante ya que de acuerdo con los fluidos producidos, el yacimiento de Los Azufres se clasificó como de tipo vapor-líquido (VAP-LIQ) y Los Humeros se considera de tipo vapor dominante. El modelo conceptual del yacimiento de Los Azufres se basó en la distribución espacial de especies químicas e isotópicas. Se estimó el "exceso de vapor de yacimiento" por medio del equilibrio de la reacción de Fischer-Tropsch ($CO_2+4H_2=CH_4+2H_2O$), el cual se utilizó para corregir la composición de los fluidos de descarga total para obtener la composición de los fluidos del yacimiento. Los resultados indicaron que la concentración de especies volátiles es mayor a niveles someros, mientras que la concentración de especies no volátiles es mayor a profundidad. Este patrón se interpretó como resultado de un proceso convectivo de ascenso y condensación parcial de vapor en el yacimiento.

En el campo de Los Humeros donde la fase líquida es escasa, se identificaron dos yacimientos. El más profundo de tipo vapor dominante con temperaturas entre 330 y 400°C y el más somero de tipo líquido dominante con temperaturas menores. El equilibrio gaseoso basado en la reacción de Fischer-Tropsch (FT) y en el de la combinación de reacciones pirita-hematita y pirita-magnetita (HSH2) proporcionó tanto la estimación de temperatura de yacimiento como la de "exceso de vapor de yacimiento". Considerando estos valores en una etapa temprana de explotación y los más recientes, se propone que los fluidos del yacimiento profundo ascienden a través de las fracturas hacia el yacimiento somero como consecuencia de la explotación.

PALABRAS CLAVE: Geoquímica de gases, modelación de yacimientos geotérmicos, Los Azufres, Los Humeros.

ABSTRACT

Geochemical models for Los Azufres and Los Humeros geothermal reservoirs are discussed. Los Azufres is defined as vapour-liquid (VAP-LIQ) and Los Humeros is mainly a vapour-dominated field.

The geochemical conceptual model for Los Azufres reservoir was based on the spatial distribution of isotopic and chemical species in the reservoir fluid. Based on equilibrium of the Fischer-Tropsch (FT) reaction ($CO_2+4H_2=CH_4+2H_2O$), the "reservoir excess steam" parameter was estimated. This parameter was used to correct the total discharge composition of fluids to obtain the composition of fluids at reservoir. Results indicated that concentration of volatile species was higher at shallower levels while non-volatile species concentration was higher at depth. This pattern suggested the occurrence of a convective process with reservoir vapour separation and condensed vapour down-flows.

For the Los Humeros geothermal field, where the liquid phase is scarce, two reservoirs were found, a hotter vapour-dominated reservoir located at depth and a liquid-dominated shallower one. Gas equilibria based on the Fischer-Tropsch (FT) reaction and on the pyrite-hematite and pyrite-magnetite (HSH2) combined reactions provided both the reservoir temperature and the "excess steam" parameters. With exploitation it seems that fluids from the hotter reservoir rise through fractures to the shallower one.

KEY WORDS: Gas geochemistry, geothermal reservoir modeling, Los Azufres, Los Humeros.

INTRODUCTION

Gas geochemistry has proved to be useful in modeling geothermal reservoirs. Current applications include: (a) gas geothermometers (D'Amore and Panichi, 1980; Arnórsson *et al.,* 1983; Arnórsson and Gunnlaugsson, 1985), that are based on variations of gas ratios with temperature in producing aquifers; (b) methods to estimate the reservoir excess steam (Giggenbach, 1980; D'Amore and Celati, 1983), which are useful when the reservoir temperature is available; and (c) methods to estimate both, the reservoir temperature and the reservoir excess steam, considering fluid equilibria with alteration minerals in the reservoir (D'Amore and Truesdell, 1985; 1995; D'Amore, 1998). Geochemical models for Los Azufres and Los Humeros geothermal reservoirs have been developed (Nieva *et al.,* 1987; Arellano *et al.,* 1998). In both reservoirs the "excess enthalpy" phenomenon was identified and the content of non-condensible gases is relatively high (Nieva *et al.,* 1983; Barragán *et al.,* 1988, Tovar and López, 1998), which evidenced that the gas phase played an important role in defining the main features of the reservoirs. For Los Azufres reservoir, reservoir temperature logs agreed with geothermometer estimations, which provided confidence on the assumption of chemical equilibrium for the system. In contrast, for Los Humeros, fluids behaviour showed partial water-rock equilibrium and reservoir temperature logs indicated higher values than those obtained by geothermometers. Due to these characteristics, different approaches were taken for every case, in order to obtain the "reservoir excess steam" parameter. This parameter allowed the composition of the reservoir fluid for the unperturbed conditions to be calculated, thus, providing reference values which are useful in reservoir monitoring to investigate the response to exploitation.

THE LOS AZUFRES AND LOS HUMEROS FIELDS

The Los Azufres geothermal field is an intensely fractured, two-phase, volcanic hydrothermal system located in the northern portion of the Mexican Volcanic Axis, in the state of Michoacán, at an average elevation of 2800 m.a.s.l. (Figure 1). At present it is the second geothermal field in Mexico, generating 88 MWe (Torres-Rodríguez and Flores-Armenta, 2000). The field was divided in two zones according to the first classification of the produced fluids, the water-dominant north zone and the steam-dominant south zone. Figure 2 shows the location of the wells of this field.

Iglesias and Arellano (1985), based on reservoir engineering, geological and geochemical data, found that in its natural state the Los Azufres geothermal field consists of an extended deep aquifer where the ascending fluid starts to boil at about 1200 m.a.s.l.. The liquid dominant region extends upwards, from 1200 to about 1700 m.a.s.l. where steam becomes the dominant phase. The two-phase steam dominated region extends until about 2400 m.a.s.l., where a region of dry or superheated steam is located. Due to these mixed thermodynamic characteristics, the system was de-

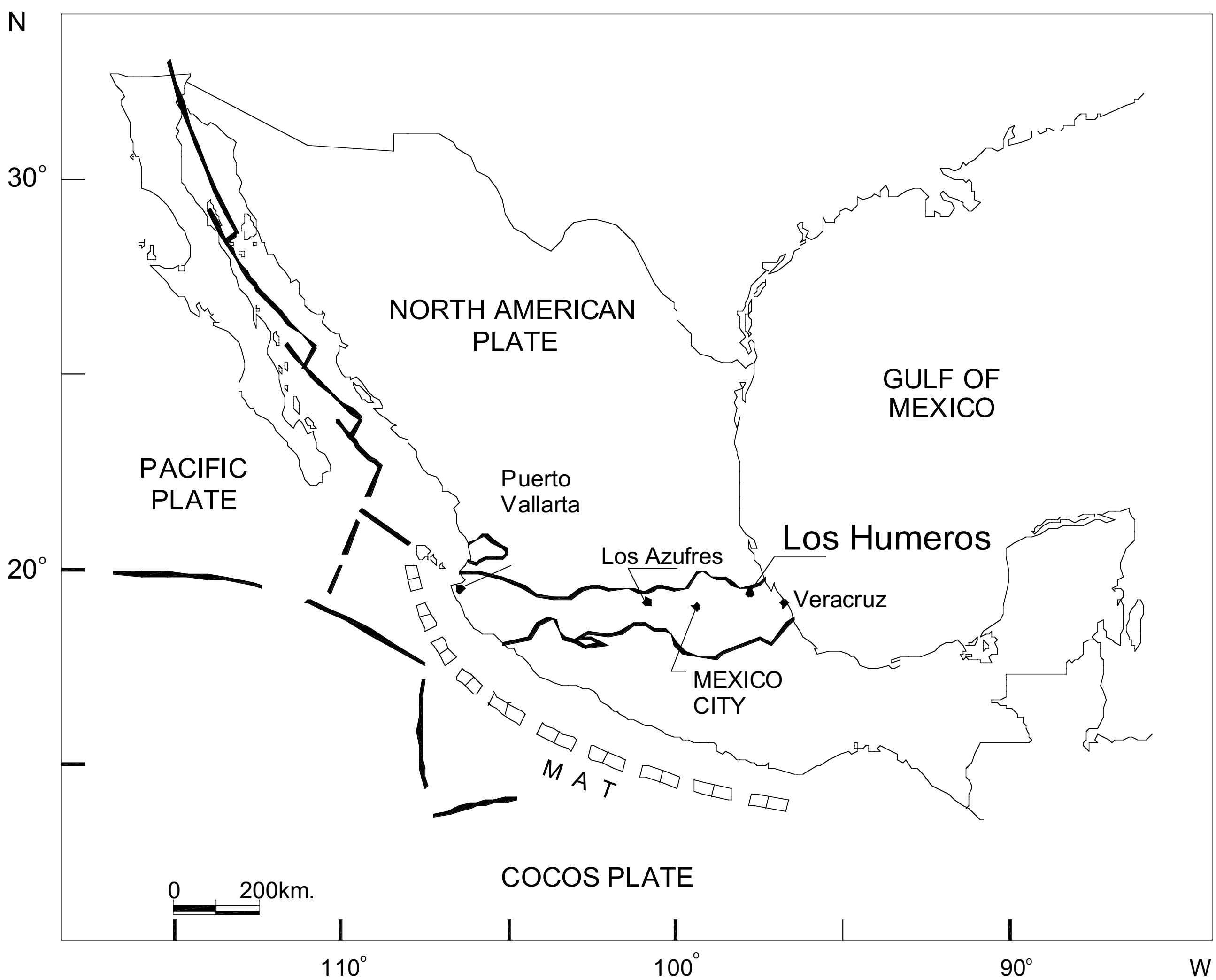

Fig. 1. Location of Los Azufres and Los Humeros geothermal fields.

fined as VAP-LIQ type, (Iglesias and Arellano, 1988), since depending on the elevation of the producing zone, wells produce superheated or dry steam or a steam- water mixture with different steam fractions.

The Los Humeros geothermal field is located in a calderic structure in the eastern part of the Mexican Volcanic Axis (Figure 1). At present 40 wells have been drilled and 40 MWe are produced (Tovar and López 1998). The field is located at an average altitude of 2800 m.a.s.l.. The reservoir producing zones are located between –12 and 1610 m.a.s.l.. Figure 3 shows the location of the wells of this field.

According to reservoir engineering, geological, mineralogical, geophysical and geochemical data, at least two reservoirs have been identified (Arellano *et al.,* 1998), in the Los Humeros geothermal field. The shallower, liquid-dominant reservoir is located between 1025 and 1600 m.a.s.l.;

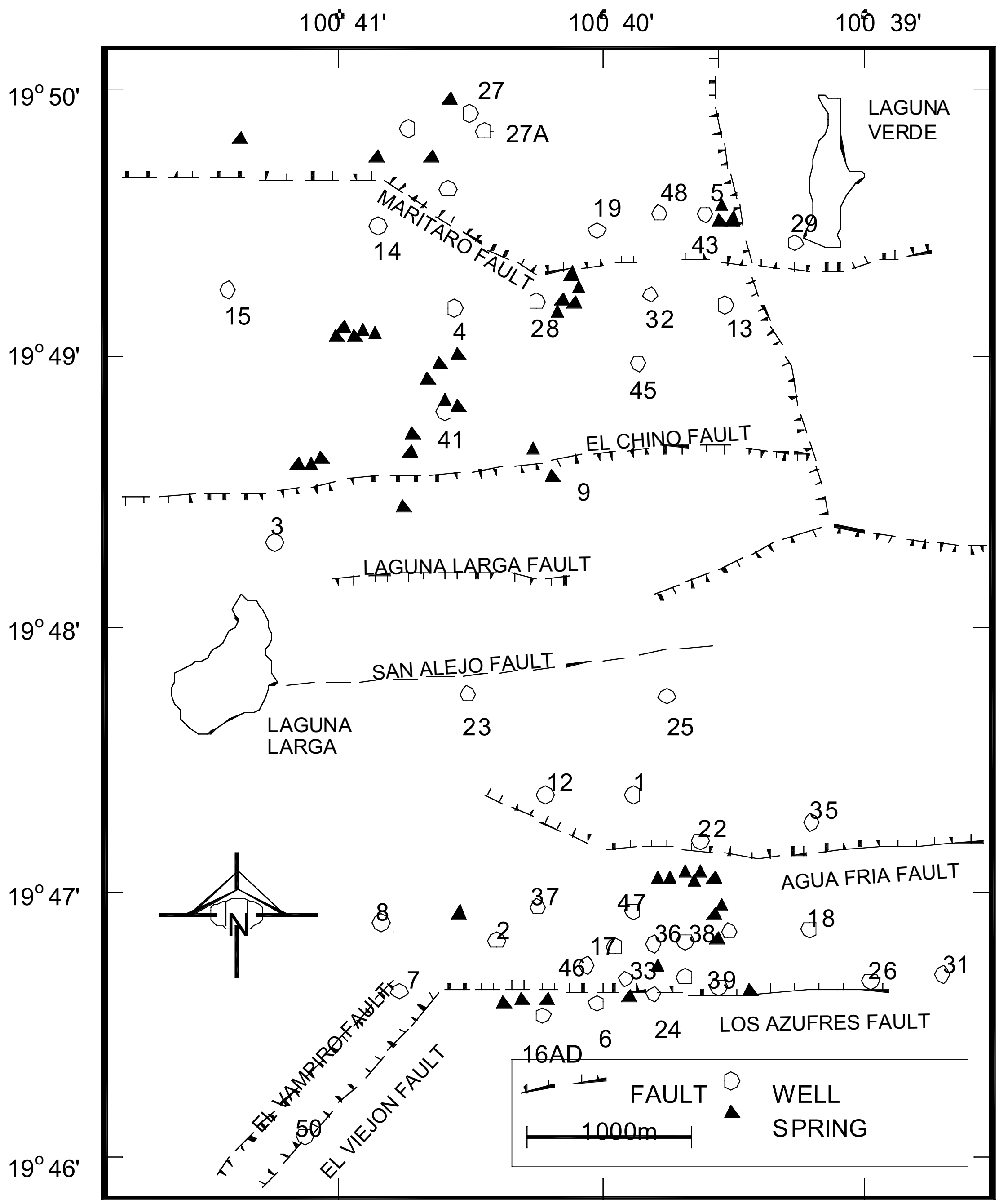

Fig. 2. Location of wells in the Los Azufres geothermal field.

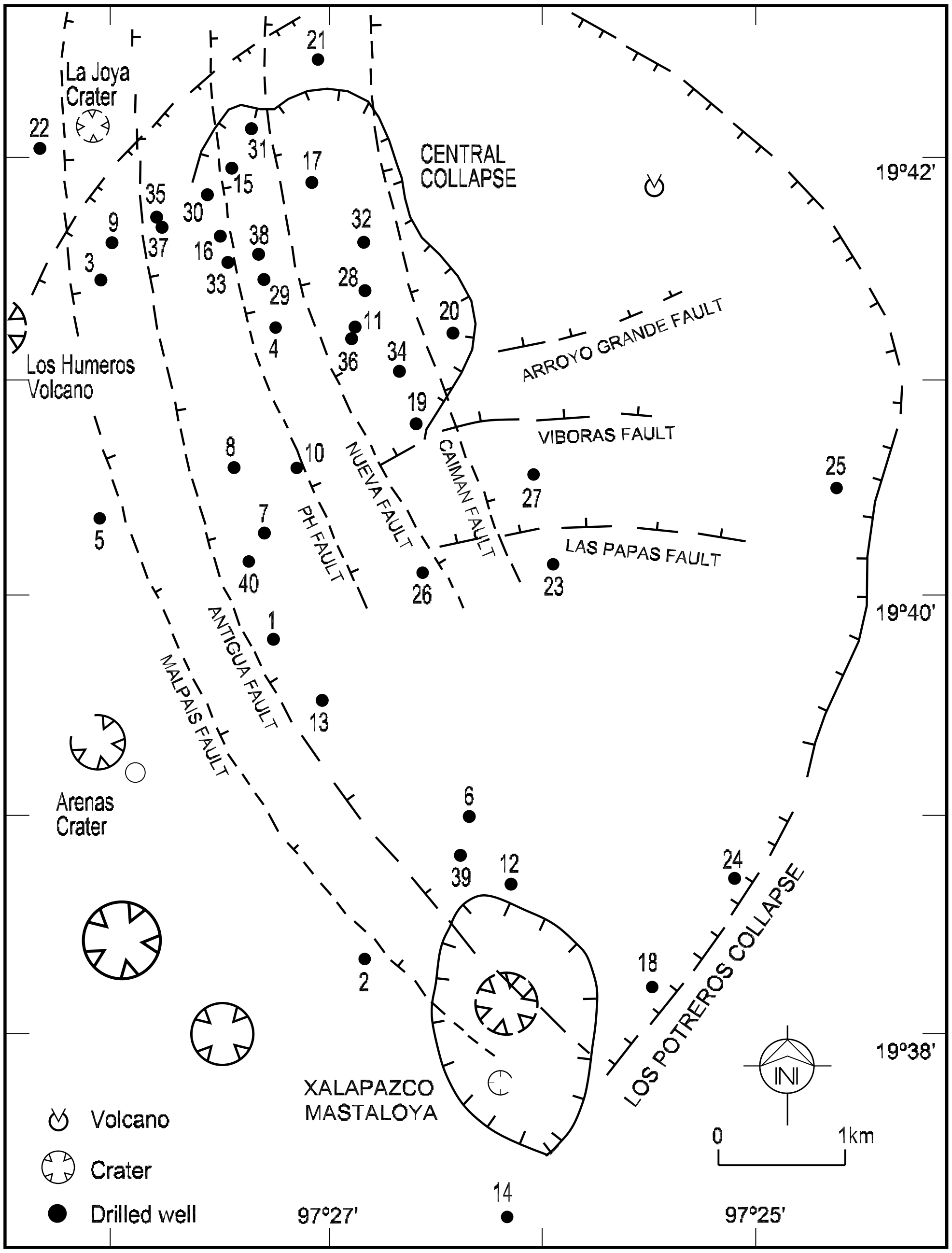

Fig. 3. Location of wells in Los Humeros geothermal field.

while the second, low liquid saturation reservoir, is located between 850 and 100 m.a.s.l. Water geochemistry was used to define important characteristics of the Los Humeros upper reservoir, but water is scarcely produced by deep wells. The lack of full water-rock equilibrium in the system has been noticed (Tello, 1992; Prol-Ledesma, 1998) and a mixing process was inferred to occur, when wells were fed by both reservoirs (Barragán *et al.,* 1988; 1991). Acid fluids were produced in the past by deep wells located in the Colapso Central zone, that originated corrosion-scaling phenomena, thus, some deep wells such as H-15 and H-16 were cemented at depth to avoid the incoming of deep fluids (Barragán *et al.,* 1989; Gutiérrez-Negrín and Viggiano-Guerra, 1990; Truesdell, 1991).

THE LOS AZUFRES GEOCHEMICAL MODEL

The Los Azufres geochemical model was postulated by Nieva *et al.,* (1987). This model was based on the spatial distribution of chemical and isotopic composition of the reservoir fluids. Gas geochemistry based on the equilibrium of the Fischer-Tropsch reaction, $CH_4 + 2H_2O = CO_2 + 4H_2$ which is assumed to be in equilibrium at reservoir conditions, allowed the "reservoir excess steam" "*y*" parameter to be estimated. This method was first proposed by Giggenbach (1980) and was modified by Nieva *et al.,* (1987) in order to make it applicable to fluids with high concentration of non-condensible gases.

The deviation of the relative proportions of the reactants in the fluid regarding the values expected at equilibrium, is interpreted as resulting from the input of a mass fraction "*y*" of reservoir steam that flows together with the liquid phase to feed the well. Thus, "*y*" is obtained according to:

$$K_c = [X_{CO2} X^4_{H2} B_{CO2} B^4_{H2} D_{CH4} P^2_{H2O}]/[X_{CH4} B_{CH4} D_{CO2} D^4_{H2}]$$

where:

$$D_i = 1 - y + y\, B_i/F$$

$$F = 1 + X_{CO2}\, B_{CO2}$$

In the above equations, X*i* represents the molal fraction of species *i* in the total discharge fluid; K_c is the value for the equilibrium constant of reaction 1 at reservoir temperature; B*i* is the distribution coefficient (temperature dependent) of species *i*; P_{H2O} is the partial pressure of water at reservoir temperature; and *y* is the reservoir excess steam, expressed in molar fraction.

Once the excess steam was estimated, it was used to correct the total discharge composition in order to obtain the reservoir fluid composition. Thus the molar concentrations of the *i*th volatile species in the liquid phase are calculated by:

$$X_{l,i} = [1 - y + (y\, Bi)/(1 + B_{CO2} X_{l,CO2})]^{-1}\, X_{td,i}\ ,$$

where the subscripts *l* and *td* refer to liquid phase and total discharge respectively.

For non-volatile components such as chloride ion, the concentration in the reservoir liquid phase is obtained by:

$$[Cl]_l = [Cl]_{td}/(1- y)\ ,$$

while the isotopic composition as oxygen-18 is corrected by:

$$\delta^{18} O_l = [(\delta^{18} O_{td} + y\, (\alpha\text{-}1/\alpha) \times 1000)/(1 - y + y/\alpha)]\ ,$$

where α refers to the oxygen-18 fractionation factor between liquid and vapour.

When a deficit of reservoir steam is calculated, it is interpreted that the fluid has lost part of the volatile species through boiling before it enters the well. In this case, the calculation of the reservoir composition for the volatile, non-volatile and isotopic species is given by:

$$X_{l,i} = [1 - y + (y\, Bi)/(1 + B_{CO2} X_{l,CO2})]\, X_{td,i}$$

$$[Cl]_l = [Cl]_{td}\, (1- y)$$

$$\delta^{18} O_l = \delta^{18} O_{td}\, (1 - y + y/\alpha) + 1000\, y\, (1\text{-}\alpha/\alpha)\ .$$

Results for the reservoir natural state were as follows. The concentrations of volatile species (CO_2) were larger in shallower strata (Figure 4) and concentrations of non-volatile species (chloride and oxygen-18) (Figures 5 and 6) increased with depth. The model established the occurrence of a process of steam upflow and partial condensation to explain such species distribution. According to the geochemical model, this behaviour seemed to be dominant in the south zone where the deuterium vs oxygen-18 relationship showed a negative slope (Figure 7). For the north zone, a positive slope for the deuterium vs oxygen-18 trend (Figure 7) was found, suggesting the presence of two different liquid phases with slightly different isotopic composition.

The chemical and isotopic composition of the reservoir fluids for the Los Azufres geothermal field, obtained for the natural state, have been used as a reference in order to investigate the main reservoir processes occurring as a result of exploitation. At present, chemical and isotopic results (Barragán *et al.,* 2001a; b) show that fluid reinjection causes interference in some wells of the south zone; while for the north zone, there is still a lack of defined tendencies in the fluids behaviour, indicating liquid phase heterogeneity as described by Nieva *et al.,* (1983). Reinjection wells in the north zone are located in the western part of the field, where probably the natural discharge of fluids is located. Without considering the wells affected by reinjection, the fluids from both zones can be grouped confirming the convective process found for the natural state fluids.

MODEL FOR THE LOS HUMEROS GEOTHERMAL FIELD

Gas composition was used to estimate reservoir temperatures and excess steam values for the Los Humeros fluids (Barragán *et al.,* 1988; 1991) by using the same method described above for the Los Azufres fluids. However, in order to obtain more realistic values for the reservoir excess steam, a reasonable estimation of the reservoir temperature is needed and whenever possible the measured or stabilized temperature should be taken. This fact was a complex matter in Los Humeros, because of the occurrence of strong ther-

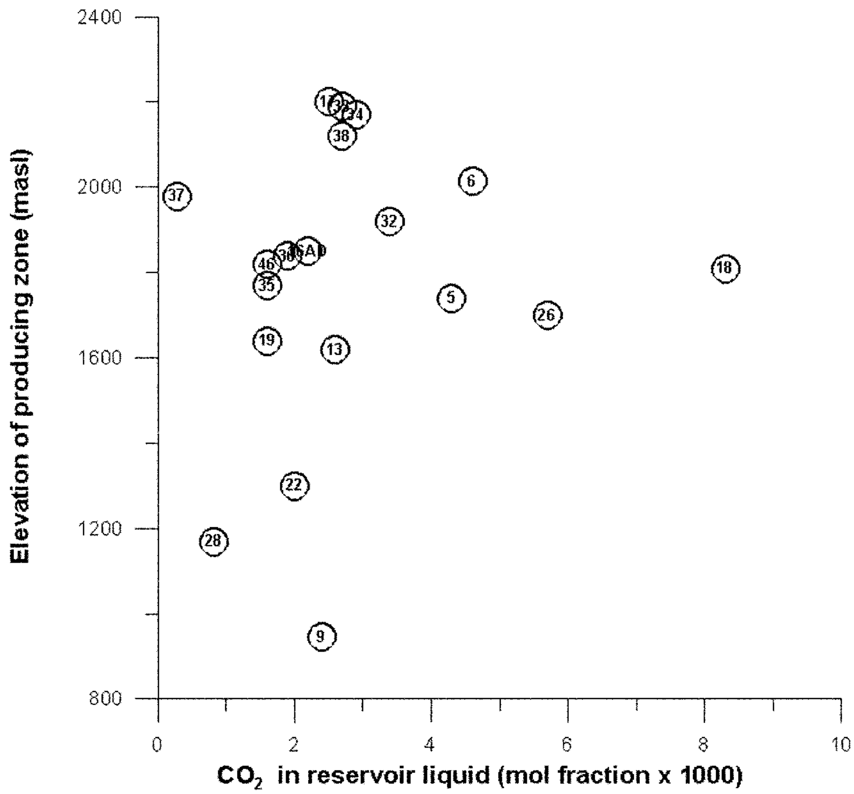

Fig. 4. CO_2 distribution in Los Azufres liquid reservoir.

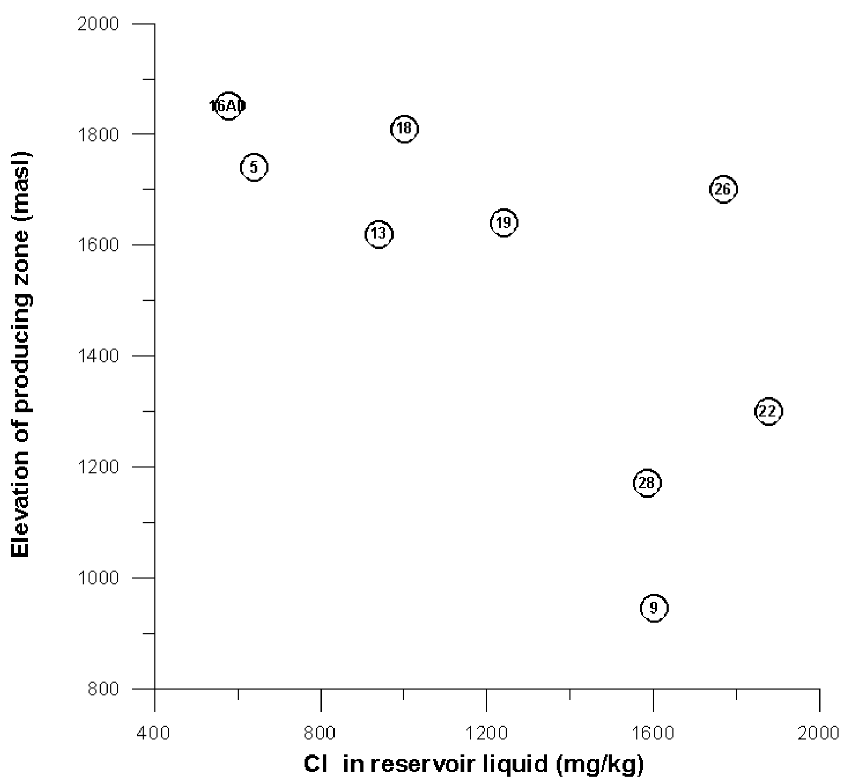

Fig. 5. Cl distribution in Los Azufres reservoir liquid.

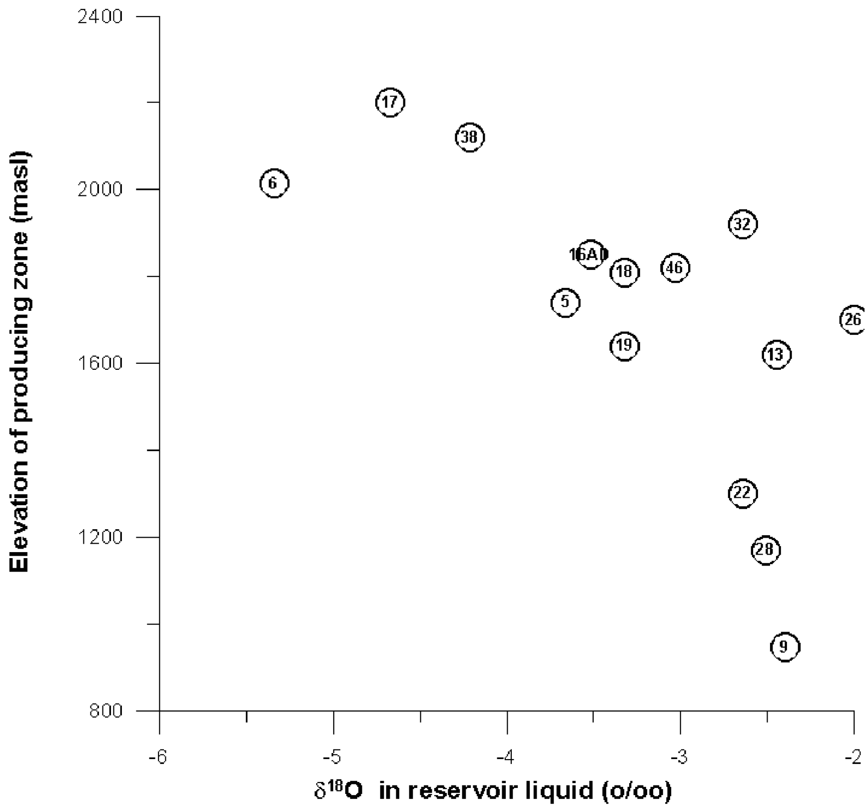

Fig. 6. Oxygen-18 distribution in the Los Azufres reservoir liquid.

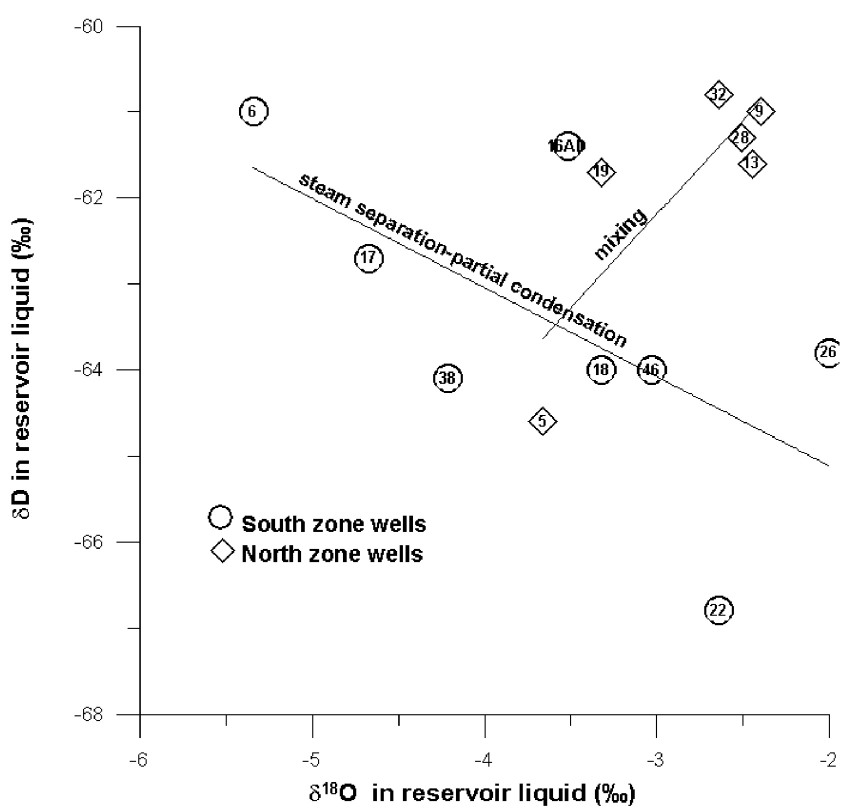

Fig. 7. Deuterium vs oxygen-18 composition of Los Azufres reservoir fluids.

mal perturbations in the reservoir (Quijano-León and Torres-Rodríguez, 1995). Stabilized temperatures were obtained by Arellano *et al.,* (1998), by using a spherical approach and reservoir temperatures between 300 and 330°C were found for the shallower reservoir and between 300 and 400°C for the deeper reservoir. D'Amore and Truesdell (1985) developed a method, which was able to estimate both the reservoir temperature and the excess steam, based on equilibria for the Fischer-Tropsch reaction and the pyrite-magnetite mineral buffer. The solution of equilibrium equations produced a grid from which the reservoir temperature and the excess steam were obtained, in a graphical way. Since this method produced unrealistic high temperatures and low excess steam values for some wells in Mexican geothermal fields, D'Amore (1998) developed another method that considers more local oxidant conditions, implying the occurrence of high concentration of H_2S and relatively low concentrations of H_2 and NH_3 in the reservoir fluid. Thus, this approach is based on the Fischer-Tropsch (FT) reaction and a new chemical reaction for the H_2S-H_2 system (HSH2). The pyrite-hematite equilibrium was combined with the original pyrite-magnetite equilibrium to obtain a new equilibrium expression named HSH2, given by

$$1.25\ H_2 + 1.5\ FeS_2 + 0.75\ Fe_2O_3 + 1.75\ H_2O = 3H_2S + Fe_3O_4\ .$$

This method was previously described (Arellano *et al.,* 1998; Barragán *et al.,* 2000) and consists of calculating the FT and HSH2 parameters from the gas composition of the samples, taking concentrations in the total fluid:

$$FT = 4\log(H_2/H_2O) + \log(CO_2/H_2O) - \log(CH_4/H_2O)\ .$$

$$HSH2 = 3\log(H_2S/H_2O) - 1.25\log(H_2/H_2O)$$

Results for Los Humeros were as follows. Figure 8 shows the grid obtained for the reservoir initial conditions. Reservoir temperature estimations were in the range from 275°C to 337°C but for well H-23 this estimation was above 350°C. Positive values for excess steam were obtained except in well H-1 which is fed by the shallower reservoir. Wells H-12, H-9 and H-19 showed an excess steam of 100%. Wells

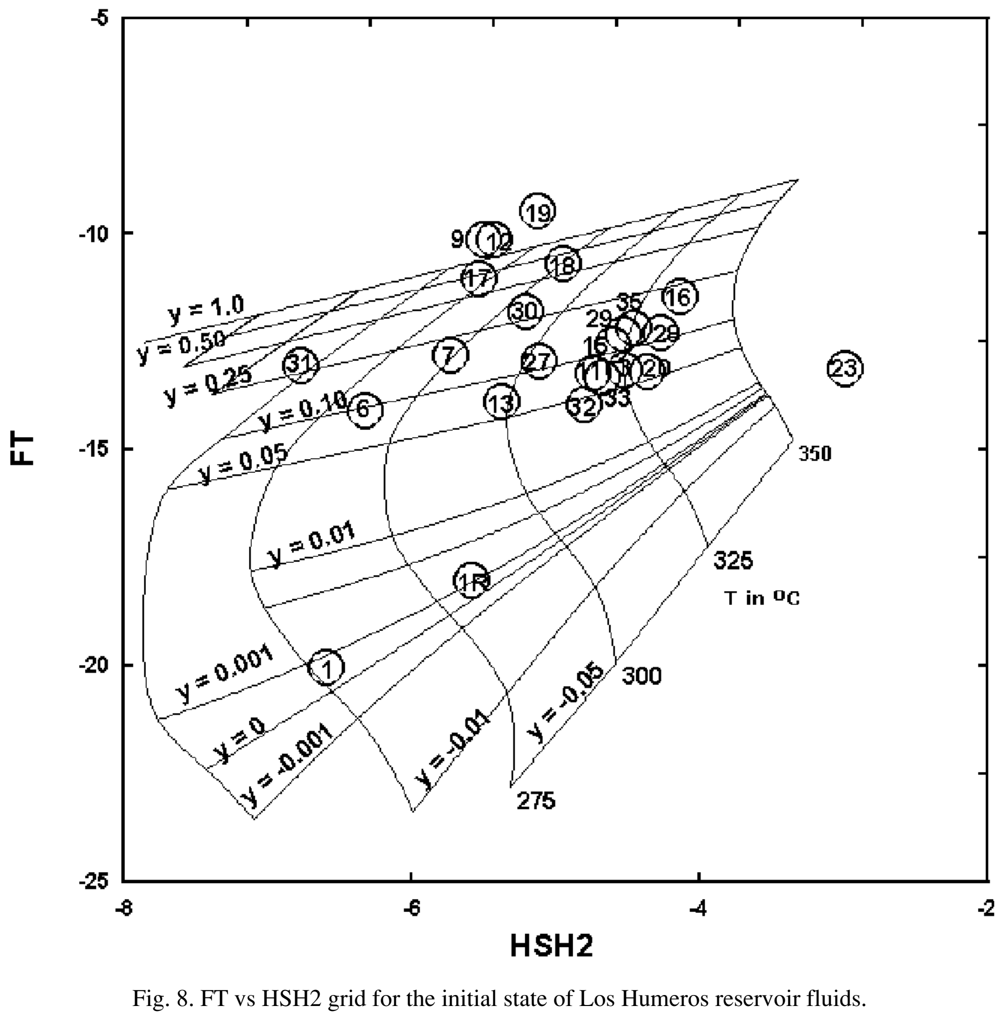

Fig. 8. FT vs HSH2 grid for the initial state of Los Humeros reservoir fluids.

H-11, H-13, H-20, H-3, H-32, and H-33 showed excess steam values lower than 10%. For well H-16 in its original completion, a reservoir temperature of 337°C and an excess steam of 20% were estimated. Wells H-17 and H-18 showed excess steam values of around 75%. For one sample of well H-23 an excess steam of 100% and a reservoir temperature of 315°C were estimated. Reservoir temperature estimations through this method are slightly lower than stabilized temperatures (Arellano *et al.,* 1998), which could be due to mixing of fluids. In contrast, for well H-35 this temperature was slightly higher than the stabilized temperature. For well H-1 the temperature estimation was slightly higher than that obtained via logged temperatures.

Reservoir temperature estimations indicated that the gas phase comes from an equilibrated high temperature (about 350°C) liquid, otherwise estimations could have been very high corresponding to the system's formation (D'Amore, 1998). Thus, results support the hypothesis that in Los Humeros a hypersaline liquid is likely to occur at depth.

Figure 9 shows the grid obtained for 1997 data. In well H-1 an overestimation of the reservoir temperature is seen, which is due to a high gas content, since there is no enthalpy increase in total discharge. Reservoir temperatures for all the wells are higher than 300°C. The highest reservoir temperature was obtained for well H-31 (335°C). Results for year 1997 show less scattering compared to those corresponding to the initial state. An explanation could be the occurrence of a heating process in the upper reservoir which at present is under exploitation, which is probably due to its exploitation, since fractures allow hotter deeper fluids to rise. This phenomenon was also pointed out by D'Amore *et al.* (1999), who also presumed that the shallower reservoir would become thinner as exploitation increases. Figure 10 shows the reservoir excess steam against the location of the producing zones according to the 1997 data. The highest values for excess steam were found for well H-15R after repairing located in the upper reservoir, and for well H-12 in the deeper reservoir. A slightly positive slope in the shallower stratum is seen, which seems to be caused by a convective process, since as depth decreases, excess steam increases.

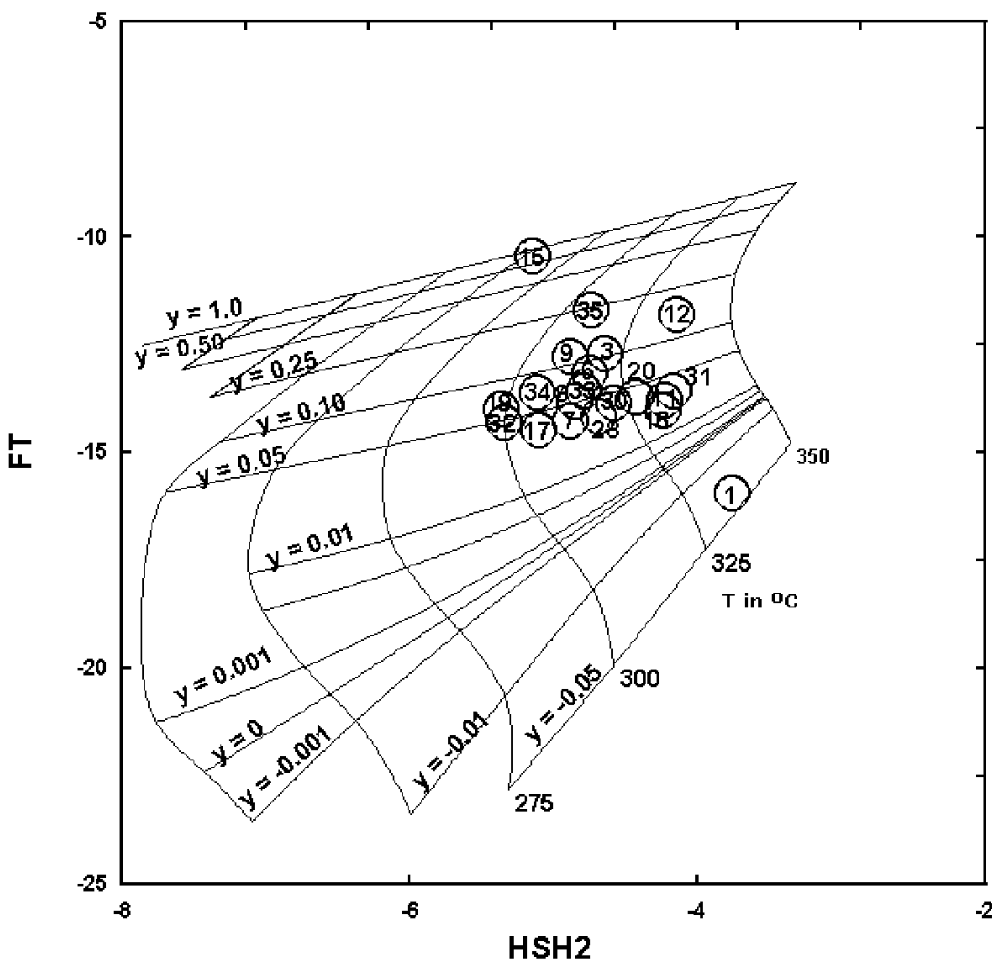

Fig. 9. FT vs HSH2 grid for 1997 data of Los Humeros reservoir fluids.

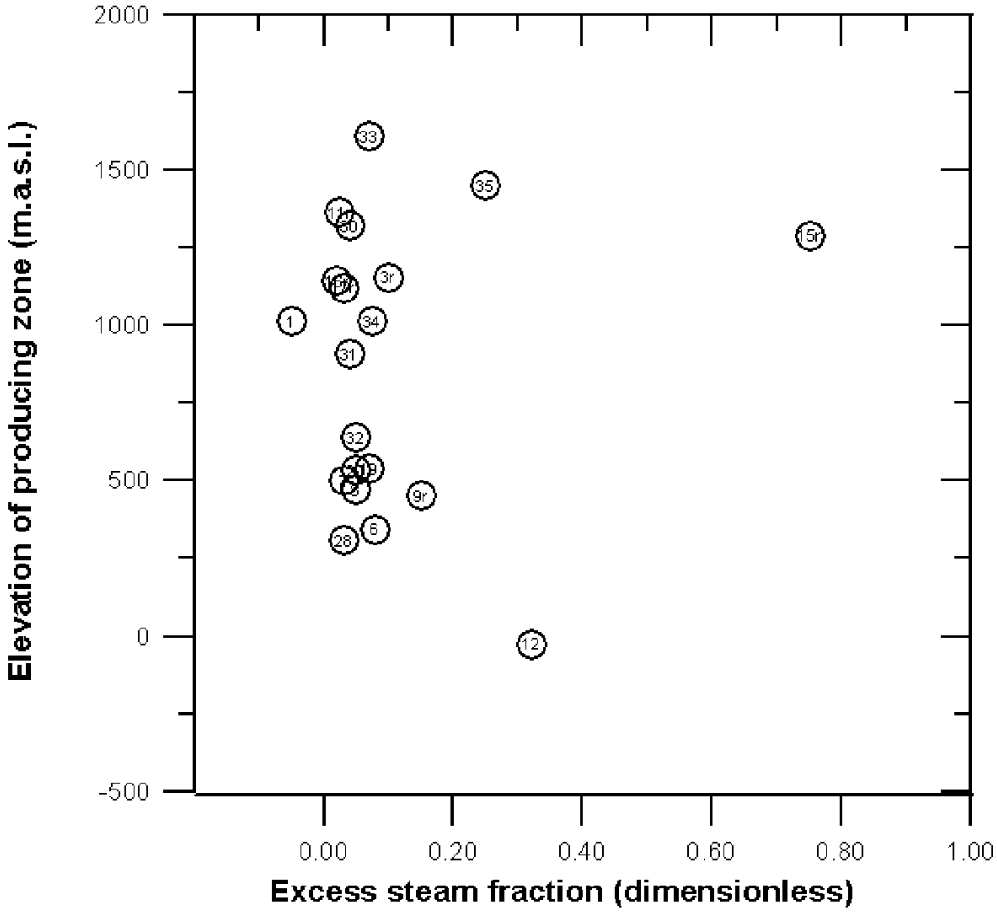

Fig. 10. Elevation of producing zones vs reservoir excess steam for 1997 data of Los Humeros reservoir fluids.

CONCLUSIONS

Gas geochemistry provided support in the development of geochemical conceptual models for Los Azufres and Los Humeros geothermal reservoirs. In the case of Los Azufres gas equilibria (FT method) allowed the estimation of the reservoir excess steam parameter, which was used to calculate the composition of the reservoir fluids. A convective process with reservoir steam separation and partial condensation was found for the natural state fluids, which explained the behaviour of chemical and isotopic species. In the case of Los Humeros, besides the reservoir excess steam, the reservoir temperature was estimated by using the FT-HSH2 method. High values for reservoir excess steam were found for deep wells since they were fed by the two identified reservoirs. After wells were deviated or cemented in order to avoid the input of hotter acid fluids, more recent data showed the occurrence of a heating process in the upper liquid – dominant reservoir due to the ascent of deep fluids through fractures to the upper reservoir.

The gas phase has also been used in monitoring reservoir changes due to exploitation allowing the occurrence of reservoir processes such as boiling or mixing to be identified.

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