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Analysis of Isotopic Patterns (1985-2003) of the Los Azufres (Mexico) Geothermal Fluids

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ABSTRACT

The analysis of chemical and isotopic data of the Los Azufres geothermal fluids indicates that at present, important reservoir changes have occurred regarding unperturbed conditions, obtained in 1987. The changes has been attributed to physical processes at the reservoir due to reinjection and reservoir utilization. According to isotopic data taken before 2000, it was seen that interference of reinjection fluids had minor effects in the northern zone of the field compared with those in the south. Until 2002, reservoir boiling and mixing of reservoir fluids with cooler fluids were the main identified processes. Mixing of reservoir fluids with cooler reinjection waters was observed in the west of the south zone, in wells located close to the reinjection area and towards the center. The 2003 isotopic patterns, that include eight new wells of the northern zone, show that, at present, reinjection interference occurs in both zones.

1. INTRODUCTION

The Los Azufres geothermal field is an intensely fractured, two-phase, volcanic hydrothermal system located in the northern portion of the Mexican Volcanic Axis geological province, in the state of Michoacán at an average elevation of 2800 m.a.s.l. At present it is the second in the country generating 188 MWe (Arellano et al., 2003). The field is divided in two zones: Maritaro liquid-dominated in the north and Tejamaniles steam-dominated zone in the south.

The reservoir engineering model of the Los Azufres reservoir (Iglesias et al., 1985) established that the natural state reservoir, consists of a deep aquifer and that the ascending fluid starts boiling at about 1200 m.a.s.l. The two-phase liquid dominant region extends upwards from 1200 m.a.s.l. 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 found.

According to Cathelineau et al, (1985 the most important hydrothermal minerals occurring at the Los Azufres geothermal system are: chlorite, pyrite, hematite, epidote, calcite, albite, adularia, zeolite and quartz which were formed by alteration of primary minerals: olivine, pyroxene/amphiboles, biotite, feldspar and matrix.

The geochemical model of the Los Azufres reservoir was proposed by Nieva et al. (1987). This model was based on the spatial distribution of chemical and isotopic species at reservoir conditions. The reservoir excess steam was estimated in the wells by a method based on equilibrium of the Fischer-Tropsch reaction (Giggenbach, 1980; Nieva et al., 1987).

The *y* values were obtained at the reservoir temperature which was estimated by the cationic (CCG) (Nieva and Nieva, 1987) or silica (Fournier and Potter II, 1982) geothermometers in two-phase wells. The measured temperatures were taken in vapor wells. The *y* values were used to correct the total discharge chemical and isotopic composition to obtain the reservoir "reference" values. As the concentration of volatile species (CO_2) was larger in shallower strata and concentrations of non-volatile species (chloride and oxygen-18) increased with depth, the model established the occurrence of a convective process, with steam up-flow and partial condensation at the reservoir. According to the geochemical model, this behavior seemed to be dominant in the south zone, while for the north, the presence of two different fluids, with different isotopic composition was proposed.

The separated water in the Los Azufres two-phase wells is sodium-chloride type with neutral pH at separating conditions. The deep reservoir fluid contains until 1600 ppm of chloride while the molar fraction of CO_2 has been calculated between 0.3 to 8.3 (Nieva et al., 1987). The pH of reservoir fluids is neutral, with values between 5.5 and 7.4 (Barragán et al., 1988). The CCG geothermometer (Nieva and Nieva, 1987) provided reservoir temperatures of more than 300°C at the northern zone, while slightly lower values, between 270 and 290°C, were estimated at the south.

The well discharges in the Los Azufres geothermal field contain a relatively high content of non-condensable gases, compared to other fields (Barragán et al., 2004a). In wells affected by reinjection, N_2 concentration has increased, since a water/air mixture is injected to the reservoir.

Isotope monitoring of fluids has been useful to investigate the occurrence of reservoir processes due to utilization in the Los Azufres field (Barragán et al., 2003a; 2004b; Arellano et al., 2003).

The objective of this work is to analyze the isotopic ($\delta^{18}O$, δD) patterns of fluids produced by wells since 1985 to 2003 in order to investigate the effects of reinjection and utilization.

2. METHODOLOGY

The location of the wells is given in Figure 1. The methodology used in this study was as follows: (a) the total discharge isotopic composition of fluids was calculated; (b) the annual δD vs $\delta^{18}O$ relationships were obtained; (c) the slopes of the δD vs $\delta^{18}O$ curves were interpreted together with injection data. In order to do this process, the isotopic and production databases provided by the Comisión Federal de Electricidad, Mexico, were used.

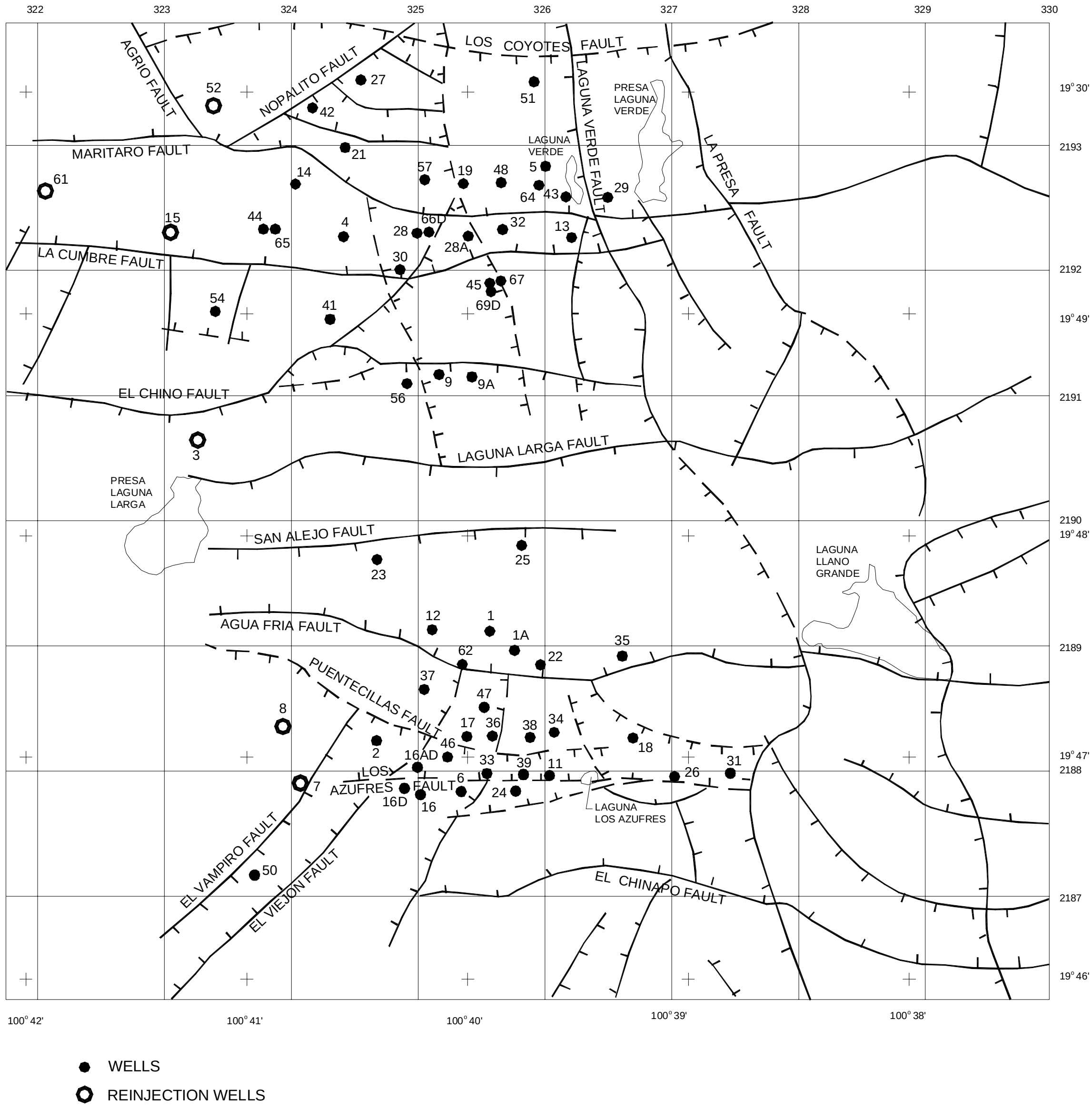

Figure 1. Location of wells in the Los Azufres Geothermal field. "AZ" was removed of the name of wells.

3. RESULTS AND DISCUSSION

3.1 Reinjection Historical Data

Fluid reinjection in the field started at early eighties according to Figures 2-5. All the reinjection wells are located at the west of the field. Reinjection wells AZ-7 and AZ-8 are located in the southern zone, while wells AZ-3, AZ-15, AZ-52 and AZ-61 are in the north.

3.2 δD vs δ ^{18}O Trends

Figure 5 shows the δD vs δ ^{18}O behavior of fluids according to 1985 data, the trends of behavior found for the reservoir natural state are shown. Important variations in total discharge composition in wells were seen at the same year. However, in a specific well, the variation of isotopic values occurs in the direction of the main trend of behavior, and is mainly due to: (a) different wellhead conditions at sampling and (b) changes in the steam/liquid ratio at reservoir. In 1985, the reinjection of fluids to the reservoir was not very important, as seen in Figures 2-5, thus, the isotopic data distribution was considered as representative of the reservoir natural state fluids. The isotopic negative slope obtained for the southern zone wells, indicates the occurrence of a convective process, while the positive slope found for the northern zone wells indicates the mixing of two different fluids. Although not mentioned in the geochemical model (Nieva et al., 1987), one of the fluids in the mixture (with lighter isotopic composition), is that occurring in the southern zone. This fluid has a δ ^{18}O and δD composition of about -3.4 and -63 (‰) respectively. This is suggested considering the point where the curves intercept each other.

The isotopically more enriched component in the mixture, seems to be that feeding the deep well AZ-28.

Scarce isotopic data was obtained during 1986-1987, (Figure 6) where all the points follow the 1985 main trends. The exception is well AZ-41, which follows the tendency of the southern zone, in spite of its location in the north. The reason is that AZ-41 is a shallow dry steam well, connected to the reservoir upper steam layer.

Figure 7 shows the δD vs δ ^{18}O plot of total discharge fluids according to 1992-93 data.

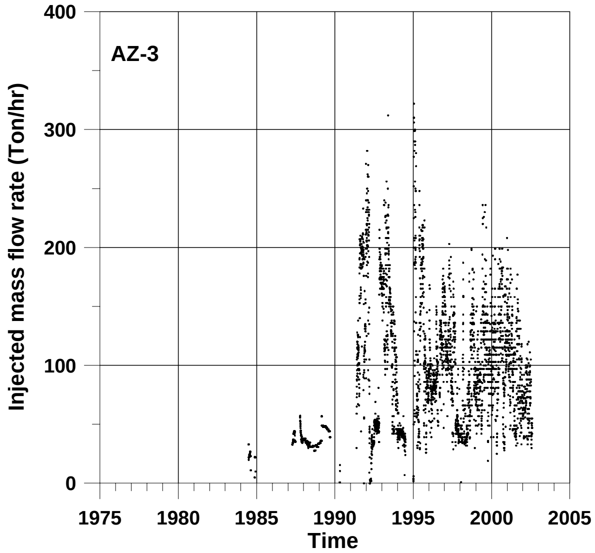

Figure 2: Injected mass flow rate vs time in well AZ-3.

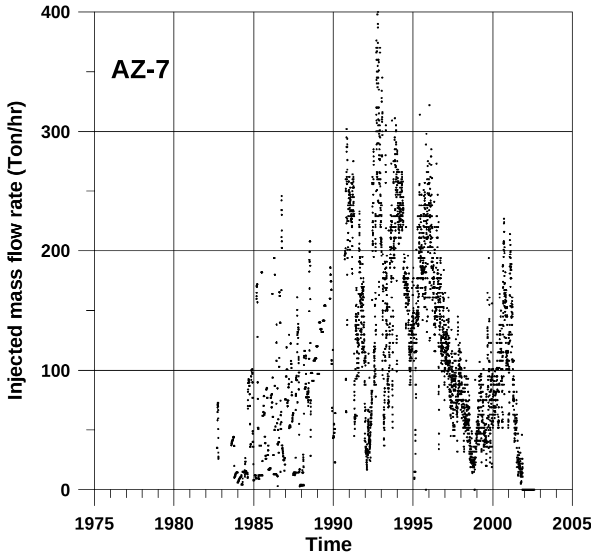

Figure 3: Injected mass flow rate vs time in well AZ-7.

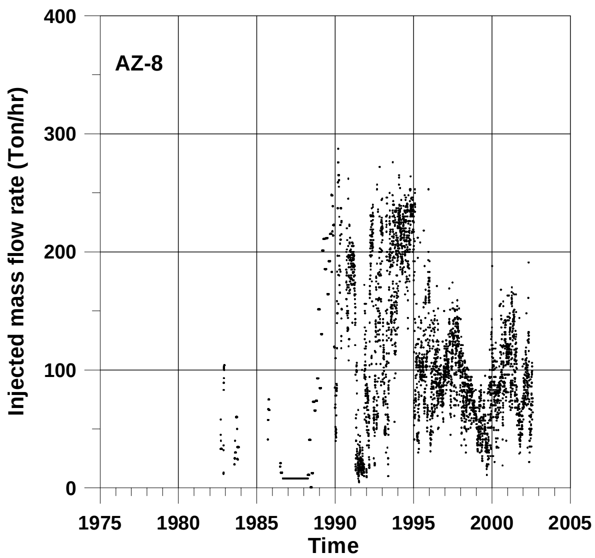

Figure 4: Injected mass flow rate vs time in well AZ-8.

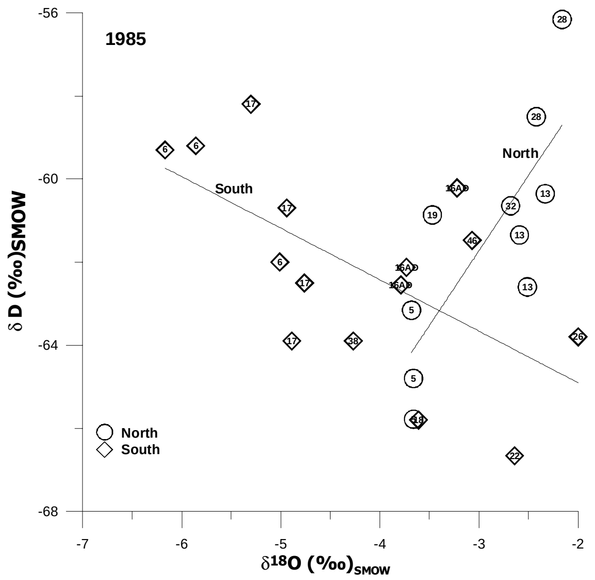

Figure 5: δD vs δ ^{18}O plot of total discharge fluids in 1985. "AZ" was removed of the name of wells.

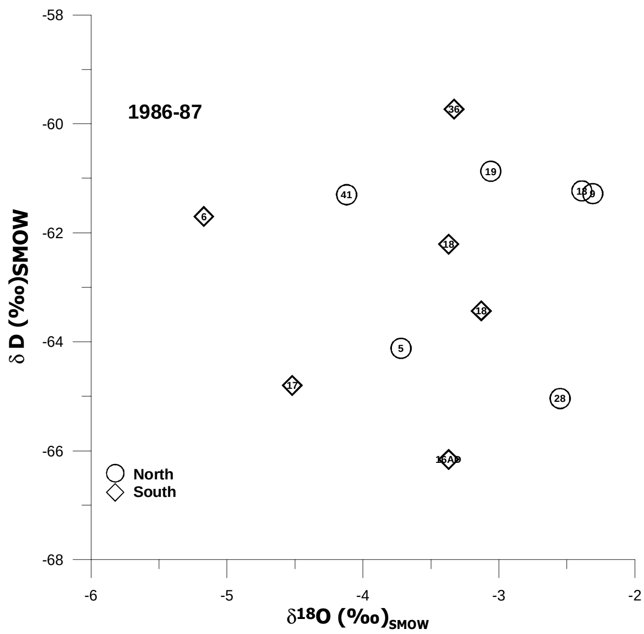

Figure 6: δD vs δ ^{18}O plot of total discharge fluids in 1986-87. "AZ" was removed of the name of wells.

During these years, only the southern zone wells were sampled, but well AZ-41 was included. The behavior shows that, in spite of the large mass flow rates injected to the reservoir in wells AZ-7 and AZ-8 in this period, there is no significant change in the isotopic values of the wells. Thus, the slope of the fitting curve, without considering the isotopic composition of reinjection wells, is negative.

Figure 8 shows the δD vs δ ^{18}O plot of total discharge fluids, according to 1994 data. In this figure, the behavior of the southern zone indicates a positive slope, which was interpreted as the result of reinjection and reservoir fluids mixing. The reinjection affected mainly wells AZ-16, AZ-16AD, AZ-2 and AZ-36. Well AZ-16 was the most affected, since its isotopic composition compares well with that of well AZ-8. The reservoir fluids composition reflects the composition of the steam wells AZ-35, AZ-17 and AZ-6. In contrast, the slope observed for the northern zone wells, gives a negative value, indicating the occurrence of boiling and steam separation in a convective process. As a result of this process, the separated steam is enriched in deuterium and depleted in oxygen-18. No correlation was found between the isotopic composition of the northern zone well fluids and reinjection fluids.

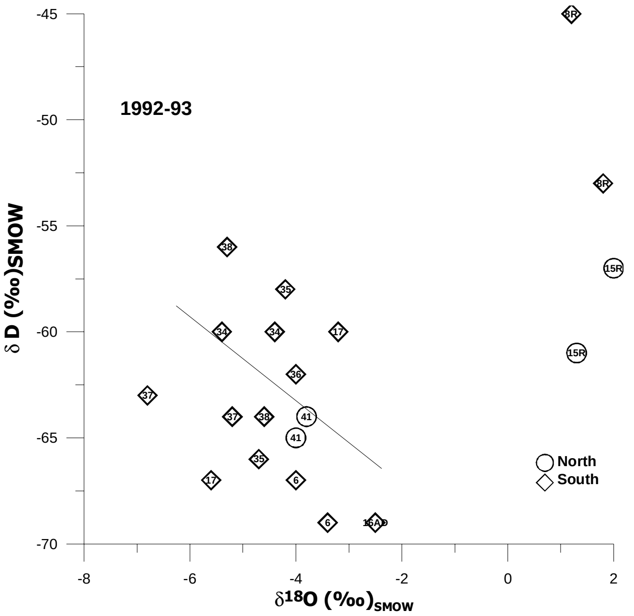

Figure 7: δD vs δ ^{18}O plot of total discharge fluids in 1992-93. "R" was added to reinjection wells name. "AZ" was removed of the name of wells.

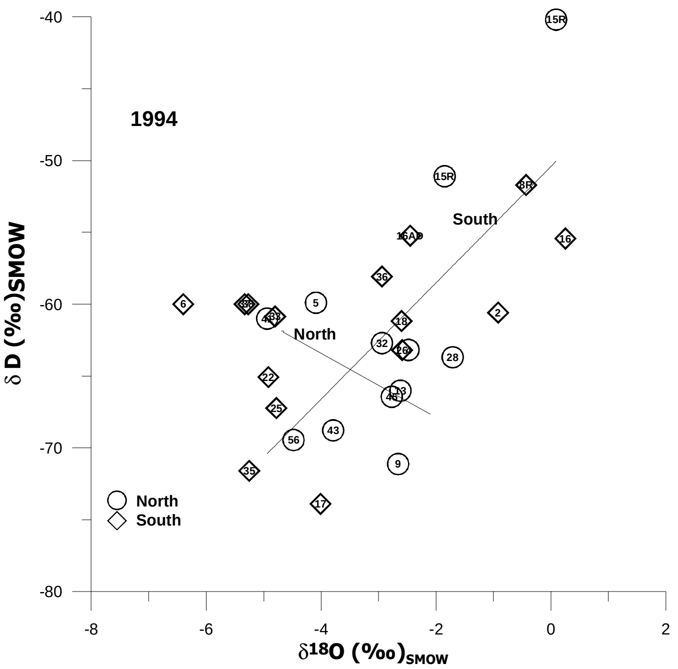

Figure 8: δD vs δ ^{18}O plot of total discharge fluids in 1994. "R" was added to reinjection wells name.

Figure 9 gives the plot of the δD vs δ ^{18}O total discharge composition of fluids according to 1995 data. In this figure, the slope, with a value of 3, obtained for the southern zone, indicates the mixing of reinjection and reservoir fluids. This relationship gives a correlation coefficient of 0.8. Wells affected by reinjection were AZ-2, AZ-46, AZ-16, AZ-16AD and AZ-33. In contrast, the isotopic pattern obtained for the northern zone does not indicate correlation between reinjection and reservoir fluids. The isotopic correlation provides a negative slope, with a lower value (-2.85) than that obtained for 1994 (-0.46). However, the analysis of chemical, isotopic and production data of individual wells, evidenced that in 1995 the well AZ-13 of the northern zone received some fluid injected in well AZ- 15, (Arellano et al., 2003). In Figure 10, the oxygen-18 in well AZ-13 follows the injection pattern of well AZ-15.

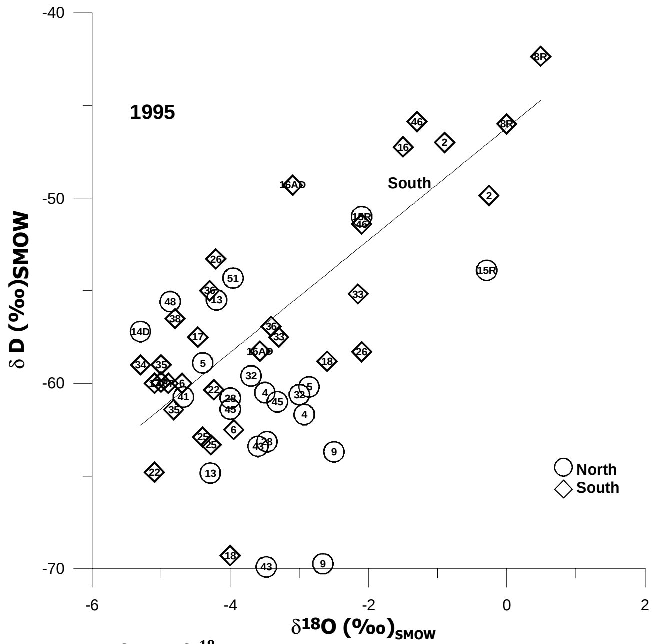

Figure 9: δD vs δ ^{18}O plot of total discharge fluids in 1995. "R" was added to reinjection wells name. "AZ" was removed of the name of wells.

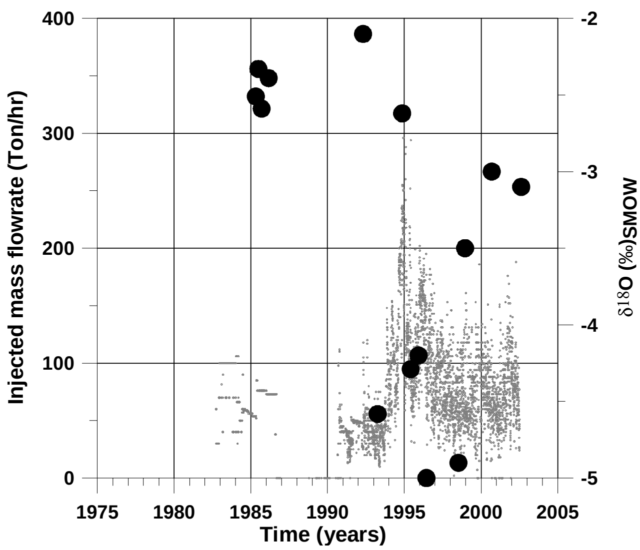

Figure 10: Mass flow rate injected in the well AZ-15 and δ ^{18}O values for well AZ-13 vs time.

In Figure 11 the δD vs δ ^{18}O plot of total discharge fluids according to 1996 data is shown. The pattern obtained for the southern zone indicates the mixing process caused by the interference of reinjection fluids. However, maybe due to a lower mass flow rates reinjected in well AZ-8 at this date, the slope of the curve, without considering reinjection data, is 1.67 with a correlation coefficient of 0.36. If the isotopic composition of reinjection fluids is considered in the correlation, such values are as follows, a slope of 3.47 and a correlation coefficient of 0.66, which were considered to be very significative. The isotopic pattern found in the northern zone fluids has a positive slope (0.7), without considering the composition of reinjection fluids. Based on the behavior of well AZ-13 in the northern zone (Figure 10) and on the positive δD vs δ ^{18}O slope obtained, it is stated that by this date, reinjection had important effects in the northern zone. Considering the isotopic composition of reinjection fluids, the slope and the correlation coefficient of the curve obtained for the northern zone were 3.29 and 0.79, respectively.

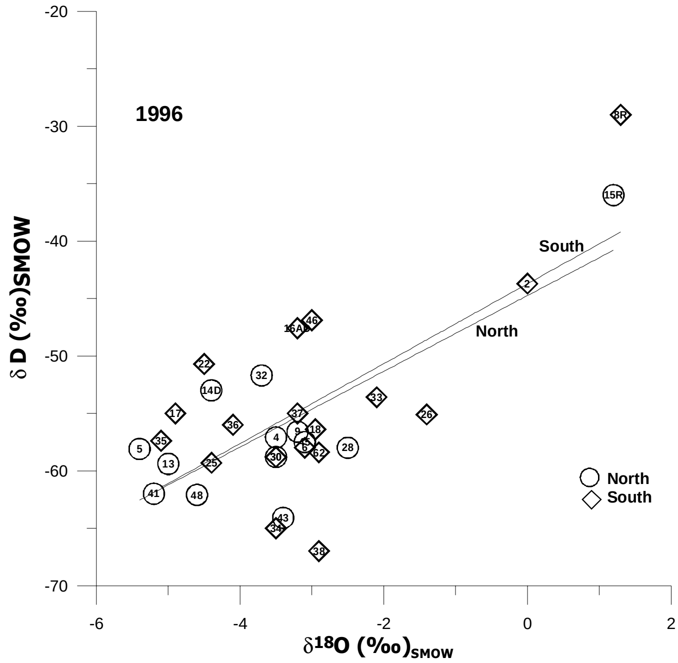

Figure 11: δD vs δ ^{18}O plot of total discharge fluids in 1996. "R" was added to reinjection wells name. "AZ" was removed of the name of wells.

Figure 12 shows the total discharge δD vs δ ^{18}O plot of 1998 data. Considering the isotopic composition of reinjection fluids in both zones of the field, the obtained curves indicate mixing processes. Both slopes are positive with values of 1.83 and 2.83 for the southern and the northern zones respectively: the correlation coefficients were 0.59 for the south and 0.72 for the north.

The decrease in mass flow rates injected in 1998 in wells AZ-7, AZ-8 and AZ-15 compared to the rates injected in previous dates, could be the reason of the change in the curve slopes, in both zones of the field.

In Figure 13 the total discharge δD vs δ ^{18}O plot according to 2000 data is shown. The isotopic patterns obtained in both zones of the field clearly indicate a mixing process due to reinjection interference. Both curve slopes are positive with values of 3. Both correlation coefficients are also very significant, 0.91 for the south and 0.83 for the north.

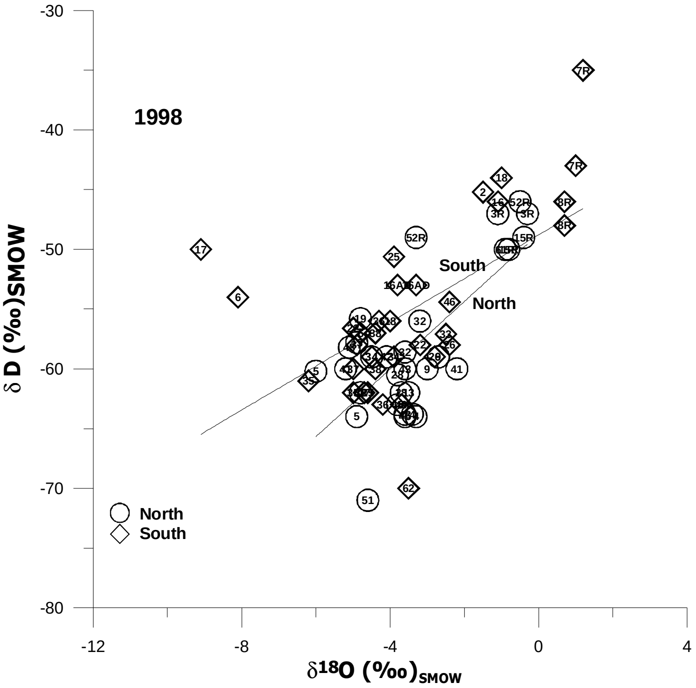

Figure 12: δD vs δ ^{18}O plot of total discharge fluids in 1998. "R" was added to reinjection wells name. "AZ" was removed of the name of wells.

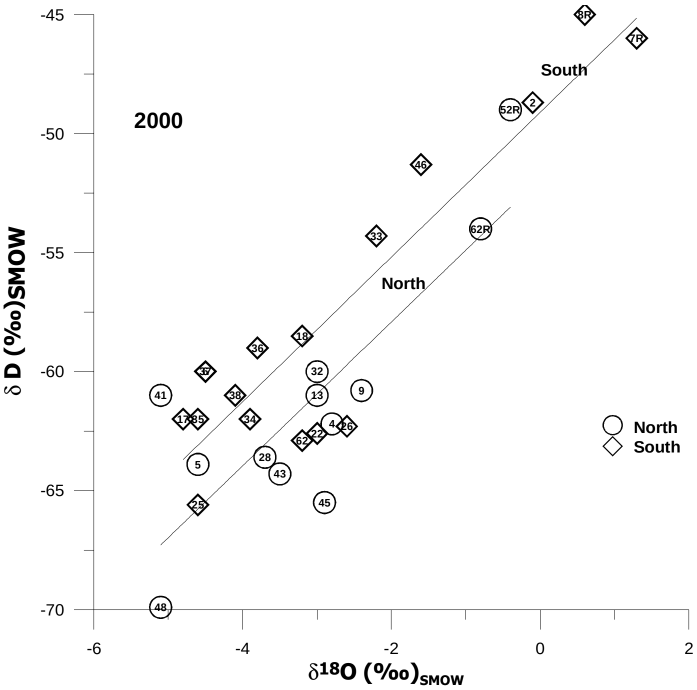

Figure 13: δD vs δ ^{18}O plot of total discharge fluids in 2000. "R" was added to reinjection wells name. "AZ" was removed of the name of wells.

The mass flow rates of injection fluids increased in 2000, after minimum values recorded around 1999. Figure 14 shows the distribution of reservoir temperatures (°C) in the field in 2000, (Barragán et al., 2003a). In this figure, the minimum values are located at the west of the field, as a consequence of reinjection, and increase towards the north east. The distribution of reservoir temperatures in the field is homogeneous, in spite of the reservoir fractured medium.

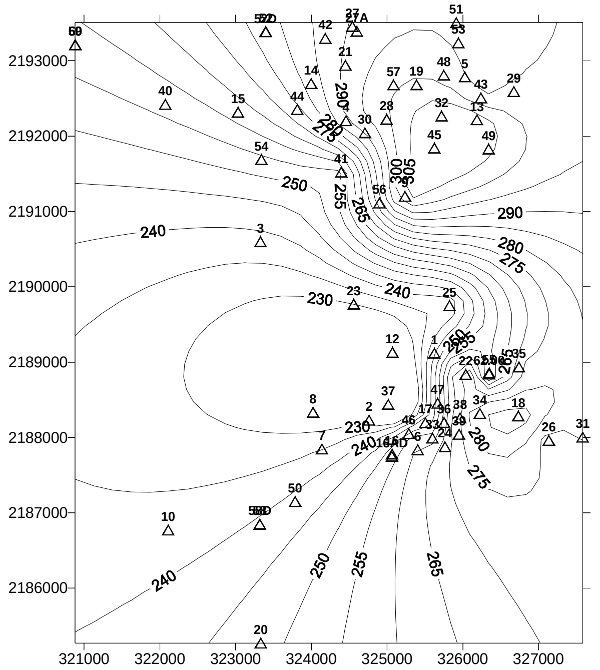

Figure 14: Distribution of reservoir temperatures (°C) in 2000. "AZ" was removed of the name of wells.

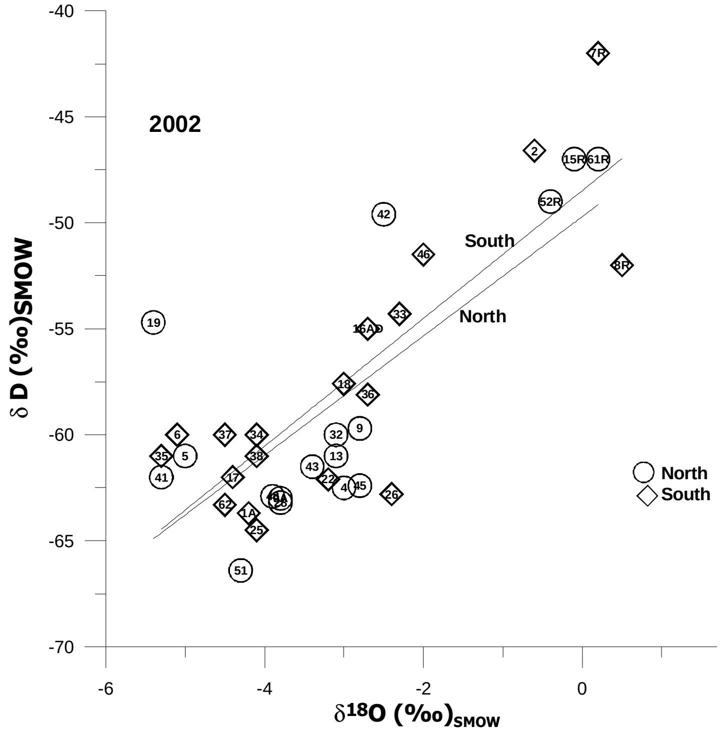

Figure 15: δD vs δ [18]O plot of total discharge fluids in 2002. "R" was added to reinjection wells name. "AZ" was removed of the name of wells.

Figure 15 shows the total discharge δD vs δ [18]O composition plot of fluids in 2002. In this figure, the isotopic composition of discharges follows a mixing trend. The slopes of the curves obtained were 2.8 and 3 for the northern and the southern zones, respectively, with correlation coefficients of 0.74 and 0.83. At this date, the maximum reinjection mass flow rates occurred in wells AZ-3, AZ8 and AZ-15, but minimum values in well AZ-7. Figure 16 shows the distribution of excess steam values (%) in the field. The maximum reservoir excess steam values were found in the areas close to the reinjection wells, in the western part of the field. The values decrease towards the east where reinjection has little effect, until zero or negative values are found,. The distribution of this parameter is also a result of reinjection, since non condensable gases tend to increase (Barragán et al., 2003a). Chloride distribution in the field follows the same pattern than that of excess reservoir steam.

Figure 17 shows the δD vs δ [18]O plot of total discharge fluids in 2003 (Barragán et al., 2003b). Eight new wells were connected to the line in the north zone, to satisfy the steam demand to produce 188 MW. The slopes of the curves in both zones of the field indicate the mixing process due to reinjection. In both curves a correlation coefficient of 0.9 was found, which was considered to be very significant. No 2003 reinjection data were available, but there would be higher mass flow rates of fluids to be disposed, considering that more wells were on line, compared with the number of wells in 2002. The 2003 δ [18]O and δD values distributions in the field are given in Figures 18 and 19. In both figures, the more enriched fluids are located close to the reinjecton wells AZ-7 and AZ-8 in the south. Oxygen-18 values become lighter toward the east and north east of the field while very light values are found close to the shallow well AZ-41 in the north. The distribution of deuterium values is very homogeneous showing lighter values to the east and to the north. Regarding 2002 data (Barragán et al., 2003a), the 2003 distributions are more homogeneous, because the well AZ-2 (located in the southern zone) which became isotopically very enriched, was not included in this analysis.

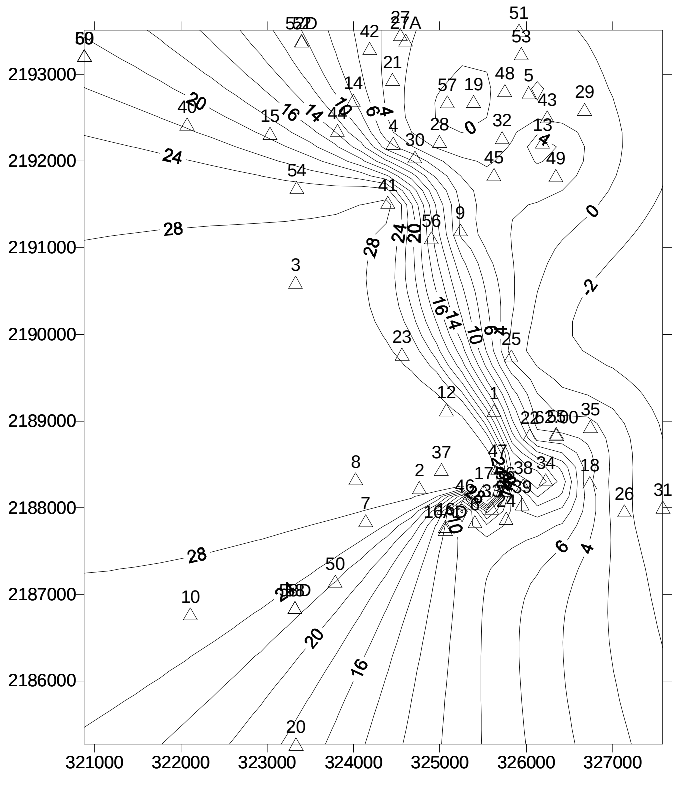

Figure 16: Distribution of reservoir excess steam (%) in 2002. "AZ" was removed of the name of wells.

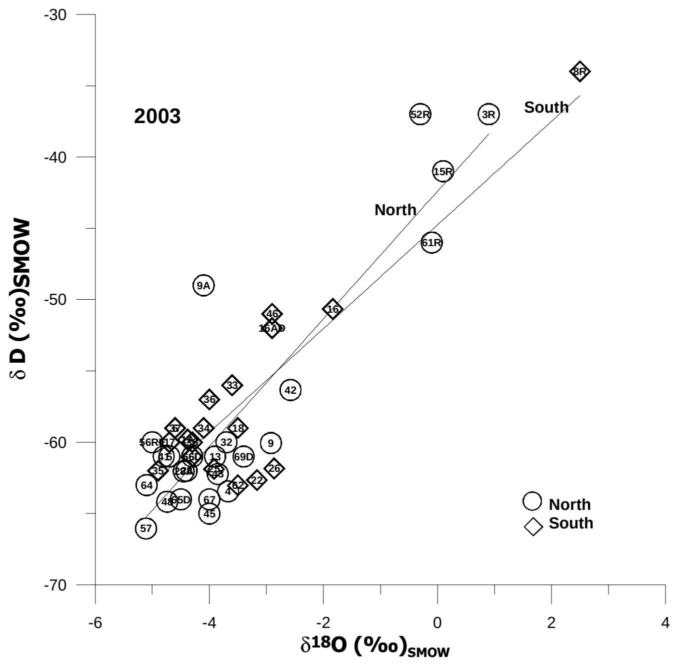

Figure 17: δD vs δ [18]O plot of total discharge fluids in 2003. "R" was added to reinjection wells name. "AZ" was removed of the name of wells.

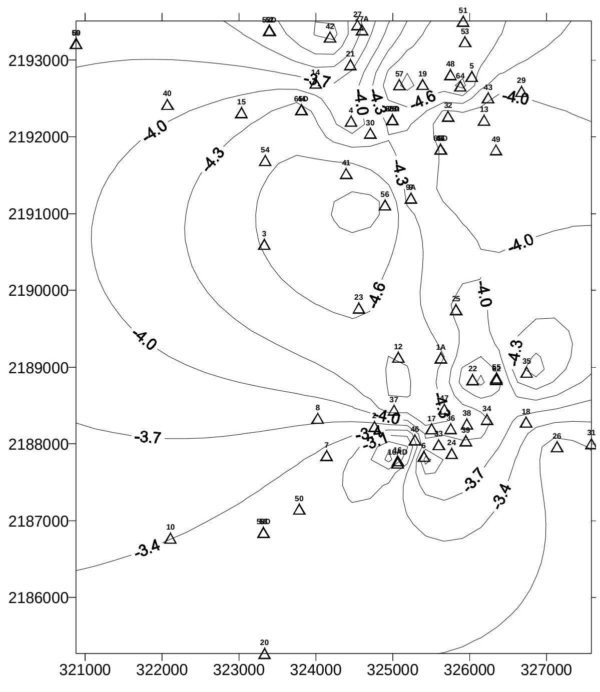

Figure 18. Distribution of of $\delta^{18}O$ in 2003. "AZ" was removed of the name of wells.

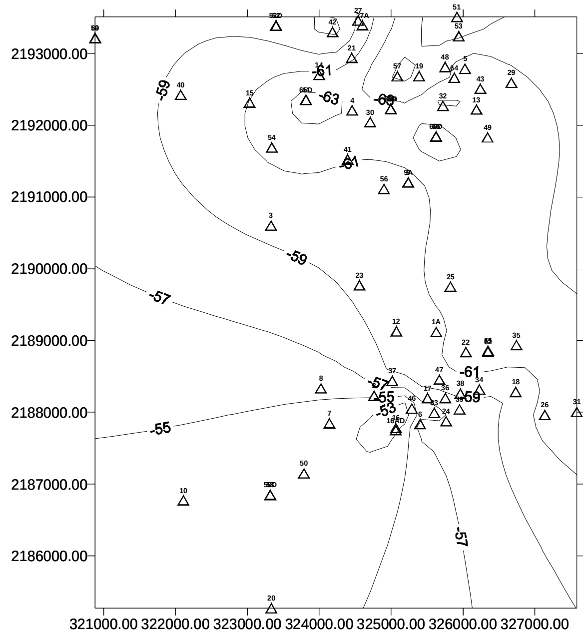

Figure 19: Distribution of δD in 2003. "AZ" was removed of the name of wells.

4. CONCLUSIONS

The 1985-2003 isotopic data of the Los Azufres geothermal fluids were interpreted in order to explain the patterns of behavior in terms of reinjection.

The results also showed that the isotopic patterns of both zones of the field obey reinjection patterns.

The results showed that in specific wells, the isotopic changes depend on the mass flow rates of reinjection fluids. The reinjection effects in the southern zone were observed since 1994, through the slope of the isotopic relationship, although the study of single wells chemical and production data showed interference much earlier. Since 1994 the slope of the isotopic trends changed to positive values of around 3, although due to the low mass flow rates injected in 1998, the slope had a lower value at that date. At present, it seems that in the southern zone, the reinjection process regulates the behavior of the wells.

In the northern zone, the reinjection effects on the isotopic composition trends were more clearly noticed since 2000 although, in the same way as in the southern zone, the data analysis of individual wells showed reinjection interference earlier.

The distribution of reservoir temperature and excess reservoir steam (and chloride among other parameters) values are also a consequence of the reinjection process, showing minimum reservoir temperatures in the west of the field but maximum excess steam values.

Although the general isotopic patterns shown give evidence on the mixing of reservoir and reinjection fluids, there are wells that receive only a small amount of reinjection recharge or are not receiving such recharge. Those wells are located at the isotopically lighter extreme of the curves. Then, there are reservoir areas in which boiling processes have been inferred to occur in both zones of the field, through the systematic analysis of production and chemical data in individual wells.

With the increase of the field installed capacity, the study of isotopic patterns of produced fluids together with the analysis of chemical and production data are recommended to better support reinjection/ utilization strategies.

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