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Mixing and Dilution Processes at the Las Tres Vírgenes (México) Geothermal Reservoir Indicated by 1997-2007 Geochemical Data

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ABSTRACT

The Las Tres Vírgenes geothermal field, located in the Baja California Peninsula (México) has currently an installed power capacity of 10 MWe. The reservoir is liquid-dominated with temperatures in the range 250-275°C. In this work we present the results of an investigation of the main physical processes at the Las Tres Vírgenes geothermal reservoir, based on the study of geochemical data for the period 1997-2007. The results indicate the occurrence of mixing and dilution processes between two end members; the characteristic reservoir fluid (average 274°C, Cl concentration of 6,745 ppm), which is typically produced by the deepest well, LV-13 (2,414 m deep), and a lower-temperature end member (171-202°C, Cl concentration of ~500 ppm), that resembles the fluids produced by the shallowest well LV-2 (1,270 m deep). According to this, the fluids discharged by wells LV-1, LV-3, LV-4 and LV-11 over time consist of mixtures of different fractions of these end members. As multiple entries to the wells were also identified, it is likely that fluid mixing occurs in the wells, which strongly promotes mineral scaling in well casings.

1. Introduction

The Las Tres Vírgenes geothermal field is located in the state of Baja California Sur (México) in the Baja California Peninsula (Figure 1). At present it has an installed power capacity of 10 MWe (Gutiérrez-Negrín, 2007) while a capacity of 10-20 MWe for the field has been estimated (Flores-Armenta and Jaimes-Maldonado, 2001). Exploration studies in the area started in 1982 and the first exploratory well (LV-2) was drilled in 1988 (Flores-Armenta and Jaimes-Maldonado, 2001). To date, at least nine wells have been drilled in two separated zones: LV-1, LV-2 and LV-5 (which are not longer producers) in the northern zone; LV-3, LV-4, LV-11 and LV-13 in the southern zone and wells LV-7 and LV-8 are located to the east of the field (Figure 1). The wells LV-2, LV-7 and LV-8 are used as injectors. The wells in the southern zone produce hotter and more saline fluids than the northern wells (Flores-Armenta and Jaimes-Maldonado, 2001). Truesdell (1998) and Portugal et al, (2000) have proposed geochemical models for the Las Tres Vírgenes reservoir. At the Las Tres Vírgenes field severe scaling has been observed to occur in some wells making necessary the use of a commercial inhibitor (Flores-Armenta and Jaimes-Maldonado, 2001).

In 2007 a study was developed to investigate the main reservoir processes occurring due to exploitation, (Iglesias et al, 2007). Some results based on fluid-mineral equilibria, indicated multiple fluid entries to the wells and fluid mixing, since saturation indices of characteristic hydrothermal minerals converged with each other at zero value for different temperatures (Barragán et al, 2009).
As it is well known that mixing of fluids with different chemical compositions strongly promotes mineral deposition (Arnorsson, 1992; Bethke 1995), it is possible that the scaling phenomena in the field, is being enhanced by such mixing processes. Then the objective of this work is to characterize the mixing and dilution processes occurring at Las Tres Vírgenes reservoir through the geochemical characteristics of fluids discharged over time, in order to give support to studies related to both the scaling phenomena and the hydrological behavior of the reservoir. This study included historical geochemical data for wells LV-1, LV-3, LV-4, LV-5, LV-11 and LV-13 provided by Comisión Federal de Electricidad.

2. Methodology

The geochemical indicators used were as follows; ion concentrations; reservoir temperature estimations from chemical geothermometers $T_{SiO_2}$ (Fournier and Potter, 1982), $T_{Na-K-Ca}$ (Fournier and Truesdell, 1973) and $T_{NaK}$ (Nieva and Nieva, 1987); total discharge enthalpies; and $\delta^{18}$O and $\deltaD$ in fluids. To identify reservoir processes, characteristic patterns obtained from the comparison of enthalpy estimations (total discharge enthalpy and enthalpies obtained from the steam tables for Na/K, Na-K-Ca and silica temperatures) of a specific well over time (Truesdell et al, 1995) were studied. To investigate mixing processes linear correlations between conservative species were obtained while to estimate the main characteristics of the end members in the mixture, we used the enthalpy-chloride mixing model (Truesdell and Fournier, 1975).

3. Results

3.1 Pre-Exploitation Conditions

Early data of the Las Tres Vírgenes wells were considered to investigate the distributions of chloride in produced fluids (Figure 2) and the Na/K reservoir temperatures (Figure 3) for initial conditions of the reservoir. As shown in Figure 2, maximum chlorides (9,000 ppm) are found in the southern zone, with decreasing trends to the north, to very low values in well LV-2, and to the east of the field, with chloride values slightly lower than 5,000 ppm in well LV-7. The reservoir temperature distribution in Figure 3 shows maximum values (> 260°C) in the southern zone (well LV-13) while temperatures of ~260°C are indicated along northern and southern wells but slightly lower in LV-2. Temperatures decrease to the east of the field to values lower than 160°C in well LV-7. These chloride and temperature distributions support that the main upflow is located in the southern block and the flow direction is towards the north, as was reported by Flores-Armenta and Jaimes-Maldonado (2001).

3.2 Evidences of Mixing

Considering that B, Li and Cl are “conservative species” (Giggenbach, 1992), they were used to investigate if the fluids produced by the wells had a single source or if more than one source is present in the system. In Figure 4, average annual B vs Cl data for all the wells were plotted and a linear tendency that suggests mixing of fluids was obtained. The best linear fit has a correlation coefficient of 0.87. As seen in Figure 4, the end members involved are the fluids from well LV-13 (the deepest well, 2,414 m), that
constitute the representative hotter and more saline component, and the fluids from well LV-2 (the shallowest well, 1,270 m), the less saline, lower temperature component. The composition of the fluids produced by the wells LV-1, LV-3, LV-4, LV-5 and LV-11 are aligned along the tendency indicating that they consist of different proportions of the two end members. In Figure 5, Li and Cl average annual data for all the wells were plotted. Again a linear tendency between both ions was found with a correlation coefficient of 0.88 and the same end members of Figure 4.

In order to support the occurrence of a mixing process, the δD vs δ¹⁸O of the fluids was plotted in Figure 6. Very few isotopic data for the wells were available, while no data for well LV-2 exist. However, a linear tendency with positive slope was obtained with a correlation coefficient of 0.69. This positive slope indicates mixing of two end members, the composition of wells LV-1 and LV-13 being the more representative of the reservoir fluids, and the fluid produced by the wells LV-4 (sampled in 2007) and LV-5 as more diluted. It is important to notice the isotopic depletion (more than 5 ‰ for δD) of wells LV-4 and LV-11 sampled in 2007 with respect to their compositions found in 2003. The variations in isotopic composition of fluids over time indicated dilution since samples taken in 2007 showed depletion regarding previous data, as follows. In well LV-4 depletions in both δ¹⁸O of ~0.7 ‰ and in δD of more than 5‰ regarding 1997 data were found while in well LV-11 such decreases were ~0.6 ‰ in δ¹⁸O and ~7‰ in δD regarding 2003 data.

3.3 Behavior of Geochemical Indicators

In order to study the changes of geochemical indicators and reservoir temperatures over time, we present the chloride concentrations of the wells over time in Figure 7. As seen in this Figure, chloride variations occur in all the wells, with a general decreasing trend over time. It is noticeable the chloride decrease of about ~2000 ppm in well LV-4 from 1996 to 2005 and the slight decrease in well LV-11 from 2001 to 2005 with important fluctuations occurring during 2005-2006. In Figure 8 it is seen that the reservoir temperature decreased ~10°C in well LV-1 from 2000 to 2003 while in Figure 9 it is seen that short-term temperature variations in well LV-4 occurred during 1999-2005; then the well was temporarily closed and started operating in 2006, with an important temperature recovery (of ~20°C) up to 2007. The chloride and
temperature variations in the Las Tres Virgenes wells over time confirm the occurrence of mixing and dilution processes suggested by the behavior of chemical and isotopic species.

In order to investigate reservoir processes for the wells and to define the time periods in which each process is dominant, we compared the total discharge, Na/K and silica enthalpies according to the method proposed by Truesdell et al (1995). In Figure 10 we present the total discharge enthalpy and the enthalpies from silica and Na/K geothermometers for well LV-4. In this figure, important variations in the total discharge enthalpy from 2001 to 2004 indicate more than one fluid entry and near-well boiling during flow to the well in response to decrease in well-bottom pressure. As a result of near-well boiling the total discharge enthalpy increases. At the same time, the inflow of lower temperature fluids to the well is identified by the pattern \( H_{\text{SiO}_2} > H_{\text{Na/K}} \) because the Na/K geothermometer is a “slow response” geothermometer compared with SiO\(_2\) geothermometer, thus indicating a previous temperature of the fluid. In 2004 the pattern \( H_{\text{total discharge}} \approx H_{\text{Na/K}} \approx H_{\text{SiO}_2} \) indicates that the well produced from an equilibrated liquid. Because of the relatively low total discharge enthalpy, it is inferred that the near-well boiling process has stopped. During 2005 the pattern observed is: \( H_{\text{SiO}_2} > H_{\text{Na/K}} = H_{\text{total discharge}} \) that indicates a thermal breakthrough of cooler water with Na/K enthalpy re-equilibration. This unusual pattern could have been induced by reduction in the production orifice, since the well was being closed at that time. During 2006 the well started production from an equilibrated liquid. In 2007 the enthalpy pattern \( H_{\text{total discharge}} = H_{\text{Na/K}} > H_{\text{SiO}_2} \) shows mixture close to the well of cooler more diluted water with equilibrated liquid. Lower silica enthalpies result from dilution without silica re-equilibration. In well LV-11 (Figure 11) during 2006 the pattern \( H_{\text{Na/K}} > H_{\text{SiO}_2} > H_{\text{total discharge}} \) indicates very clearly the mixture in the well of cooler more diluted water with equilibrated liquid, while during 2007 the pattern \( H_{\text{Na/K}} > H_{\text{SiO}_2} = H_{\text{total discharge}} \) results from mixing with cooler water near the well with re-equilibration of silica enthalpy but not of Na/K enthalpy.

The enthalpy histories for well LV-13 are given in Figure 12. The general enthalpy pattern observed \( H_{\text{total discharge}} > H_{\text{SiO}_2} > H_{\text{Na/K}} \) indicates near-well boiling for short periods of time which correspond to increases in total discharge enthalpy and because of the constant pattern observed (up to 2006): \( H_{\text{SiO}_2} > H_{\text{Na/K}} \) mixing with cooler water near the well also occurs.
Based on the investigation of reservoir processes, apart from short time near-well boiling processes found for wells LV-4 and LV-13, it could be said that the more important processes that were identified to occur in the studied wells were the entry of lower temperature waters and the multiple entries of fluids to the wells for relatively long periods of time. However, such processes were not severe in well LV-11, which during 2003-2004 showed a stable behavior.

### 3.4 Enthalpy-Chloride Mixing Model

The temperature and chloride concentration of the end members involved in the mixtures were estimated by using the enthalpy-chloride model (Truesdell and Fournier, 1975). Annual average Na/K enthalpies vs annual average total discharge chlorides for the wells were plotted in Figure 13 and a linear tendency between both parameters was obtained. From this, an average reservoir (Na/K) enthalpy of 1203 kJ/kg (274°C) and a
chloride concentration of 6745 ppm were obtained for the reservoir fluid, while for the diluting water, an enthalpy of 798 kJ/kg (187°C) was estimated. The salinity of the diluting water seems to be that found for the shallowest well LV-2 (1,291 m deep), which produced fluids with a chloride concentration in separated water of ~500 ppm, from a reservoir with a temperature between 171-202°C. This agrees with results from the chemical linear trends observed in which the diluted end member was found to be similar to that produced by the well LV-2. From this result, it could be suggested that the shallower aquifer extends along the southern zone or that a similar shallower aquifer could occur at the southern zone of the field.

4. Conclusions

The analysis of geochemical data of fluids from Las Tres Vírgenes geothermal field suggest that the fluids produced by the wells seem to result from mixing of two end members in different proportions. At the same time, the results obtained from the investigation of the main reservoir processes over time, indicate that lower temperature, more diluted fluids enter the wells for relatively long periods of time supporting the hypothesis of mixing and dilution from geochemical data. Thermal breakthrough of cooler water was also identified to occur. While the hotter component was characterized by the fluid produced by the deepest well (LV-13), the more diluted component of the mixture was defined as similar to that produced by the shallower well of the field (LV-2). As no other components were identified for this mixing, and the composition of the fluids were aligned on the linear trends independently of well location (northern and southern zones), it could be suggested that the shallower aquifer feeding well LV-2, extends towards the southern zone or that another similar aquifer occurs at the southern zone. From the results of this study it is proposed that the severe scaling phenomena observed in the field could be attributed to the chemical nature of the fluids but also to the mixing of different fluids, since this process strongly enhances scaling.

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