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Response to Exploitation of the Los Azufres (Mexico) Geothermal Reservoir

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ABSTRACT

The response to exploitation of the Los Azufres geothermal reservoir was investigated through the evolution of thermodynamic patterns of reservoir fluids. The study comprised the period since the beginning of exploitation in 1982 to 2002. Thermodynamic conditions of reservoir fluids were obtained by heat and fluid flow simulation in wells using the “WELFLO” simulator and well production data as input. The initial thermodynamic conditions of fluids in the north zone of the field were located in the compressed liquid region while the first response to exploitation consisted on a pressure decrease and an enthalpy increase in wells. The long term response implies very small changes in pressure but large enthalpy increments. For the south zone wells, the initial thermodynamic conditions indicated the presence of compressed liquid, two phase fluid and steam. The first response to exploitation, was noticed through a pressure decrease and an enthalpy increase in wells, while the processes for the long term response are as follows: decrease in both pressure and mass flowrate, boiling, cooling, steam production and in wells affected by reinjection, an increase in both pressure and mass flow rate.

1. INTRODUCTION

The Los Azufres geothermal field is located at about 90 km of Morelia city in the state of Michoacán (Figure 1). The field is found in the Los Azufres sierra which reaches elevations of more than 3200 m. a. s. l. Wellhead elevations vary approximately between 2750 and more than 3000 m. a. s. l. Neighboring valleys are located some hundreds of meters below the field average elevation. In the field, two well defined zones of geothermal fluids discharges are found: Maritaro in the north and Tejamaniles in the south. Both discharge zones are separated by some km each other, in which no surface manifestations occur (Figure 1). At present, the installed capacity of the field is 188 MWe (Torres, 2003, pers. comm.).

In this work, the results of the reservoir response to exploitation through the study of thermodynamic conditions of fluids from twenty wells are presented. Also, the study included a systematic analysis of chemical, isotopic and production well data from 1982 to 2002 for the wells, in order to correlate the changes occurred at reservoir to the possible causes. Thirteen wells are from the south zone (Az-2, Az-17, Az-18, Az-22, Az-25, Az-26, Az-33, Az-34, Az-35, Az-36, Az-37, Az-38 and Az-46) and seven are from the north (Az-4, Az-5, Az-9, Az-13, Az-19, Az-28, and Az-43).

The objectives of the study were as follows: (a) to identify the main processes that have occurred and are occurring in the Los Azufres reservoir as a consequence of fluids and heat extraction as well as the reinjection of waste fluids in the reservoir, and (b) to correlate such effects with their possible causes.

2. GEOLOGICAL SETTING

The geology of the Los Azufres geothermal area has been described by De la Cruz et al., (1983), Dobson and Mahood (1985), Cathelineau et al., (1987), Ferrari et al., (1991) and Pradal and Robin (1994) among several authors. A brief summary of the main geological units of the field is given as follows (Figure 1):

Mil Cumbres andesite. This unit is considered to be the local basement and consists of approximately 3000 m thick of a rock sequence of basaltic andesites to dacites with the following sequence: 600 m thick layer of basalts in the basement, 1700 m thick layer of andesites in the middle and 700 m thick of dacites in the upper layer. The age for this unit varies from 18.1 MY in the bottom to 5.9 MY in the upper part. Some evidences of this unit can be observed in both zones of the field.

Zinapecuaro andesite: This unit consists of both andesitic lavas and basaltic andesites that are located in the Zinapecuaro, Michoacan city, whose age varies from 0.87 to 0.85 MY. This unit is not shown in Figure 1.

Agua Fria rhyolite: The basement in the central part is covered by the Agua Fria rhyolite which consisted of lava domes and fragmented flows of rhyolite with flow bands and spherules. Three domes are found inside the field while eight more are located outside the field. The age for these units varies from 1.6 to 0.84 MY.

San Andres dacite: This unit covers the all the previously described units and is located in the east part of the field. This unit consists of dacites with flow bands, plagioclase phenocrystals and aphanitic inclusions. The age of this unit varies from 0.36 to 0.33 MY.

Yerbabuena rhyolite: This unit consists of ten domes of rhyolites (rich in silica), rhyodacites and gravitational sliding material located in the west of the field. The age of this unit varies from 0.3 to 0.14 MY.

Ciudad Hidalgo basalts: This unit consists of 52 cineritic cones composed by basalt spillings and pyroclastic material located in both east and west sides of the field. The age for this unit is approximately 0.15 MY. This unit is not shown in Figure 1.

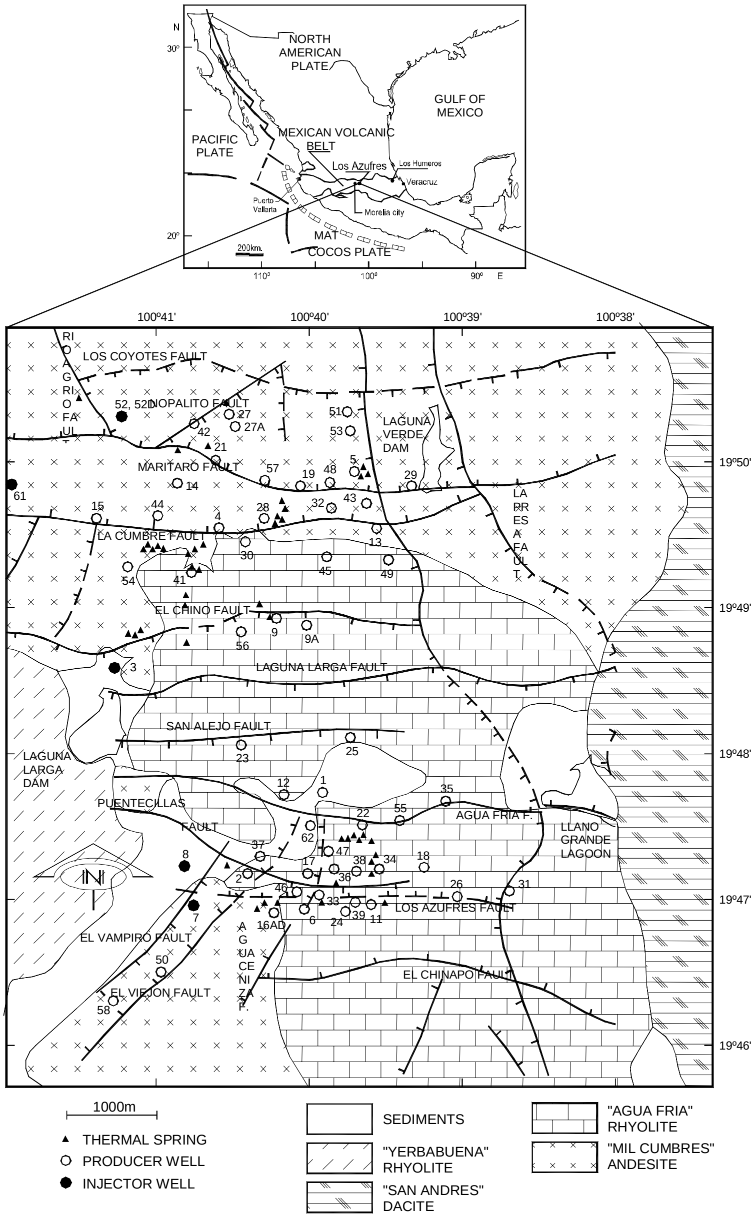

Figure 1. Location of the Los Azufres geothermal field, geology of the zone and well locations. "A-" was removed before the well number in all figures for simplicity.

Sediments: This unit consists of pumice sands, altered deposits, soils and alluvions.

In the Los Azufres reservoir three structural systems have been identified (De la Cruz et al., 1983). The older system with NE-SW direction affects mainly the andesitic basal rocks. The El Vampiro, El Viejon and Agua Ceniza faults located in the south west of the field belong to this system. The second system with E-W direction dislocates the San Andres dacite and the Agua Fria rhyolite. The Los Coyotes, Maritaro, La Cumbre, El Chino, Laguna Larga, San Alejo, Agua Fria, Puentecillas, Los Azufres and El Chinapo faults belong to this sytem. The more recent structural system has a NNW-SSE direction and the Laguna Verde, La Presa and Rio Agrio faults belong to this system.

3. RESERVOIR INITIAL THERMODYNAMIC CONDITIONS

A vertical one-dimensional conceptual model for the Los Azufres reservoir based on geological, geochemical, reservoir engineering and drilling data of 25 wells of the field was developed by Iglesias et al., (1985). The vertical pressure profile of the undisturbed reservoir against the elevation of producing zones is given in Figure 2. The solid line represents the pressure profile corresponding to a boiling water column (BPPD: boiling pressure profile against depth; Grant et al., 1982). As it is seen in figure the fit of the BPPD model is good for the range of elevations from 350 to 1800 m. a. s. l. Above this elevation, approximately to 1830 m. a .s. l. the behavior of a group of wells (Az-17, Az-33, Az-34, Az-36, Az-38 and Az-41) differ from the BPPD model. The BPPD model being a static model is considered as a good approximation for the reservoir unperturbed conditions. However this model is not suitable for low liquid saturation reservoirs since it is not able to fit properly the dynamic characteristics of two-phase flow for low liquid saturation conditions. The wells that differ from BPPD model are in fact low liquid saturated and they are aligned on a sub-vertical profile which is characteristic of steam-dominated reservoirs. This model shows that in the reservoir there exists a deep (below 1280 m. a. s. l.) and hot (approximately 303°C) aquifer. The deep compressed liquid ascends to approximately 1280 m. a. s. l. where the fluid starts boiling. The two-phase liquid-dominated region extends from 1280 to 1830 m. a. s. l. where the steam becomes the dominant phase, controlling the reservoir pressure. The two-phase steam-dominated region extends upward to approximately 2400 m. a. s. l. In Figure 3 the semi-log pressure-enthalpy diagram for the initial conditions of fluids in the field is shown. This figure was taken as the basis to study the thermodynamic evolution of the reservoir fluids.

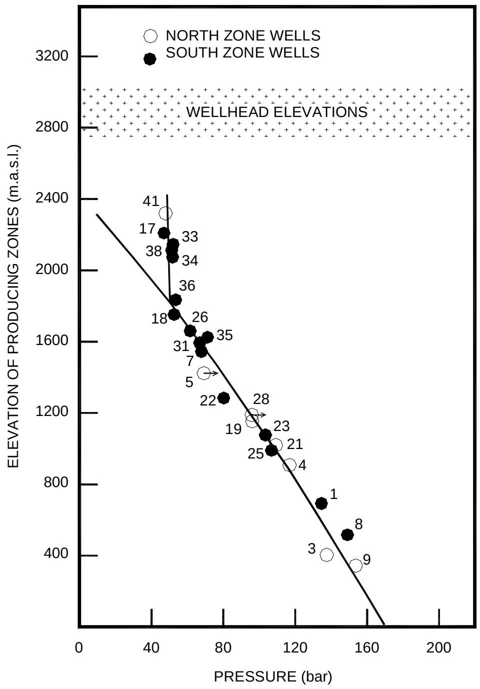

Figure 2. Natural vertical profile of the Los Azufres geothermal reservoir (Iglesias et al., 1986).

4. RESERVOIR EXPLOITATION

The exploitation of the Los Azufres geothermal field is briefly described as follows. In 1982 the commercial exploitation of the field started with the operation of five 5 MWe each units. In 1987 one additional 5 MWe unit was installed while in 1989 one 50 MWe unit accounted for a total field capacity of 80 MWe. In 1991 the operation of two 5 MWe each units started and the field capacity was increased to 98 MWe in 1994 when one 5 MWe unit and two 1.5 MWe binary cycle units were put in operation. In 1996 two 5 MWe units were removed and the capacity of the field was 88 MWe (Torres and Flores, 2000). 25 MWe were installed in the north and 63 MWe in the south of the field. At present four additional 25 MWe units have been installed and started operating during 2003.

5. FLUIDS PRODUCTION AND REINJECTION

The production and reinjection of fluids has been variable in time depending on the operation of generating units. In Figures 4 and 5 the production and reinjection data against time are given. As it is seen, the maximum fluid production

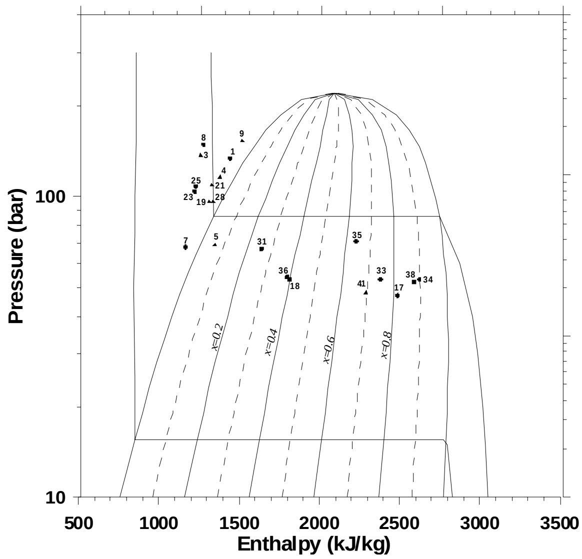

Figure 3. log of reservoir pressure against well bottom enthalpy diagram showing the initial fluid thermodynamic conditions of the wells.

(more than 13 MTon/year) occurred in 1993 when the field had an installed capacity of 90 MWe. The reinjection/production ratio has largely varied with time, with an annual average of 50% for the last ten years. The fluids are reinjected at a temperature between 40 and 50°C at the atmospheric pressure. All the reinjection wells are located in the west of the field. Wells Az-3, Az-15, Az-52 and Az-61 are from the north while Az-7 and Az-8 are from the south.

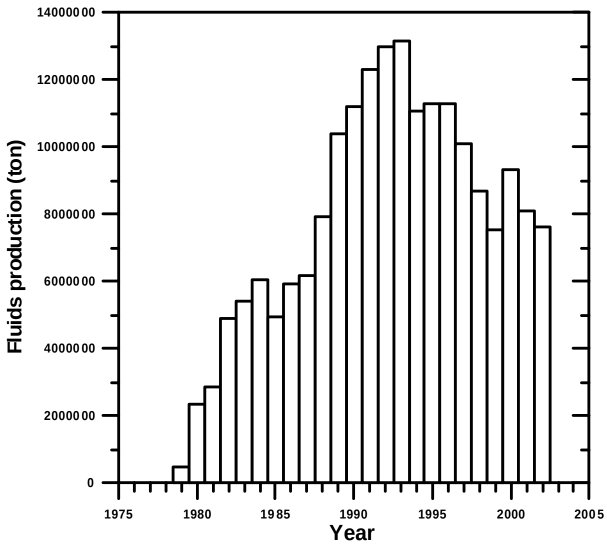

Figure 4. History of fluid total production in the Los Azufres geothermal field in time.

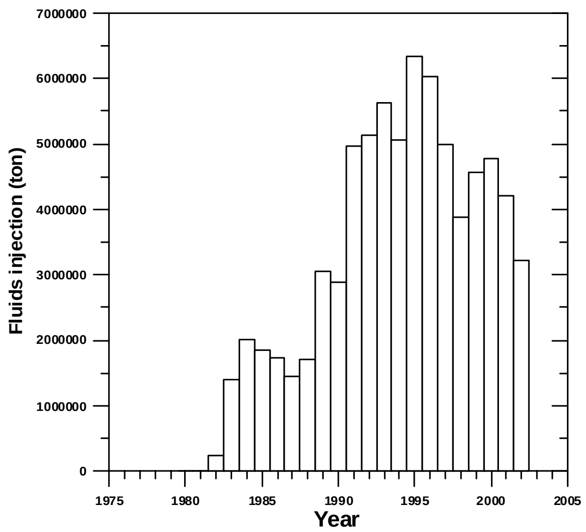

Figure 5. History of total fluid reinjection in the Los Azufres geothermal time in time.

6. METHODOLOGY

In order to identify the main processes that have occurred and are occurring in the Los Azufres reservoir as a consequence of heat and fluids extraction as well as the reinjection of waste fluids, the methodology proposed by Arellano et al., (2003) was used: the analysis of chemical, isotopic and production data for 20 wells was made. In particular the evolution of the following parameters was studied:

- Estimated well bottom pressure, enthalpy and temperature and the mass flowrate of wells,
- The comparison of the total discharge enthalpy (H_{TD}) with enthalpies for liquid corresponding to the temperatures obtained by a cationic (H_{CCG}; Nieva and Nieva, 1987) and the silica (H_{SIL}, Fournier and Potter, 1982) geothermometers, according to the method proposed by Truesdell et al., (1995),
- Chloride composition in total discharge and in separated water,
- δ^{18} O and δ D.

The well bottom pressure, enthalpy and temperature were estimated by the WELFLO well simulator (Goyal et al., 1980). WELFLO is a simulator for geothermal wells that uses finite differences approach and considers multi-phase, one-dimensional and steady state flow, which is useful in simulating vertical wells with variable diameters. This model has been validated against field data (Goyal et al., 1980). Input data for WELFLO simulator were the well’s geometry (length, diameters, etc.), mass flowrate and wellhead pressure and enthalpy of the wells.

7. RESULTS

By using the described methodology it was possible to find the main processes occurring in the vicinity of a given well and then correlate them to the possible causes. As an example, the case of the well AZ-13 located in the north zone of the field is shown. This well is 1215 m depth with a liner of 194 m (1021-1215 m). Production data are available from May 1980 to June 2002. The mass flowrate of the well shows an irregular behavior and a trend to decrease is noticed since 1987 (Figure 6). The well bottom pressure gradually decreases (Figure 7) and the enthalpy significantly increases since 1990 (Figure 8). The enthalpies comparison (Figure 9) indicates that until 1989 a local near well boiling process occurred. Since 1990 a general boiling process took place causing the well to produce superheated steam (Figure 10). This indicates that this well is not receiving important recharge of fluids. However it is important to mention that in 1995 an increase in the produced mass flowrate and a decrease in enthalpy were noticed. Both processes occurred when the more important injection peak in well AZ-15 was recorded (Figure 11). When this injection peak decreased, the mass flowrate of well Az-13 also decreased and the enthalpy increased. The δD behavior of well Az-13 also follows the injection pattern of well Az-15 (Figure 11) confirming the interference. These facts suggest that some of the injected fluid in well Az-15 arrived to the production zone of well Az-13, although the injection level was not high enough to produce important changes in the thermodynamic conditions of the fluid that feeds the well Az-13.

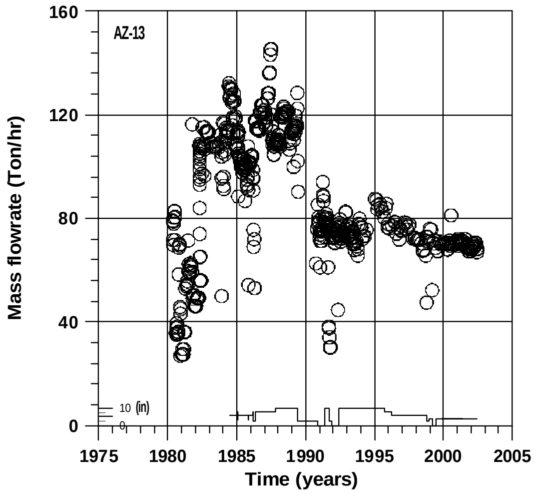

Figure 6. Mass flow rate produced by well Az-13 against time. Production orifice diameter is also presented.

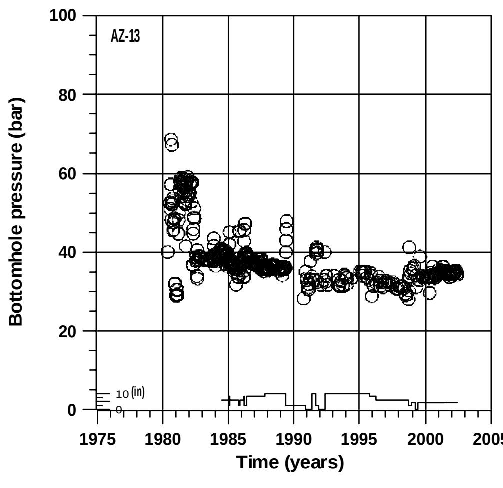

Figure 7. Well bottom pressure of well Az-13 against time. Production orifice diameter is also presented.

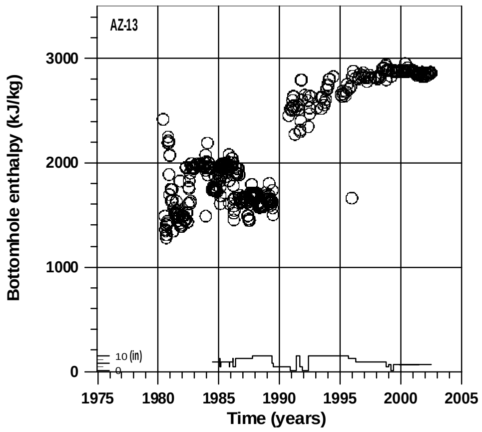

Figure 8. Well bottom enthalpy of well Az-13 against time. Production orifice diameter is also presented.

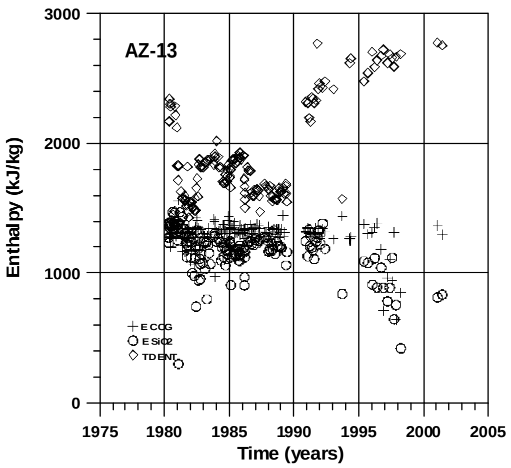

Figure 9. Total discharge enthalpy for well Az-13 and enthalpy values obtained by CCG and silica geothermometers.

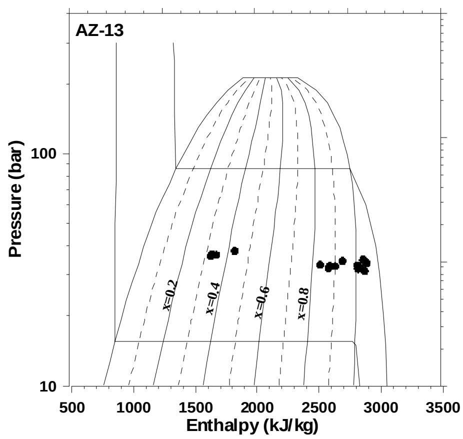

Figure 10. log of well bottom pressure against enthalpy for well Az-13. Annual average values are shown.

7.1 North Zone Wells

In Figure 3 it is seen that the north zone wells (Az-4, Az-9, Az-19, Az-21 Az-28 and Az-5) in their initial state are located in the compressed liquid region. In Figure 12 annual average values for pressure and enthalpy of studied wells from the north zone of the field are given.

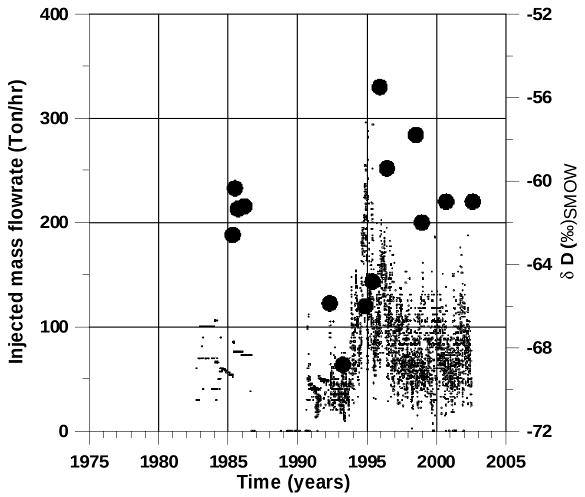

Figure 11. Mass flowrate injected in well Az-15 and total discharge deuterium for well Az-13 against time.

By comparison of Figures 3 and 12 it can be seen that the studied wells initially responded to fluids extraction with a pressure decrease and an enthalpy increase. For the long term response, it is seen that wells Az-4 and Az-9 do not show large changes in enthalpy. This is because the well Az-4 has two production liners which produce from different aquifers, being the shallower relatively cooler than the main reservoir, which avoids the increase in enthalpy. Well Az-9 is located in the central part of the field, where there is a low density of wells. For this reason it shows a relatively stable behavior with no important boiling processes. Wells Az-5, Az-13, Az-28 and Az-43 show very small changes in pressure but large changes in enthalpy. The analysis of chemical and production data for these wells indicates that that some of fluid injected in well Az-15 has arrived to the producing zones of wells Az-13, Az-28 y Az-43 and that some of the fluid injected in well Az-52 has arrived to wells Az-5 and Az-43. However, the level of injection does not seem high enough to produce important changes in thermodynamic conditions of the fluid feeding the mentioned wells.

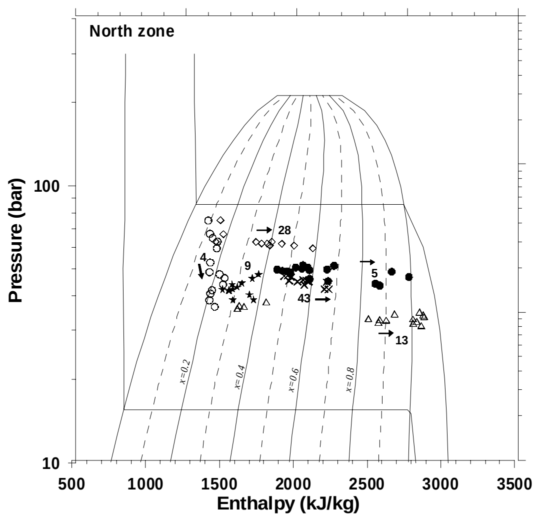

Figure 12. log of well bottom pressure against well bottom enthalpy of wells from the north zone.

7.2 South Zone Wells

For initial conditions (Figure 3) the wells of the south zone were found in the following regions: compressed liquid (Az-1, Az-7, Az-8, Az-23 and Az-25), two phase liquid-dominated (Az-18, Az-31 and Az-36) and two phase steam-dominated (Az-17, Az-33, Az-34, Az-35 and Az-38). The initial response to exploitation of the south zone wells consisted of a decrease in pressure and an increase in enthalpy. The long term response has been more complex than that found for the north zone wells, since changes as: decrease in pressure and mass flowrate, boiling, cooling, steam production and in some cases increases in pressure and mass flowrate, have been identified. Opposite to the behavior found for the north zone where reinjection interference is very small, in the south zone this process rules the behavior of many wells. Among the studied wells reinjection causes important effects in wells Az-2, Az-33, Az-34, Az-37 and Az-46. In Figure 13 the behavior of wells Az-2, Az-34 and Az-37 is shown, as it is seen, some pressure increase and enthalpy decrease were noticed to occur in these wells. Among the wells that receive some amount of reinjected fluid are the following: Az-6, Az-17, Az-22, Az-36 and Az-38. These wells show small pressure and enthalpy changes during the last years.Wells Az-25 and Az-26 do not seem to receive injection fluids and a local boiling process has developed (Figure 14). Both wells do not maintain the mass flowrate, the well bottom pressure decreases and the enthalpy increases. This situation could cause that in the near future the well bottom conditions change to two phase steam dominated or superheated steam.

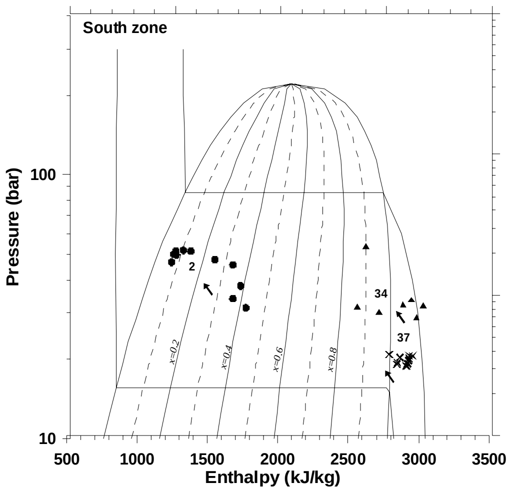

Figure 13. log of well bottom pressure against well bottom enthalpy for wells Az-2, Az-34 and Az-37.

In well Az-18 an important boiling process similar to that identified in well Az-13 of the north zone seems to occur. Wells Az-18, Az-25 and Az-26 do not seem to be very well connected to the important network system that conducts reinjection fluids.

8. CONCLUSIONS

The chemical, isotopic and production well data analysis for twenty wells of the Los Azufres geothermal field allowed the identification of the main reservoir processes occurring as a result of exploitation.

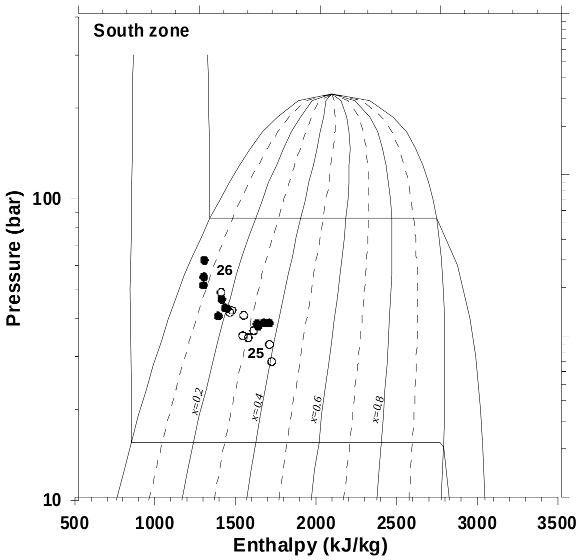

Figure 14. log of well bottom pressure against well bottom enthalpy for wells Az-25 and Az-26.

The initial response of the north zone wells to exploitation consisted of a pressure decrease and enthalpy increase. The long term response shows that the thermodynamic conditions of the fluid feeding the wells have changed from compressed liquid to two phase steam dominated and superheated steam.

The data analysis for the north zone wells indicates that some amount of fluid reinjected in well Az-15 has arrived to the producing zones of wells Az-13, Az-28 and Az-43 while some fluid reinjected in well Az-52 has arrived to the wells Az-5 and Az-43. However, the level of injection does not seem high enough to produce important changes in thermodynamic conditions of the reservoir fluid feeding the wells.

The response to exploitation of the south zone wells is more complex than that found for the north zone wells, since changes such as: decrease in pressure and mass flowrate, boiling, cooling, steam production and in some cases increases in pressure and mass flowrate, have been inferred.

In contrast to the minor effects caused by reinjection in the north zone, in the south zone reinjection rules the behavior of a number of wells such as: Az-2, Az-33, Az-34, Az-37 and Az-46. However, there are wells in the south zone, such as: Az-18, Az-25 and Az-26 which are located relatively far from the reinjection wells and do not seem to be connected to the important network system that conducts reinjection fluids. For these reasons, local and generalized boiling processes were inferred to occur in them.

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