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Analysis of Geochemical and Production Well Monitoring Data — A Tool to Study the Response of Geothermal Reservoirs to Exploitation

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Additional information is available at the end of the chapter

Abstract

Geothermal resources used to generate power are complex systems. The hydrothermal, high-temperature geothermal reservoirs, which are the only commercially exploited ones up to now, are usually found several (1-3 km) kilometers deep, and they should be exploited in a sustainable way. Thus, in order to support decisions on optimal exploitation policies, efforts focused on investigating how reservoirs respond to exploitation are routinely made. The better strategies always involve a compromise of controlling energy extraction from geothermal reservoirs without overexploiting the resource. Currently, methods based on the analysis of monitoring data of either the geochemical characteristics of fluids discharged (water and steam) or production data gathered from wells have been used to assess the reservoir performance, making it possible to predict the occurrence of negative processes in terms of production. However, by the analysis of combined geochemical and production data through simulation of wells, the well-bottom thermodynamic conditions of fluids are included in the study, allowing more reliable results to be obtained. Besides, the comparison of actual patterns of behavior of chemical and production indicators with those characteristic for typical processes, helps in identifying different physical phenomena and in deciding which is dominant in the case of the occurrence of more than one processes.

Keywords: Geothermal fields, reservoir exploitation, thermodynamic conditions, fluid geochemistry, well simulation

1. Introduction

Geothermal resources should be exploited in a sustainable way; therefore, geochemical studies focused on investigating how reservoirs respond to exploitation are routinely performed in order to support decisions on optimal exploitation policies [1]. As high-temperature geothermal reservoirs are usually found several (1-3 km) kilometers deep, indirect methods based on the monitoring of both: the geochemical characteristics of fluids discharged and production data of wells are used to assess their performance. The chemical and isotopic compositions of fluids produced by wells at an early exploitation stage are useful to develop preliminary geochemical models for the reservoirs from which it is possible to obtain reference values of geochemical indicators [2]. A detailed reservoir conceptual model often includes information on well production, which is obtained when wells are evaluated in order to characterize the resource in terms of electricity generation capacity. This task includes the study of well production data under different operating conditions during the development stage of the field to obtain thermodynamic reservoir parameters such as pressure, enthalpy, and steam quality among others, which constitute important reference values [3]. During exploitation, the variations in well production and geochemical data with respect to such references can be correlated to typical patterns of behavior indicative of the occurrence of physical reservoir processes.. In this work, both geochemistry of fluids and well production data are combined to investigate the response of geothermal reservoirs to exploitation. As usually either geochemical or production data are used, this methodology combining both disciplines is documented and illustrative examples for Mexican fields are described [4-6].

2. Methodology

2.1. Well production over time

The economic aspects of a geothermal project are strongly influenced by the well production since the heat (which is the main objective to be exploited in geothermal fields) is transported from the reservoir to the wellhead by the fluids. The production of liquid and steam from geothermal wells usually changes over time due to exploitation; therefore, the analysis of well production behavior over time provides valuable information to identify reservoir physical processes. According to [7] the "normal" behavior of the mass flow of a well at constant wellhead pressure or constant throttle should decline smoothly with time, as reservoir pressure falls. Abnormal behavior appears as a change in mass flow and this could be a sign of mechanical damage in the well such as casing break, liner collapse, or scaling. For this reason, the rates of decline or increment (even temporal) in well production of at least the most representative wells of the field should be assessed.

In order to study and make use of well production data to estimate and predict production decline rates in geothermal wells, two methods have been used. (a) The decline curves method [8], which has been successfully used in the oil industry, has also been used in geothermal fields although with limited success. For example in The Geysers, California (USA), the decline

curves method allowed the electricity capacity of a specific area to be estimated in order to optimize the number of productive and replacement wells necessary to supply the required steam to the power plants [9, 10]. This method has also been used in other geothermal fields such as Larderello (Italy) [11], Cerro Prieto (Mexico) [12], Wairakei (New Zealand) [13], and Los Azufres (Mexico) [3]. (b) Subsequently, [14] have proposed the harmonic decline curves method, which seems to be more appropriated for geothermal wells data than the decline curves method and hence, it has been widely used. Either by using a mathematical model or a simple qualitative approach, the analysis of the (liquid and steam) well production behavior over time will provide valuable information on the processes occurring at the reservoir.

2.2. Analysis of thermodynamic conditions of fluids over time

As soon as the commercial exploitation of a geothermal field starts, some changes in the original reservoir pressure, enthalpy, temperature, etc. distributions take place which are due to both: fluids extraction operations and the occurrence of natural or induced recharge to the reservoir. The magnitude of these variations mainly depends on formation permeability and on the amounts of both the fluids extracted and the recharge. Sometimes the changes in reservoir thermodynamic parameters, as compared with reference or starting conditions, could indicate negative effects in the reservoir, which, in turn, could have an impact on the power generation. Typically, a change in enthalpy indicates a change in reservoir fluid, normally, mass flow also changes with changing enthalpy. This is due to change in pressure drop in the well [7]. If a liquid-dominated reservoir at or near boiling point is exploited, falling pressures induce boiling and the development of two phases at the reservoir. Thus, the higher steam fractions in the fluids entering the well result in higher discharge enthalpies; hence, enthalpies evolution reflects the occurrence and rate of boiling at the reservoir. This is why the monitoring of thermodynamic conditions of fluids entering the wells over time, should be routinely performed.

Usually in two-phase wells, the reservoir temperature can be estimated through chemical geothermometers, being the more important these based on cationic ratios such as the Na/K, [15] and Na-K-Ca [16] and these based on silica solubility [17]. There are some general guidelines in the use of geothermometers that should be considered when choosing the more appropriate geothermometer to estimate the temperature of the stable reservoir in geothermal fields. For example, according to [1], the loss of calcium from the water in calcite precipitation phenomena when the water boils leads to an increase in the Na-K-Ca temperatures. Then, in geothermal fields where calcite deposits occur, the use of the Na/K geothermometer is advisable, since it is independent of boiling mechanisms because it is based on a concentrations ratio rather than on a single concentration. Also, considering that Mg reequilibrates very quickly after changing thermal conditions, the K/Mg geothermometer [18] would not provide the more reliable temperature estimations for the stable reservoir but the temperature at which the last equilibrium occurred.

In steam wells temperatures can be estimated through gas geothermometers [18, 19-23]. According to [18], because of relatively low and similar solubility of both species, the H_2-Ar geothermometer can provide reliable reservoir temperatures, while in conjunction with the

CO_2-H_2 geothermometer, it allows the equilibrium state of the system to be assessed. The gas geothermometers provide temperatures for the fluids at the entrance of the wells, which most often compare well with both, those obtained through wells simulation and those estimated by a silica geothermometer. In order to select the more suitable gas geothermometers to be used for a specific geothermal reservoir, the calculation of those for which data are available is advisable and, then, decision can be made based on contrasting the temperatures obtained with results from other sources (i.e., measured temperatures or simulation temperatures).

2.3. Analysis of the chemical composition of water over time

Geothermal fluids usually contain salts in a large range of concentrations. The salinity and the species dissolved in the fluids largely depend on the dominant water–rock interaction processes that take place at high temperatures. The variations of the chemical composition of fluids over time provide important information on the response of the reservoirs to exploitation. For instance, processes like the mixing with cooler groundwaters can be recognized by decreasing trends of both, reservoir temperatures and chlorides (and other solutes) over time. As another example, the process of boiling with limited recharge will increase the discharged fluid enthalpy but decrease the chlorides in total discharge fluids, over time [1, 24-26]. Thus, it is suggested to study the changes in concentrations of ions such as chlorides, sodium, potassium, calcium, sulphate, boron, and silica in both the separated water and the total discharge over time to identify the processes involved.

2.4. Analysis of the chemical composition of steam over time

For a long time, the chemical composition of the water has been used to identify the main reservoir physical processes while the steam composition was not fully used due to the sensitivity of gas reactions to pressure changes and also due to factors affecting steam/water ratios or gas solubilities in water, which made difficult the estimation of concentrations of gases at the reservoir. Currently, the understanding of typical effects that reservoir processes cause on the steam has significantly improved [21, 23, 27-29], thus monitoring of steam constitutes a useful tool to investigate reservoir processes. In addition, there are reservoirs in which the water remains immobile and hence only dry steam is produced. For them, the variations of CO_2, N_2, H_2S, total gases, and the N_2/Ar ratio over time could indicate boiling, entry of peripheral fluids, sulphur scaling, etc. If gas/steam ratio, H_2, CH_4, CO_2, and H_2S are available, gas equilibria methods can be used to estimate the reservoir temperatures, in situ steam fraction of fluids entering the wells, and the volumetric liquid saturation at the reservoir [2, 21, 23, 27, 29].

2.5. Analysis of δ ^{18}O and δD in fluids

As the fractionation of δ ^{18}O and δD between two phases is sensitive to temperature changes, isotopes are used to identify processes like boiling, steam separation and condensation in geothermal reservoirs. Thus, the changes in isotopic δ^{18}O and δD composition of fluids produced in geothermal fields are useful to indicate how reservoir processes like mixing, boiling, steam separation, condensation, among others are progressing during exploitation.

Also, based on the differences in δD and $\delta^{18}O$ compositions of characteristic sources (local groundwater, seawater, etc.) and reservoir fluids, natural recharge processes induced by exploitation can be recognized and evaluated. In geothermal fields, where reinjection of produced fluids (isotopically enriched by evaporation) takes place, the increases in $\delta^{18}O$ and δD (as well as chloride) in wells is a clear indication that reinjection returns arrived to their production zones. Isotope monitoring data are usually interpreted together with chemical and production data to have more reliable conclusions. It is important to mention that $\delta^{18}O$ and δD data from samples collected (condensed steam, separated water) should be recalculated to total discharge fluid, taking into account, besides the steam/liquid partition coefficients (that depend on temperature) [30], the well operation conditions, the sampling point, the type of sample (separated water, condensed steam), sampling conditions (pressure), as well as the conditions at which the fluid has undergone every steam separation process before the sample was collected. To estimate the isotopic composition of reservoir fluids, the isotopic composition of the total discharge along with the reservoir temperature and the fraction of steam at the reservoir are also needed. Methods to perform these calculations are given by [2, 31-33].

2.6. Additional data

Besides the chemical and production data of wells, the analysis should also consider information on well drilling and completion and well repairing data (when available) since such processes could produce changes in the variables behavior. As can be seen, this methodology is based on evidence from independent multidisciplinary approaches to obtain more reliable interpretations on the reservoir evolution to support decisions on optimal exploitation policies of the resource.

2.7. Summary

In summary, in order to perform an analysis to investigate the physical processes occurring at the reservoir, at least, the evolution of the following parameters over time should be considered:

a. Mass flow rates of fluids produced (water, steam, and mixture).

b. Well-bottom pressure, enthalpy, and temperature (calculated by a numeric well simulator).

c. The comparison of different enthalpy estimations for the wells over time. Such enthalpy estimations include the total discharge enthalpy and these obtained from reservoir temperature estimations through a cationic and silica geothermometers, as proposed by [34].

d. Chlorides in the total discharge and separated water.

e. CO_2 in the total discharge and the reservoir.

f. $\delta^{18}O$ and δD in the total discharge.

According to [34], both the silica and the cationic geothermometers estimations have different reequilibration rates. Because silica solubility is a function of temperature, the silica concentration in the fluid adjusts immediately with temperature variations. Then silica geothermometers are "fast-response"type, giving the temperature of the fluid "close" to the well. In contrast, cationic geothermometers like Na/K and Na-K-Ca reequilibrate more slowly to temperature variations, then being "slow-response" type and providing the temperature of the fluid relatively "far" from the well. This temperature is more representative of that at the stable reservoir. Silica geothermometers compare well with temperatures obtained by simulation of wells, which correspond to those for the fluid entering the well. Silica and cationic temperature estimations are used to interpolate their respective enthalpies from steam tables considering a saturated liquid phase. Resulting enthalpies are then plotted over time, together with the enthalpy of the total discharge (measured at the wellhead) to make comparisons among them either for specific time periods of well production or for the whole production history of the well. Table 1 provides typical patterns and the related processes.

Pattern	Physical process
$H_{TD}=H_{SiO2}=H_{Na/K}$	**Reservoir liquid phase**
$H_{TD}>H_{SiO2}= H_{Na/K}$	**Reservoir boiling**
$H_{TD}=H_{SiO2}> H_{Na/K}$	Cooler water entry
$H_{TD}>> H_{Na/K} >>H_{SiO2}$	Condensing in well
$H_{TD}>> H_{Na/K} >H_{SiO2}$	Near well boiling
$H_{TD}>>H_{SiO2}> H_{Na/K}$	Cooler water entry with reservoir phase segregation
$H_{SiO2}> H_{Na/K} = H_{TD}$	Breakthrough of cooler water with Na/K enthalpy reequilibration
$H_{TD} = H_{Na/K}> H_{SiO2}$	**Mixing close to the well of equilibrated liquid with cooler more diluted water**

Table 1. Typical patterns for well enthalpies' comparisons and related processes [34].

3. Examples

3.1. Boiling processes

Exploitation induces disturbances regarding natural-state conditions of the reservoir due mainly to the extraction of fluids. If fluids from an initially liquid-equilibrated reservoir are extracted at a higher velocity than that of the natural (or artificial) recharge, pressure losses will occur promoting boiling and the development of two-phase conditions. Depending on boiling intensity, localized or near-well boiling affects locally at the entrance of the wells, while generalized or reservoir boiling takes place when localized boiling increases as a result of the

lack of enough recharge to the reservoir. To illustrate the occurrence of boiling processes, the case of well AZ-13 of the Los Azufres (Mexico) geothermal field [5] is given as follows.

The production data of well AZ-13 (1215 m deep) are given in Figure 1. The thermodynamic conditions of the fluids entering the well were estimated by the WELLSIM program, a numerical simulator of the flow of heat and fluids in geothermal wells [35]. Reservoir temperatures were estimated by the Na/K [15] and silica (quartz) [36] geothermometers. Input for the simulator included production data and the geometry of the well. Figure 1A shows the wellhead pressure history. In Figure 1A at the bottom, the nominal diameter of the production orifice is given; this is useful to correlate changes of production variables to changes in the production orifice. The mass flow rate of the well varied with time showing a decrease since 1990 (Figure 1B). In fact, the well was closed by July 1989 and started operation in October 1990 when drastic changes in well production relative to 1989 data were evident; while steam production slightly increased, the liquid production largely decreased. The well-bottom pressure gradually decreased while the enthalpy significantly increased since 1990 (Figures 1 C and D). This behavior is indicative of boiling.

The pattern of enthalpies comparison $H_{TD} > H_{Na/K} > H_{SIL}$ (Figure 1 E) indicates that local near-well boiling occurred up until 1989. After 1990, when the 50 MWe unit was brought online, generalized boiling resulted in a significantly higher steam fraction and the pattern of enthalpies comparison was $H_{TD} \gg H_{Na/K} \gg H_{SIL}$ (Figure 1 E). This last pattern, along with the discharge of a very chloride diluted liquid (Figures 1 F and 2) indicates that high-temperature steam condensation is occurring in well casings and possibly in the reservoir. In Figure 3, the evolution of the fluid entering the well AZ-13 is shown in a semilog well-bottom pressure versus enthalpy plot in which the curve for saturated water was plotted as background and arrows indicate the tendency of the points over time. The steam fraction of the fluids entering the well AZ-13 was increasing over time causing the change in production regime from two-phase to steam at the wellhead. Pressure-enthalpy data for 2000 and 2001 indicated that the well was producing from a superheated steam zone of the reservoir.

Another example to illustrate the occurrence of important boiling processes is the case of well AZ-18 [4]. This well is 1328 m deep with 315 m of slotted liner. Production data for this well include from July 1980 to December 2001. From 1980 to 1985 an irregular behavior of the mass flow rate (Figure 4A) and the bottom-hole variables as pressure (Figure 4B) and enthalpy (Figure 4C) is seen. From 1986 to 1994, the mass flow rate gradually decreases, the well-bottom pressure is maintained at about 40 bar and the enthalpy increases to a value of 2700 kJ/kg, due to boiling. As a result of boiling, the chloride concentration in the liquid increased but it decreased in the total discharge to a negligible value, as the amount of water decreased (Figure 4D). On the contrary, because of boiling, the total discharge CO_2 increased until 1997 (Figure 4E), while in 1998 due to lower wellhead pressure, the CO_2 decreased. The estimated enthalpies comparison pattern (Figure 4F) indicates near-well boiling ($H_{TD} > H_{Na/K} = H_{SiO2}$) [34]. From 1995 to 1999, the enthalpy increased to about 2850 kJ/kg and the enthalpies comparison pattern observed ($H_{TD} \gg H_{Na/K} \gg H_{SiO2}$) indicated condensing processes. In Figure 5, it is seen that the fluid entering the well changed from two-phase liquid dominant conditions to two-phase steam dominant and even to super-heated vapor.
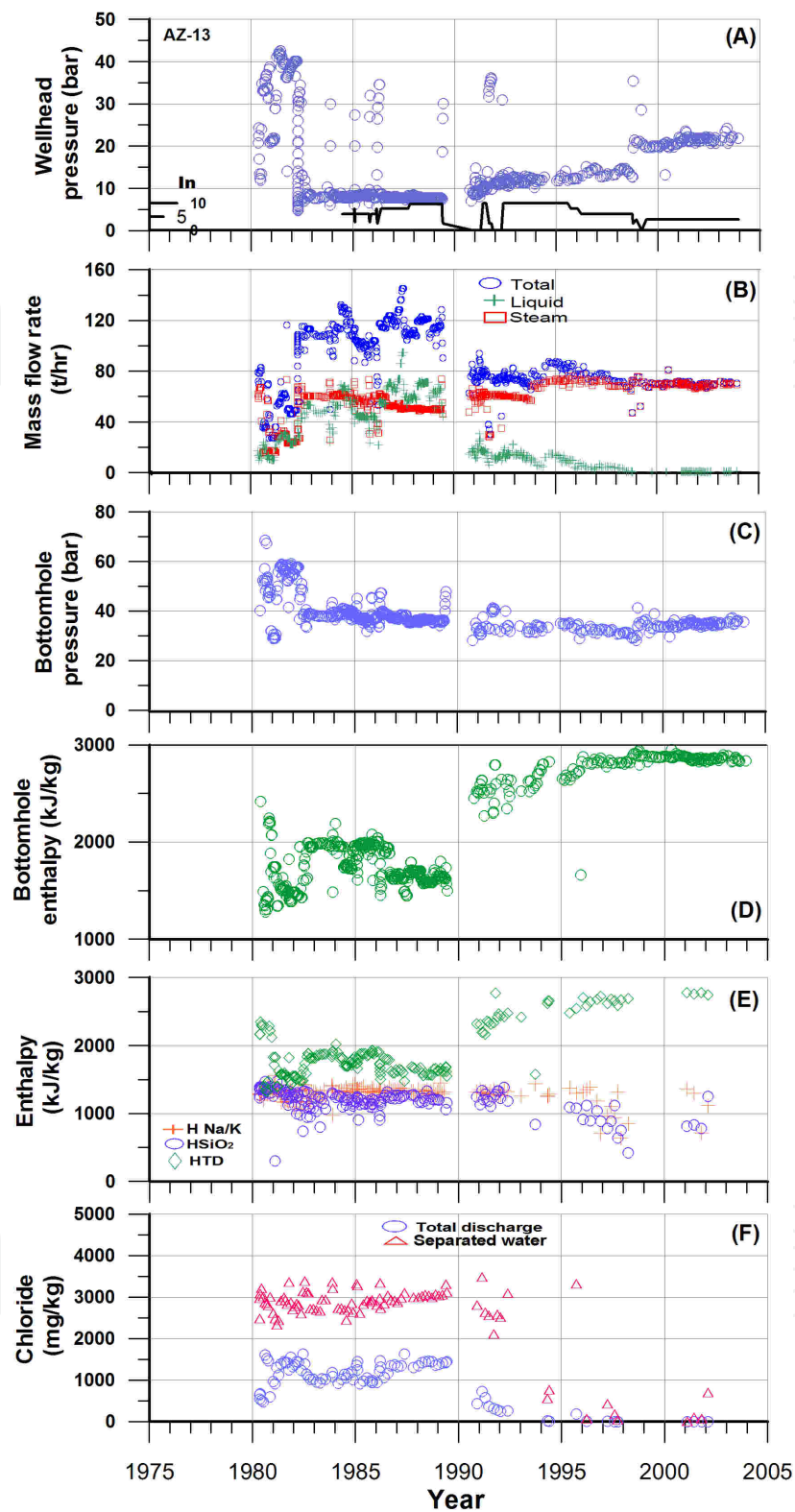
Figure 1. Time series of (A) wellhead pressure and orifice diameter; (B) mass flow rates; (C) bottom-hole pressure; (D) bottom-hole enthalpy; (E) total discharge, Na/K, and silica estimations of enthalpy; and (F) chlorides in total discharge and separated water for well AZ-13.
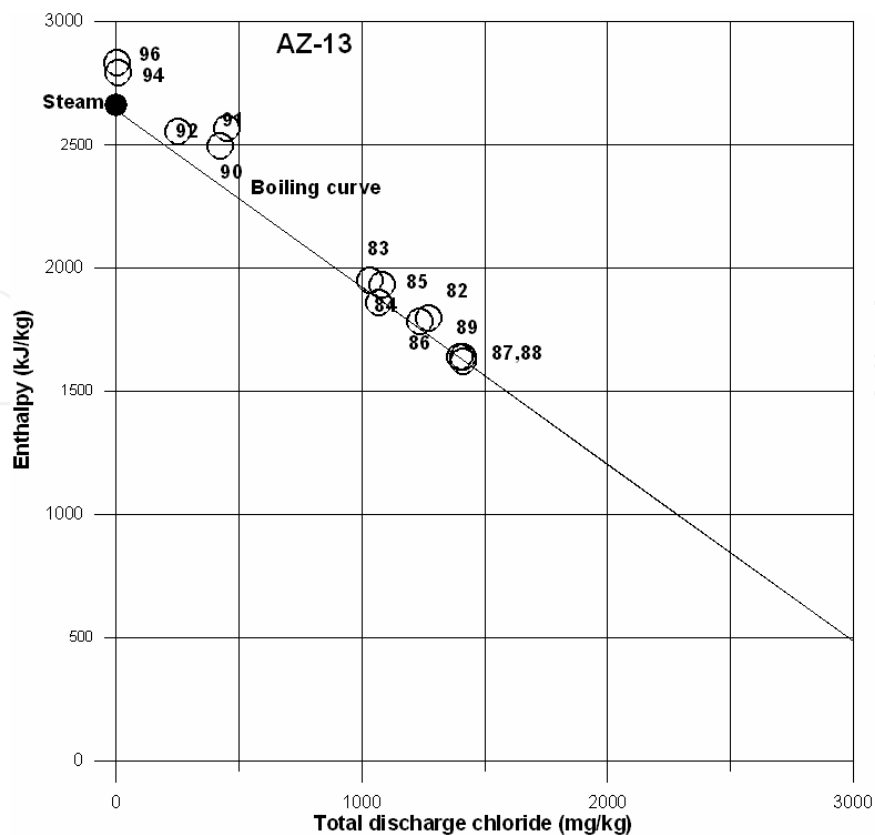
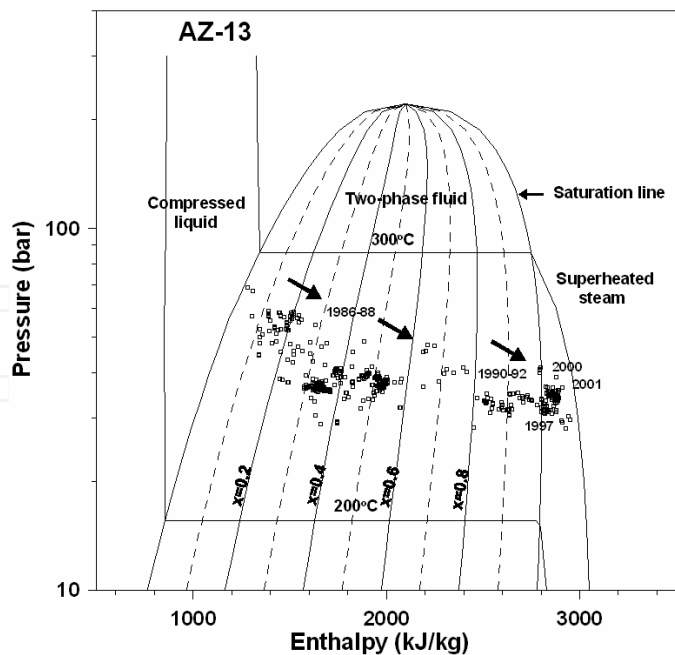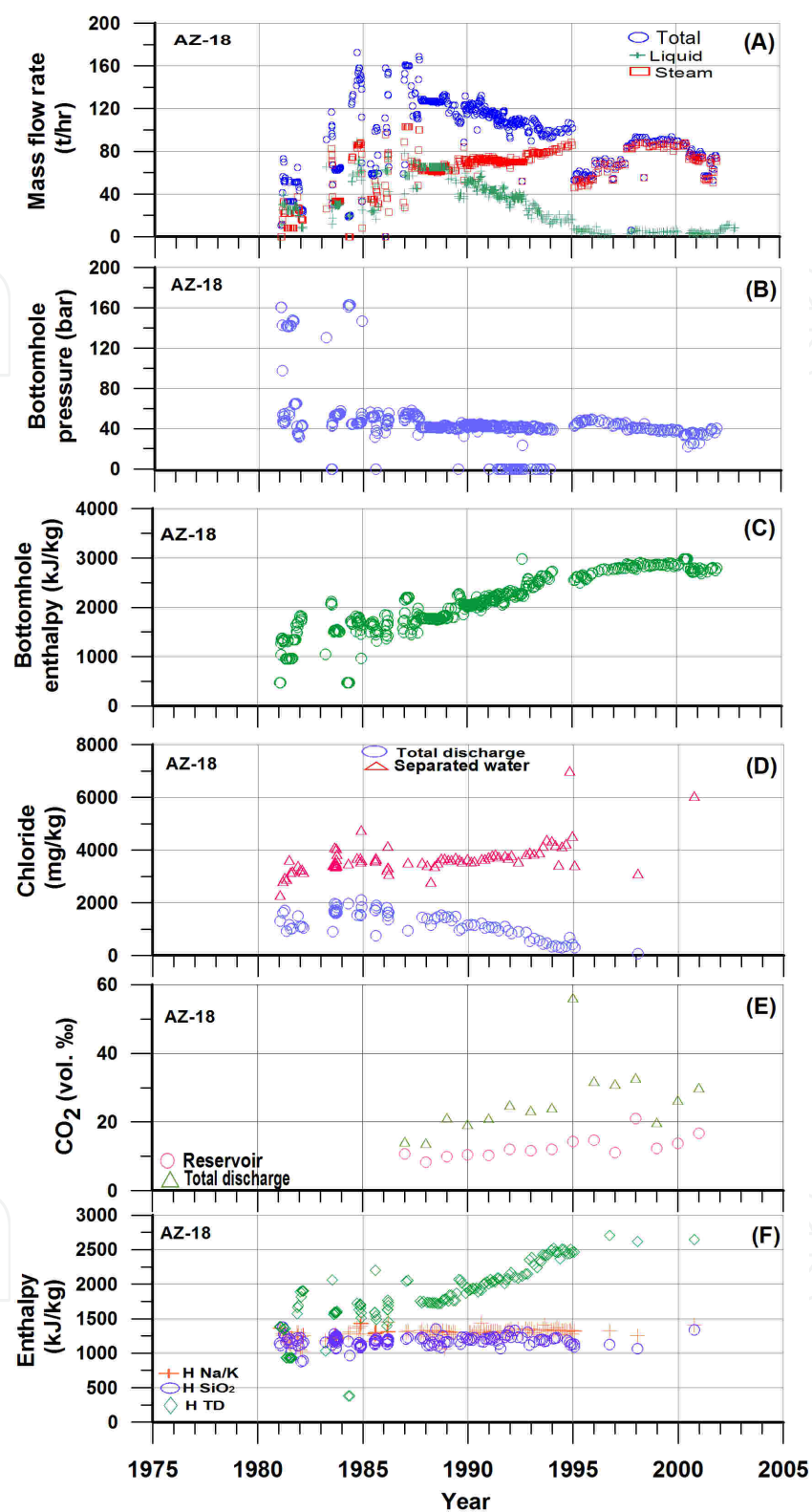**Figure 2.** Annual average enthalpy vs total discharge chlorides for well AZ-13.
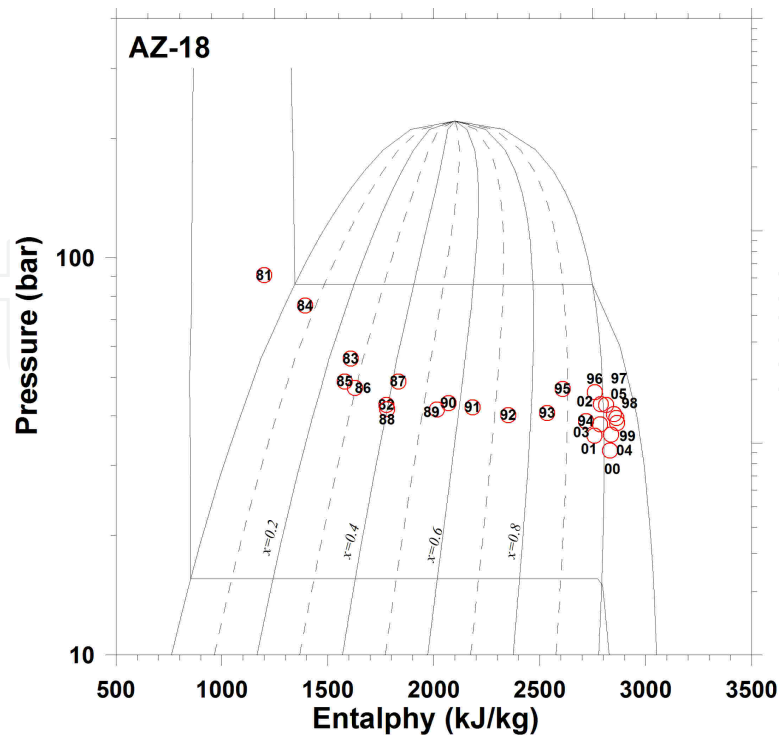

Figure 3. Well-bottom pressure vs well-bottom enthalpy for well AZ-13. The rows indicate evolution of thermodynamic conditions of fluids entering the well, from two-phase to steam.

Figure 4. Time series of (A) mass flow rates, (B) bottom-hole pressure, (C) bottom-hole enthalpy, (D) chlorides in total discharge and separated water, (E) CO_2 in total discharge and in the reservoir, and (F) total discharge, Na/K and silica estimations of enthalpy for well AZ-18.

Figure 5. Well-bottom pressure vs well-bottom enthalpy for well AZ-18.

3.2. Cooling and mixing processes

The pressure difference between hot and cold aquifers increases as a result of exploitation and this situation can induce the entry of cooler waters from neighboring aquifers to geothermal reservoirs. The cooler water entry process can be identified by geochemical changes of the fluids produced since most often cooler waters are more diluted than hot geothermal fluids then dilution effects are observed over time. As an example, the case of the Las Tres Vírgenes geothermal field [6] is given. In order to identify reservoir processes for the wells and to define the time periods in which each process was dominant, the comparison of the total discharge, Na/K and silica enthalpies according to the method proposed by [34] was used. In Figure 6, the total discharge enthalpy and the enthalpies from silica and Na/K geothermometers for well LV-4 are given. In this figure, important variations in the total discharge enthalpy from 2001 to 2004 indicate more than one fluid entry to the well and also near-well boiling of the fluids flowing 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 $H_{SiO2} > H_{Na/K}$, 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 $H_{TD} \cong H_{Na/K} \cong H_{SiO2}$ indicates that the well was producing 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 $H_{SiO2} > H_{Na/K} = H_{TD}$, which indicates a thermal breakthrough of cooler water with Na/K enthalpy reequilibration. 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 $H_{TD} = H_{Na/K} > H_{SiO_2}$ shows mixture close to the well of cooler, more diluted water with equilibrated liquid. Lower silica enthalpies result from dilution without silica reequilibration. In well LV-11 (Figure 7) during 2006 the pattern $H_{Na/K} > H_{SiO_2} > H_{TD}$ indicates very clearly the mixture in the well of cooler, more diluted water with equilibrated liquid, while during 2007 the pattern $H_{Na/K} > H_{SiO_2} = H_{TD}$ results from mixing with cooler water near the well with reequilibration of silica enthalpy but not of Na/K enthalpy.
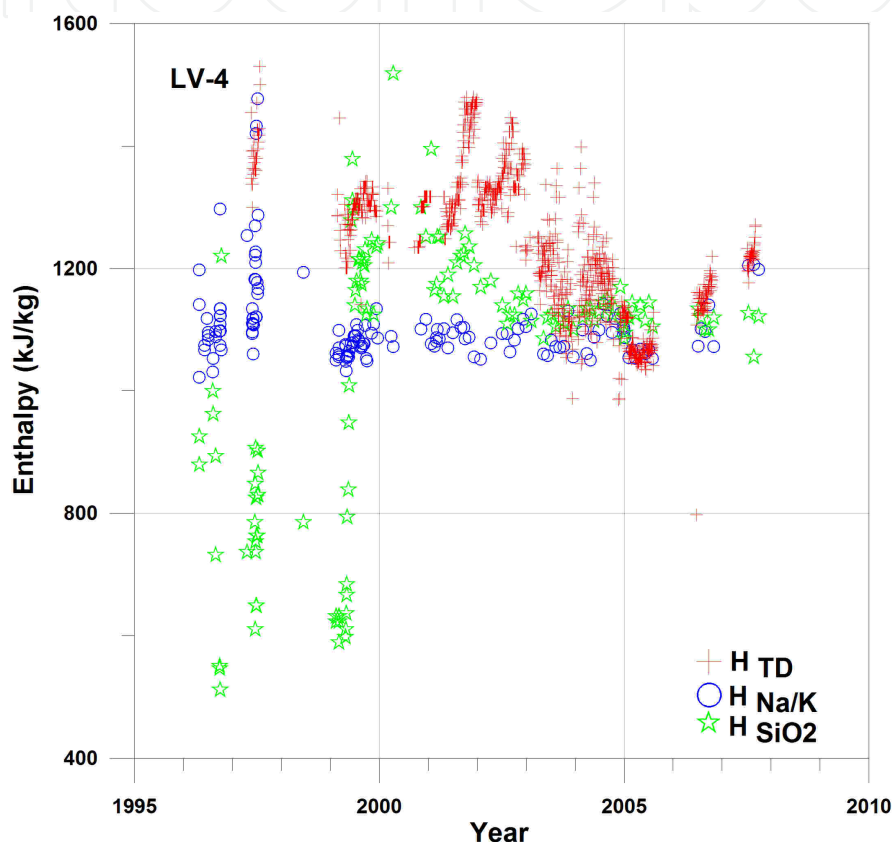

Figure 6. Time series of total discharge, Na/K and silica enthalpy estimations for well LV-4.

The enthalpy histories for well LV-13 are given in Figure 8. The enthalpy comparison pattern observed – $H_{TD} > H_{SiO_2} > H_{Na/K}$ – indicates near-well boiling for short periods of time, which corresponds to increases in total discharge enthalpy, and because of the constant pattern observed (up to 2006) – $H_{SiO_2} > H_{Na/K}$ – 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, since during 2003-2004 it showed a stable behavior.
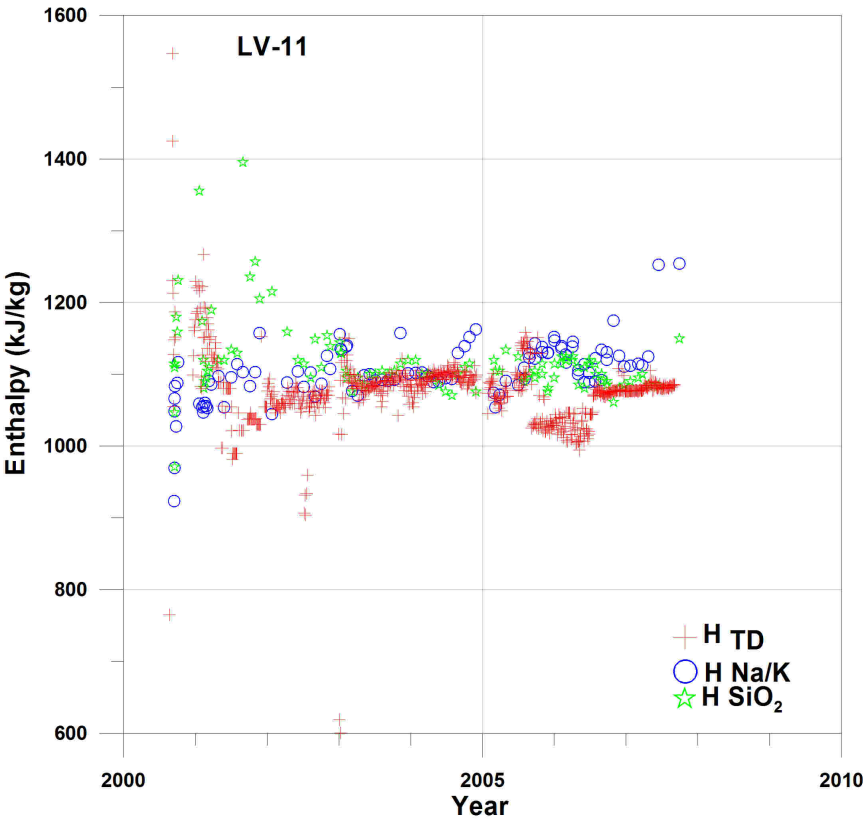
Figure 7. Time series of total discharge, Na/K and silica enthalpy estimations for well LV-11.
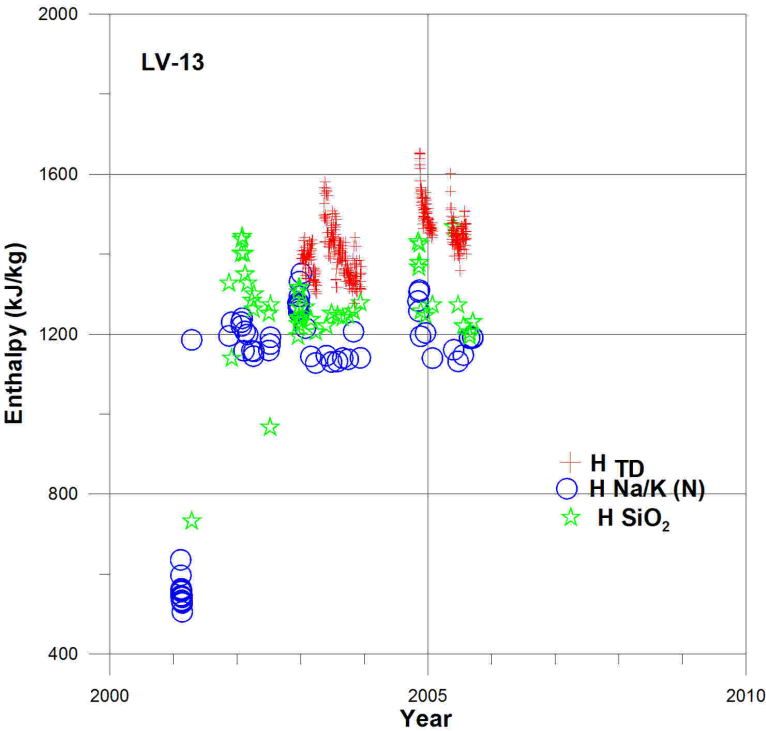

Figure 8. Time series of total discharge, Na/K and silica enthalpy estimations for well LV-13.

From the enthalpies comparison method used in the Las Tres Vírgenes wells, it is clear that more diluted and cooler water with respect to the reservoir fluid is entering the reservoir because of exploitation. In order to estimate the enthalpy of the diluting end-member involved in the mixing process, the enthalpy-chloride model [37] was used [6]. To follow this approach, annual average Na/K enthalpies versus annual average total discharge chlorides for the wells were plotted in Figure 9. As seen in the figure, a linear tendency of the data indicates that the reservoir fluids which originally plot on the boiling line with an average reservoir (Na/K) enthalpy of 1203 kJ/kg (274°C) and chloride concentration of 6,745 mg/kg become cooler and more diluted over time because of mixing. For the diluting water, an enthalpy of 798 kJ/kg (187°C) and a chloride of ~500 mg/kg were estimated.
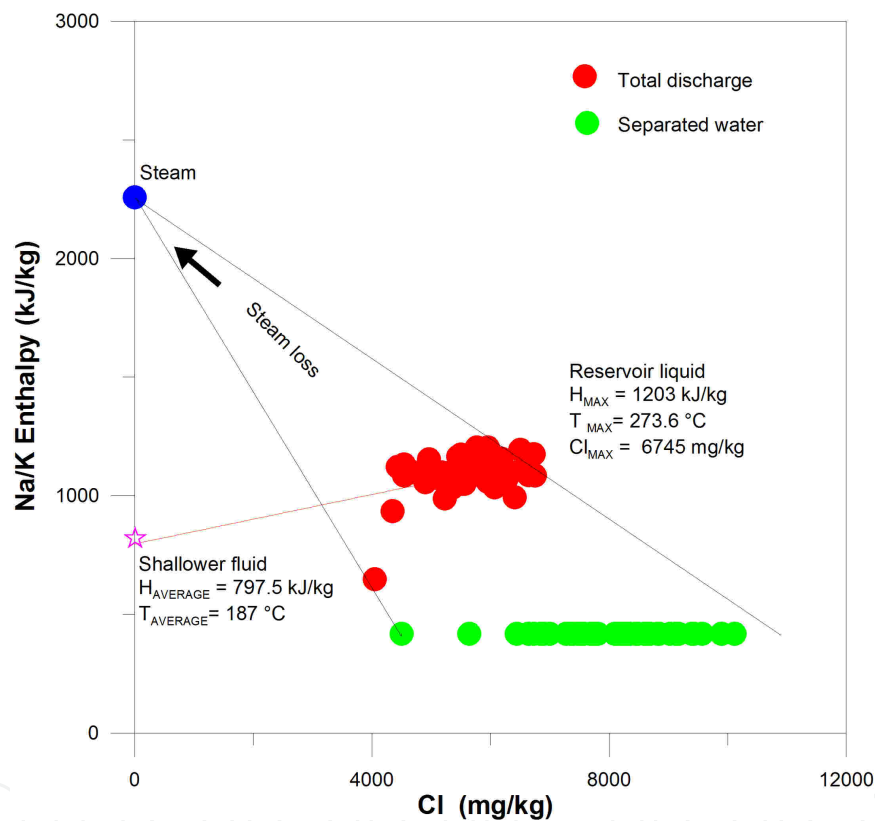

Figure 9. Enthalpy vs chloride mixing model.

The estimated chloride of the diluting water can be found by lineal relationships between two conservative components as B versus Cl, given in Figure 10, considering well compositions. In such relationships, the diluting end-member was the fluid for the well LV-2, which was the shallower well drilled in the field and for which temperature estimations agreed with the temperature found for the diluting end-member from the enthalpy-chloride model. At present, well LV-2 is no longer productive; therefore, new samples are not available to confirm these results. From this study it was proposed that the severe scaling phenomena observed in the field could be attributed to both the chemical nature of the fluids and the mixing of different fluids, since mixing phenomena strongly enhances scaling [24-26, 38].
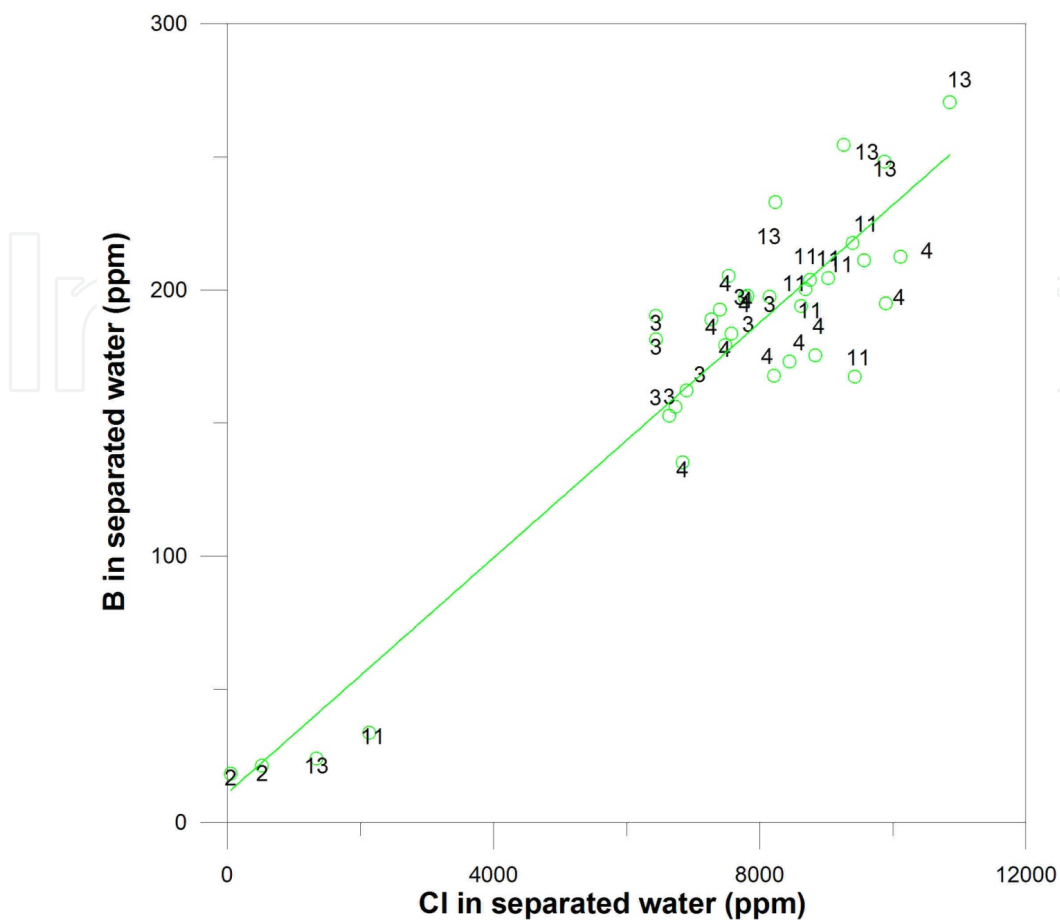
Figure 10. B vs Cl in separated water for the Las Tres Vírgenes wells.

3.3. Production of reinjection returns

The historical data on mass flow rates of fluids reinjected to the reservoir through specific reinjection wells could be related to production and geochemical data of production wells to assess the influence of reinjection. Isotope and chemical data of reinjection fluids can also be related to characteristic geochemical changes in fluids produced by wells affected by reinjection.

In order to investigate if reinjection fluids have arrived to the production zone of well AZ-13 of the Los Azufres geothermal field, production data of the well AZ-13 were analyzed together with histories of reinjection wells and isotope data for both, the producer well and the injection fluids [5]. As seen in Figures 1B and D in 1995, the mass flow rate produced by the well AZ-13 slightly increased while enthalpy slightly decreased. Both effects occurred when the mass flow rate of water injected into well AZ-15 (Figure 11) was at its maximum level. The distance between these wells is about 3 km. When the injection mass flow rates decreased, the mass flow rate of well AZ-13 also decreased and the enthalpy increased. Variations in δD of fluid discharged from well AZ-13 also follow the pattern of injection into well AZ-15 (Figure 11); the fluid produced by well AZ-13 was depleted in δD when injection rates were low and was

enriched when the rate was high. This behavior occurs because the reinjected fluid becomes isotopically enriched by evaporation at the surface. These observations suggested that some of the injected fluid in well AZ-15 arrived at the production zone of AZ-13, although the amount was not high enough to produce significant changes in the thermodynamic conditions of the fluid that feeds well AZ-13. In general, the behavior described for the well AZ-13 is typical of the wells in the north zone of the Los Azufres geothermal field. The reinjection effects in Los Azufres geothermal field are more important in the south zone wells [5].
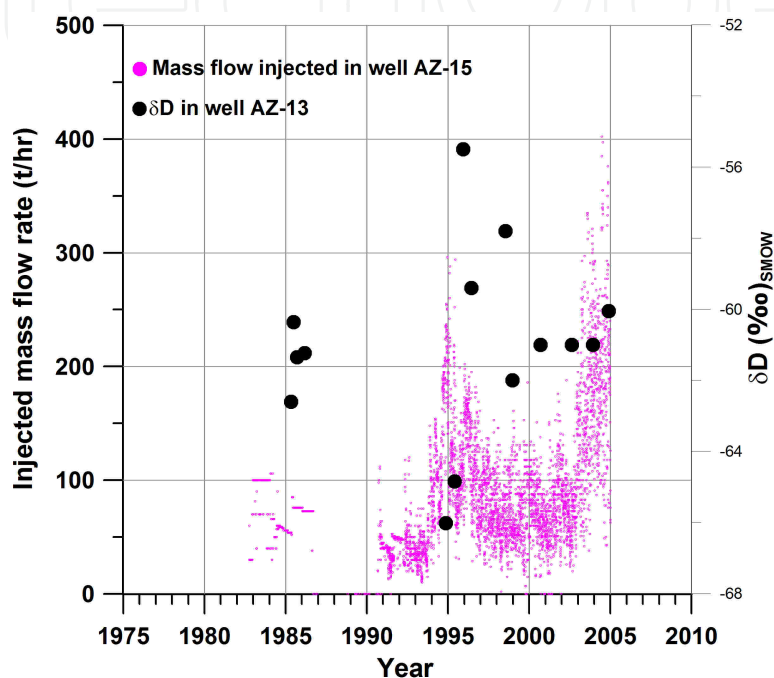
Figure 11. Mass flow rate injected in well AZ-15 and δD in the total discharge of well AZ-13 over time.

Clear evidence of the production of reinjection returns was obtained for well AZ-2 located in the south zone of the Los Azufres geothermal field; this well behavior was studied by [4]. Well production and estimated well-bottom parameters for well AZ-2 over time are given in Figure 12.

Production data for this well consisted of two stages: from April 1978 to April 1984 and from May 1988 to April 2001. During the first stage of production, an irregular behavior of production (Figure 12A) and in estimated well-bottom variables, as pressure (Figure 12B) and enthalpy (Figure 12C) is observed. By then, injection in wells AZ-7 and AZ-8 just started; thus, reinjection was not the only event affecting well behavior. Such irregular behavior seems to be related to mechanical damage in the pipe. For the second production stage, the well still showed a very irregular behavior, but in this case, an enrichment in chlorides since May 1988 (Figure 12D) and a decrease in Na/K enthalpy for the feeding fluid regarding these for silica and for the total discharge is indicated (Figure 12E). Also, the variations in well-bottom pressure (Figure 12B) and well-bottom enthalpy (Figure 12C) are in opposite directions. For pressure increments enthalpy decreases are seen. Pressure increments are related to recharge
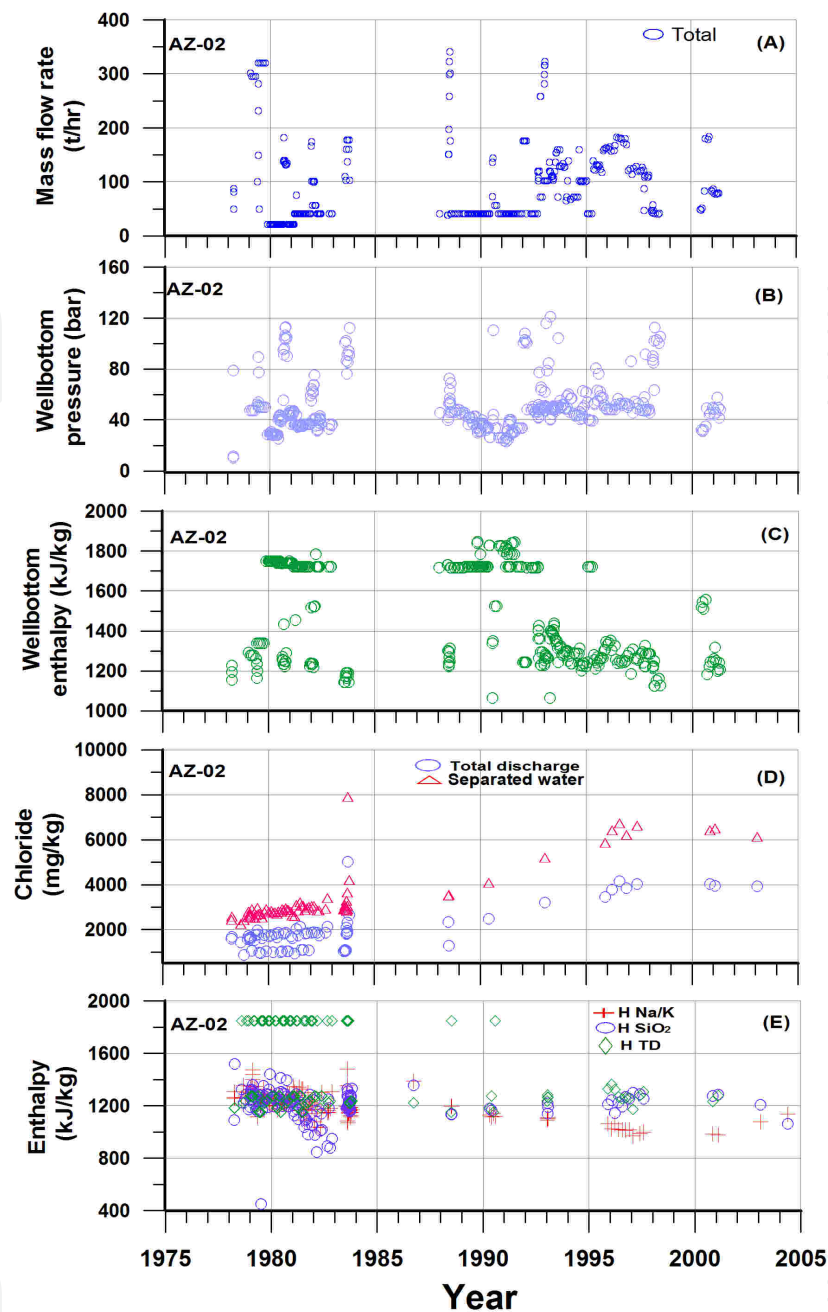
Figure 12. Time series of (A) mass flow rates; (B) well-bottom pressure; (C) well-bottom enthalpy; (D) chlorides in total discharge and separated water; and (E) total discharge, Na/K and silica enthalpy estimations for well AZ-2.

processes while decreases in enthalpy indicate that the recharge is a lower enthalpy fluid as compared with that of reservoir fluids. The well production also shows large variations (Figure 12A), which are related to the amount of recharge arriving to the production zone of the well. At the same time, the mass flow rate (Figure 12A) and the δ^{18} O of well AZ-2 follow the same pattern as the mass flow rate injected in well AZ-7 (Figure 13). These reinjection effects could not be associated with well AZ-8 because of significant reinjection in this well that started in 1990. Thus, it could be concluded that during the second production stage, the feeding fluid

of well AZ-2 was being gradually replaced by another fluid having higher salinity and lower temperature than original fluid. It seems feasible that this fluid comes mainly from injection in well AZ-7. This cooler fluid during flowing to the well AZ-2 is heated in contact with the reservoir rock; however, it is not heated enough and the well produced a relatively cooler fluid.
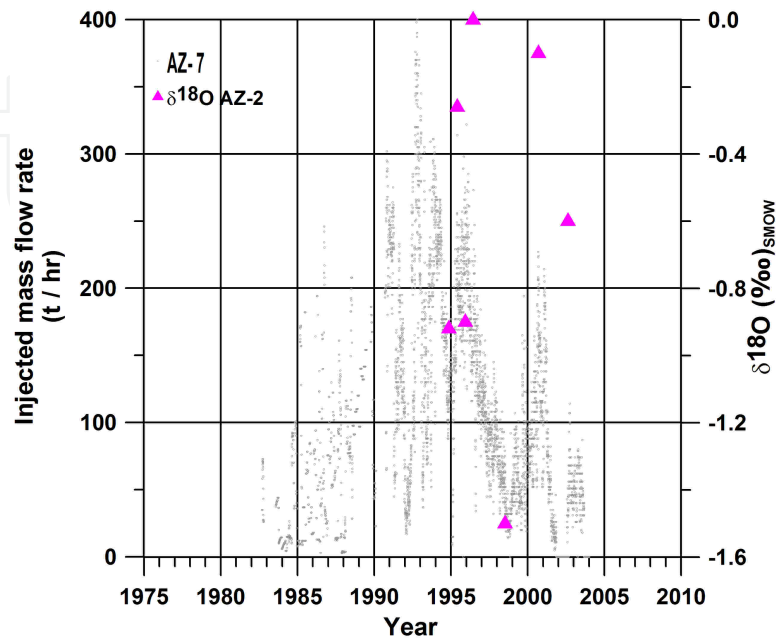

Figure 13. Mass flow rate injected in well AZ-7 and δ^{18} O of the total discharge of well AZ-2 over time.

4. Conclusions

Exploitation of geothermal resources produces changes in geochemical and production data of wells regarding natural-state conditions, due to the extraction (and sometimes the reinjection) of fluids. These changes can be used to investigate the main physical processes in the reservoir as a result of exploitation through the analysis of monitoring data of wells. A methodology based on the variations of geochemical and production data of wells over time was described. This innovative, combined methodology provides more reliable estimations of reservoir processes than current techniques based either on geochemical or production data, since the thermodynamic conditions of well-bottom fluids are included into analysis. In this regard, the main tendencies of well-bottom pressure and enthalpy data obtained from simulation of wells in suitable diagrams indicate how exploitation impacts the reservoir and help delineating future strategies. This approach can be used not only for single wells but also to study groups of wells to investigate zones of the reservoir affected by a specific process. The methodology has been successfully used to investigate the response of Mexican geothermal reservoirs to exploitation, in which the main processes identified included mixing, boiling, and production of reinjection returns in production wells, and examples for them have been provided. The results from this approach together with the results from other disciplines provide support in field management on delineating optimal exploitation strategies to prolong the reservoir lifetime.

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