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Reservoir Characteristics and Exploitation-Related Processes at the CP IV Sector of the Cerro Prieto (México) Geothermal Field

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ABSTRACT

The CP IV sector (100 MWe) is located at the NE part of the Cerro Prieto geothermal field and started commercial exploitation in 2000. In this work the main characteristics of the CP IV reservoir, initial conditions and response to exploitation (2000-2005), were estimated. Well-bottom thermodynamic conditions were obtained by using the WELLSIM simulator and production data as input. The interpretation of the chemical and isotopic behavior of fluids together with well-bottom thermodynamic conditions allowed a reservoir conceptual model to be obtained. Results suggested the existence of two zones with different characteristics (southern and northern blocks), separated each other by the Fault H. At the southern block, located towards the E-SE, wells with high enthalpy (≥ 2000 kJ/kg), low chloride (≤ 7000 mg/kg), high CO_2 (≥ 6‰ mol) and relatively δD depleted (≤ -94‰) fluids were found. In contrast, in the northern block, located towards the W-NW, the wells produce lower enthalpy (<1800 kJ/kg), higher chloride (~12,000 mg/kg), lower CO_2 (< 6‰ mol) and higher δD (>-94‰) fluids compared to southern wells. The main reservoir processes were related to exploitation and included: boiling and steam condensation in wells at the NW and in the periphery of CP IV and the entry of lower temperature waters in the central part of CP IV.

1. INTRODUCTION

The Cerro Prieto (México) geothermal field is located in the Baja California state, (Figure 1). The reservoirs in the field are found in a tectonic basin emplaced between the Cerro Prieto fault to the east and the Imperial fault to the west and filled of alluvial and deltaic sediments. The exploitation area comprises about 15 km^2 where more than 300 wells (1250 - 3550 m deep) have been drilled. The field is divided in four sectors: Cerro Prieto I (CP I) located in the west; Cerro Prieto II (CP II) in the southeast; Cerro Prieto III (CP III) in the north and Cerro Prieto IV (CP IV) in the east of CP III (Figure 1). Two reservoirs have been identified, the α reservoir located at depths between 1000 and 1500 m in the CP I area and the deeper β reservoir (≥ 1500 m deep) which extends all over the field. At present (May 2009) the installed power capacity is 720 MW. The behavior of the CP I, CP II y CP III areas has been discussed (Lippmann, 1987, Truesdell et al.,1989, Truesdell et al., 1997, Lippmann et al., 2000; Lippmann et al., 2004) while scarce information related to the main characteristics and behavior of CP IV has been documented (Rodríguez, 2003; Barragán et al., 2006; 2008; Arellano et al., 2009). The development of the CP IV sector started in 2000-2004 when 21 wells (of 30 existing wells) were drilled to meet the steam requirements of the CP IV power plants (100 MWe).

In this work the main characteristics and the initial response to exploitation of the CP IV sector are described. The study was based on the analysis of chemical, isotopic and production data of 28 wells. The objectives of the work are: (a) To identify the main processes that have occurred and are occurring at the CP IV reservoir due to exploitation and (b) to relate the effects to the possible causes.

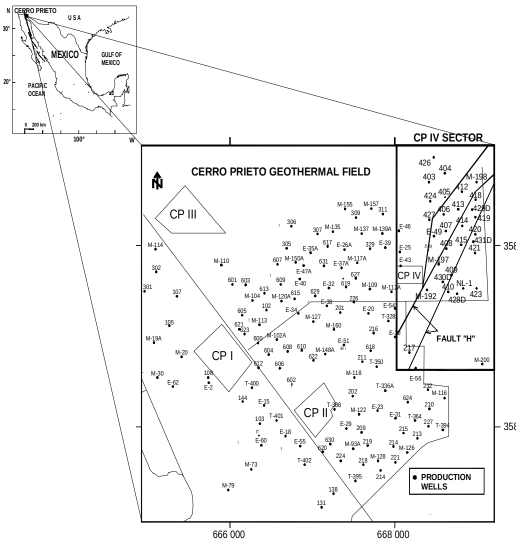

Figure 1. Locations of the Cerro Prieto geothermal field, CP IV sector, CP IV wells and Fault H.

2. METHODOLOGY

In order to estimate the response of the reservoir to the extraction of fluids and heat, an analysis of chemical, isotopic and production data for each well was developed and subsequently a general analysis was performed. For each well the evolution of liquid, steam and total mass flow rates produced, well-bottom pressures and enthalpies were estimated through the WELLSIM simulator (Gunn and Freeston, 1991) following methodology given by Arellano et al., (2005). Subsequently, the evolutions of: total discharge and reservoir chlorides; total discharge and reservoir CO_2; and δ^{18} O and δD in total discharge over time, were studied.

Reservoir processes were identified by the enthalpies comparison method (Truesdell et al., 1995). Enthalpies for silica "fast response" geothermometer (Fournier and Potter, 1982) and Na/K "slow re-equilibration" geothermometer

(Nieva and Nieva, 1987) were compared to the total discharge enthalpies over time in order to obtain characteristic patterns related to specific reservoir processes.

The reservoir chloride concentrations (Cl_{RES}) were based on the calculation of the total discharge steam fraction, considering the enthalpy of the liquid phase at the reservoir temperature ($H_{LIQUID\ (TRES)}$), instead of the total discharge enthalpy, and the enthalpies of steam and liquid phases at separating conditions, according to Truesdell et al., (1989):

$$Cl_{RES} = Cl_{LIQUID\ (SEP)} \times (H_{VAPOR\ (SEP)} - H_{LIQUID\ (TRES)}) / (H_{VAPOR\ (SEP)} - H_{LIQUID\ (SEP)})$$

Where $H_{LIQUID\ (TRES)}$ is the enthalpy of the liquid phase at the reservoir temperature while $H_{LIQUID\ (SEP)}$ and $H_{VAPOR\ (SEP)}$ are the enthalpies of the liquid and vapor phases at separation conditions.

The total discharge and reservoir CO_2 were calculated through gas equilibria based on the Fischer-Tropsch reaction, using the method proposed by Nieva et al., (1987).

3. RESULTS

3.1 Fluids Production at CP IV

The extraction of fluids from the CP IV reservoir started in 1985 with wells M-192 and M-197. By 2000 nine additional wells had been drilled, and by 2004, 28 wells were in production (Figure 2). As for October, 2005 the reservoir had produced about 150 million tones of fluids of which, 51% was steam and 49% liquid to surface conditions. The steam was used to drive the four power units of CP IV (100MW) which started operation in 2000. Up to 2005 in CP IV, no fluids had been re-injected back to the reservoir.

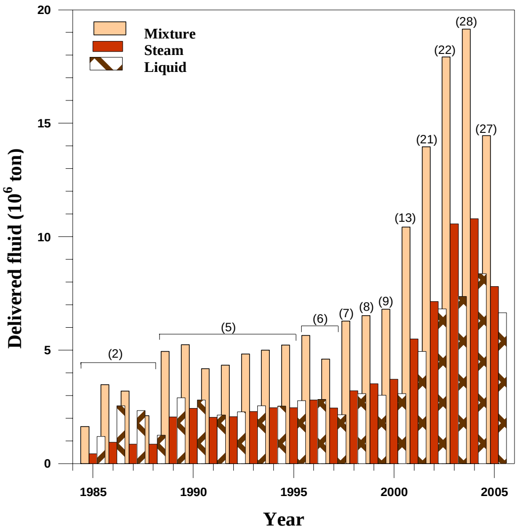

Figure 2. Mass flow rates produced by CP IV sector wells. The number of wells in operation for the years considered is also given.

3.2 Estimation of Reservoir Natural Conditions

In order to have a reference for the non-disturbed reservoir state, the initial data of all the CP IV sector wells (E-48, E-49, M-192, M-197, M-198, 403, 406, 413, 415, 420, 424 and 426) in production since the beginning up to 2001 were studied. In Figure 3 the initial distributions of (a) wellhead enthalpies, (b) reservoir chlorides, (c) reservoir temperatures estimated by the Na/K geothermometer (Nieva and Nieva, 1987), (d) CO_2 in total discharges and (e) δD in total discharges are shown. As seen in Figure 3 (a) the enthalpy increases from the west, with values < 1,600 kJ/kg to the east with values > 2,200 kJ/kg. In the

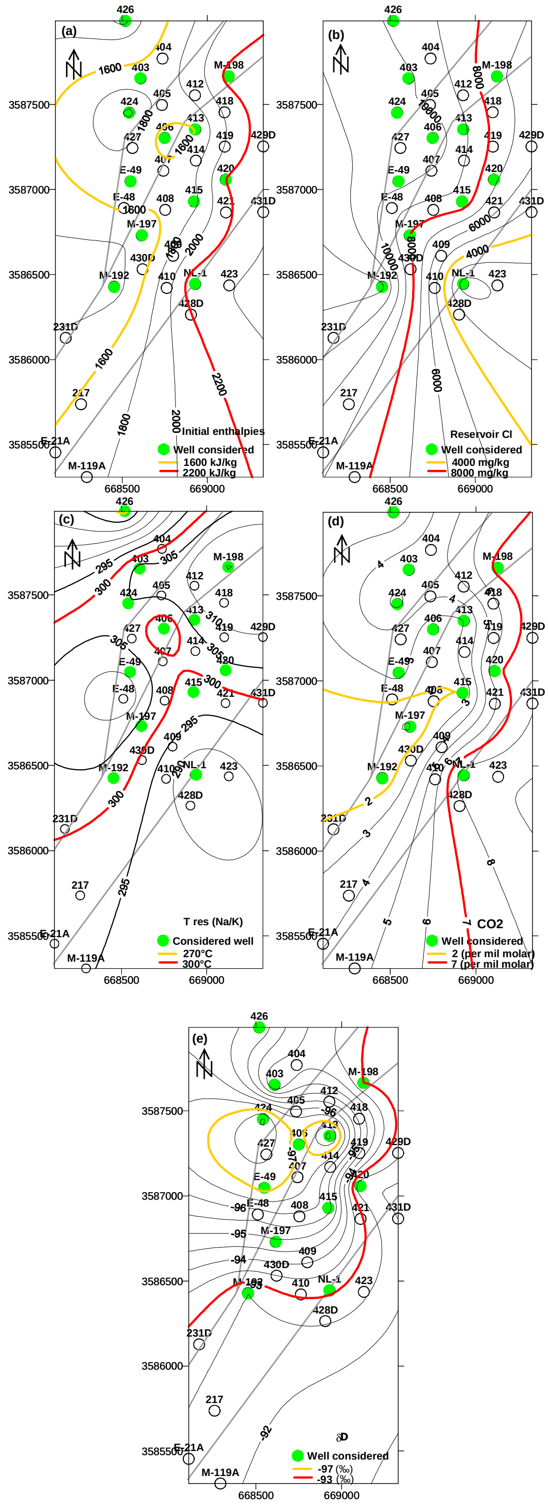

Figure 3: Distributions of (a) wellhead enthalpies; (b) reservoir chlorides; (c) Na/K reservoir temperatures; (d) total discharge CO2 and (e) total discharge δD according to initial data of the CP IV sector.

north-central part of the zone the wells 406 and 413 show enthalpies of about 1,600 kJ/kg, this abrupt change in the distribution pattern suggests the entry of shallower fluids through the Fault H. The reservoir chlorides behave opposite than enthalpies, they decrease from west to east direction. In the west part, close to the well M-192 chlorides are higher than 12,000 mg/kg and decrease in a narrow area to values lower than 2,000 mg/kg in well NL-1. The occurrence of this high-chloride zone had been observed by Lippmann at al. (2004) in the CP II area which was interpreted to be due to the entry of high-chloride fluids to the reservoir through the lower part of Fault H. According to Figure 3 (c) the higher reservoir temperatures (>300 ºC) are found lying the Fault H trace, mainly in the northeast part close to the well M-198. Temperatures decrease towards the northeast and towards the southeast (to 270-280 ºC) where probably the Fault H has lower influence. As seen in Figure 3 (d) the CO_2 distribution shows the higher values at the east of CP IV (>7 ‰ molar) where the enthalpies showed the higher values indicating relatively high steam fractions in produced fluids. As volatile specia partition preferentially into steam, the high enthalpy wells produce high CO_2. As it is seen, the CO_2 distribution compares well with that for the enthalpy. The initial distribution of δD (Figure 3 (e)) shows that the higher values, of -93 (‰) are found in both the east and south parts of CP IV while the lower values, of -97 (‰) are located in the wells 413 and 424 in the zone where low enthalpies had been identified because of the entry of shallower fluids. The distributions suggest that in a relatively small area, of about 2.5 km^2, large variations in parameters are observed. This is probably due to the fact that the Fault H divides the zone in two blocks with different characteristics. One of them is delimited from the wells 429D, 420, 409 and 410 to the east- southeast, in which high-enthalpy (>2,000 kJ/kg), low-chloride (≤7,000 mg/kg), high CO_2 (>6 ‰ molar) and high δD (-94 ‰) wells are located. This zone was named *southern block*. In contrast, from wells 419, 415 and 430D to the west-northwest the wells show relatively lower enthalpies (1,400- 1,800 kJ/kg), chlorides reach values up to 12,000 mg/kg, CO_2 values are < 6 ‰ molar and δD values are < -94 ‰. This zone was named *northern block*. The different characteristics of wells described above are seen in an enthalpy-chloride diagram (Figure 4) where initial data for all the CP IV wells were included. The fitting line shown was taken as a reference to study the behavior of some representative wells over time.

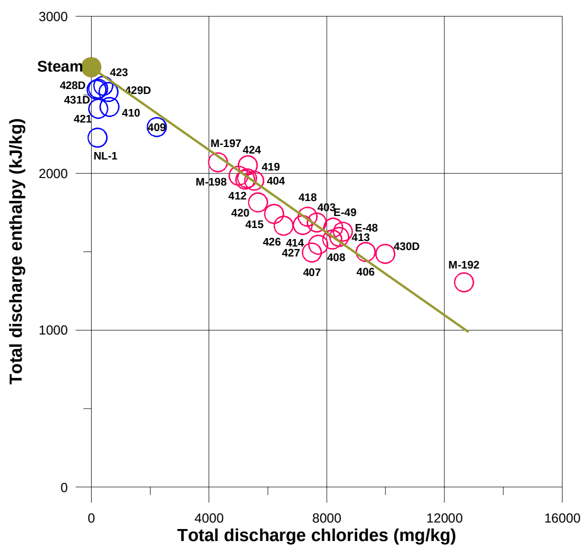

Figure 4: Enthalpy vs chloride plot for initial data of CP IV wells.

3.3 2005 Conditions of CP IV Reservoir

3.3.1 Enthalpy

In Figure 5 the 2004 and 2005 enthalpies distributions of CP IV wells and four wells of CP II (217, 231D, E-21A and M-119A) are shown. As seen in the figure, in 2004 in the central part of CP IV a group of wells (406, 407, 408, 413, 414 and 427) with enthalpies ≤ 1,600 kJ/kg was observed. From this group of wells the tendency of the enthalpies was to increase towards all directions, with the maxima values in the boundaries of the sector. For example, to the northeast, the well M-198 (2,313 kJ/kg); to the east the wells 429D and 431D (2,480 and 2,550 kJ/kg); to the southeast the well 423 (2,530 kJ/kg), to the southwest the well M-197 (2,508 kJ/kg); to the west the well E-49 (2,340 kJ/kg) and to the northwest the well 424 (2,480 kJ/kg) are found. For the 2005 data it is seen that the area of wells with enthalpies of ≤ 1,600 kJ/kg has increased, including the well 419. Other wells that show enthalpy decreases > 50 kJ/kg regarding 2004 data are 404, 406, 412, 415 and M-192. In contrast, the wells showing average enthalpy increases > 50 kJ/kg are 403, 420, 423, 424, 429D, 430D and M-198.

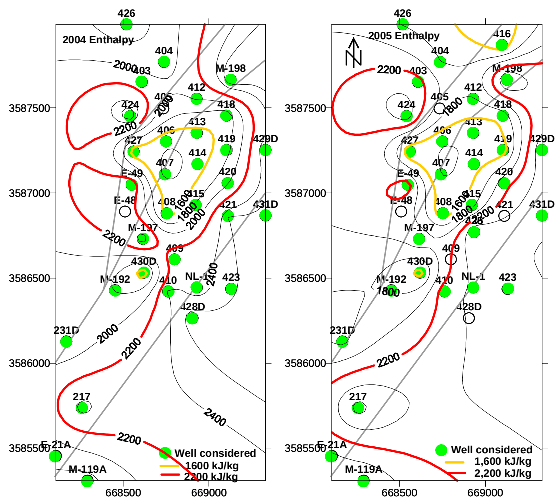

Figure 5: 2004 and 2005 distributions of the wellhead enthalpy for CP IV wells.

In Figure 6 the well-bottom pressure-enthalpy behavior of wells 406, 419, M-192, 403 and 423 is seen. These wells were taken as representative in order to describe the main processes occurring at CP IV area. In the figure, the first and the last production data were represented. The fluid entering the wells 406, 407 and 430D is a compressed liquid considering the estimated well-bottom pressure. Wells 406 and 407 show enthalpy decrease and pressure increase indicating the presence of lower temperature fluids. In Figure 6, the behavior of well 406 is shown. In the wells 404, 408, 412, 413, 415, 418 and 419 a decrease in both enthalpy and pressure is observed which is related to the occurrence of local boiling with steam decrease. In Figure 6 the behavior of well 419 is shown. All these wells except well 404 are located in the low-enthalpy zone (enthalpies ≤ 1,600 kJ/kg) and are being affected by the entry of the shallower lower temperature fluids. In the wells 414, 427, E-48 and M-192 the pressure significantly decreases while enthalpy slightly increases, this is probably due to a local boiling process with steam gaining. This occurs as the lower temperature fluid approaches the feeding zone of wells. In Figure 6 the behavior of well M-192 is given. In the wells 403, 420 and E-49 the pressure significantly decrease (in average 16.4 bar/year) while enthalpy significantly increases (in average 75.6 (kJ/kg)/year). This indicates the occurrence of a moderate boiling process with gaining steam. This boiling was defined as moderate since the enthalpies show values slightly higher than 2,000 kJ/kg. For the wells 403 and E-49 there are evidences that lower temperature fluids are recharging their feeding zones. However the rate of this recharge fluid is lower than the extraction rate of the well, this causes the pressure decrease and the enthalpy increase. In Figure 6, the behavior of well 403 is given. The wells 409, 410, 421, 423, 428D, 429D, M-197, M-198 and NL-1 that belong to the *southern block* show very high enthalpies (≥2,300 kJ/kg) and hence, for them important boiling processes are inferred. In most of them, high-temperature steam condensation also occurs. In Figure 6 the behavior of well 423 is shown.

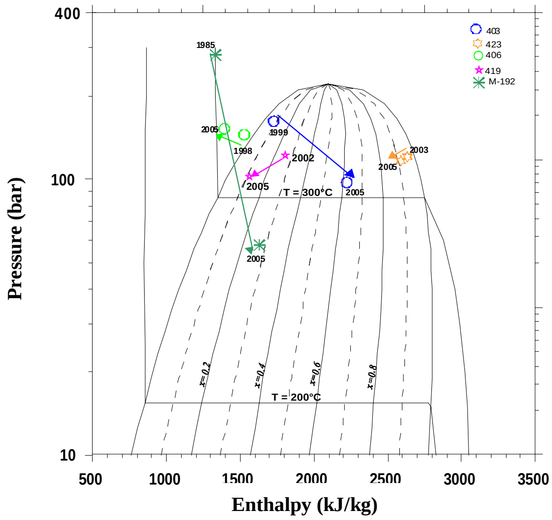

Figure 6: Well-bottom pressure vs enthalpy for selected CP IV wells.

3.3.2 Chlorides

In Figure 7 the reservoir chlorides distributions for 2004 and 2005 are given. As seen in the figure, in 2004 the higher chlorides are found in the southwest part of CP IV (values up to 15,500 mg/kg are shown for well 231D) where CP II wells are located. The figure suggests that a high- chloride fluid entry occurs through the lower part of Fault H. Chlorides decrease to the northeast (well 430D with 10,000 mg/kg) but rather to the east where high-enthalpy wells are found. In the zone of low-enthalpy wells, chlorides variations are as follows. In well 406 chlorides range 8,200 mg/kg and in well 413 the higher chlorides of the zone 10,400 mg/kg are observed.

Chlorides in high-enthalpy wells range values < 6,000 mg/kg. In 2005 the higher chlorides are found to the southeast of CP IV, where CP II wells are located, and decrease towards well 430D and to the east, where high-enthalpy wells are located. Low-enthalpy wells (406, 407, 408, 412, 413, etc.) show in general a chloride decrease trend. Thus the well 406 has the lower chloride concentration (6,600 mg/kg) and well 413 the higher value (~10,000 mg/kg).

The enthalpy-chloride diagram for the representative wells (406, 419, M-192, 403 and 423) is shown in Figure 8. In the figure it is seen that well 406 is moving towards a more diluted lower temperature fluid direction indicating a dilution of reservoir fluids. In contrast, well 419 is moving along a boiling line in the loss of steam direction. This is related to a boiling rate reduction caused by the entry of lower temperature fluids that decreases the enthalpy and increases chlorides in the total discharge. The well M-192 is an example of wells with local boiling with gaining steam. In Figure 8, this well is moving close to the boiling line, not showing very high enthalpy in spite of an important pressure decrease. In well 403 a moderate boiling process with gaining steam is inferred. This well has the same pressure loss as well M-192. However, the enthalpy increase observed in well 403 is rather higher than that for well M-192. What it is seen in Figure 8 is the development of a boiling front that produces the enthalpy increase and chlorides decrease. The behavior of well 423 is representative of the occurrence of important boiling processes with steam condensation. Due to this process, the wells show minimum chlorides, very high enthalpies and relatively low pH in fluids discharged.

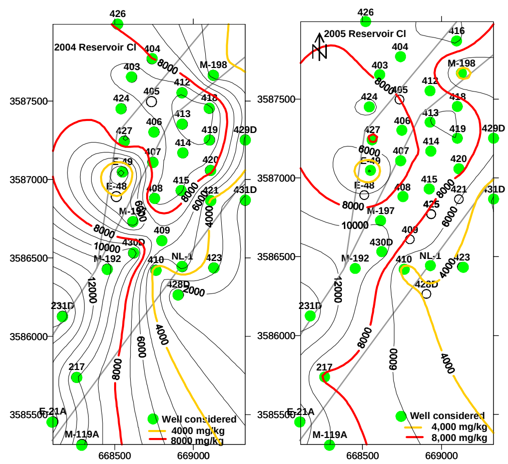

Figure 7: 2004 and 2005 distributions of reservoir chlorides for CP IV wells.

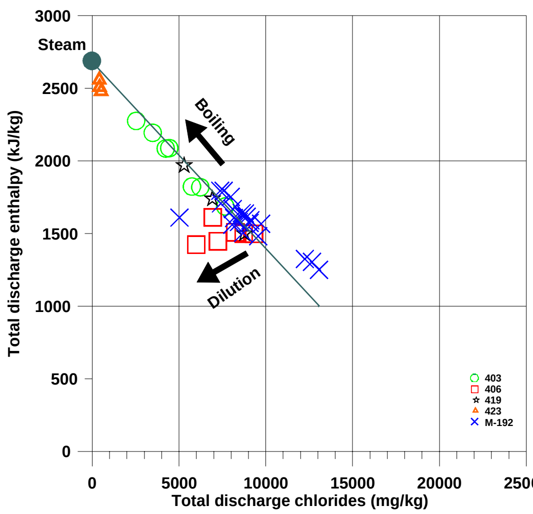

Figure 8: Enthalpy-chloride diagram for representative wells, according to average annual data.

3.3.3 Reservoir temperatures

Reservoir temperatures distributions for 2004 and 2005 for CP IV are given in Figure 9. Temperatures were estimated by the Na/K geothermometer (Nieva and Nieva, 1987). In both distributions it is observed that maximum temperatures > 300°C are located in the SSW-NNE direction of CP IV along the Fault H trace. In 2005 the 300°C iso-line is practically lying in the lower border of the fault system indicating the influence of these on the reservoir hydrological behavior. Temperatures decrease towards the central part of CP IV (wells E-48 and E-49) where minimum values are found although most of the wells show relatively high temperatures, in the range of 270 - 310°C. Regarding 2004 distribution in that for 2005 it is noticeable the change in the 300 °C iso-line which in 2004 was extended from the east to the west in the northern part of CP IV and in 2005 this line no longer extends to the northeast. This is probably due to a slight cooling effect in the north central part of CP IV caused by the down-flow of lower temperature fluids through Fault H, as was discussed for the chlorides behavior.

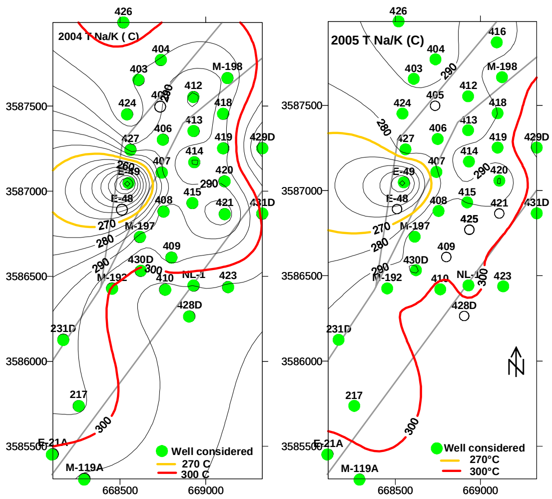

Figure 9: 2004 and 2005 distributions of Na/K reservoir temperatures for CP IV wells.

3.3.4 Total Discharge CO_2

In Figure 10 the 2004 and 2005 distributions of total discharge CO_2 for CP IV wells are given. As it is seen in the figure, in 2004 two zones with relatively low CO_2 values (≤ 2 ‰ molar) are distinguished, one is found in the southwest of the area where the higher chlorides were seen while the other where the low-enthalpy wells are located.

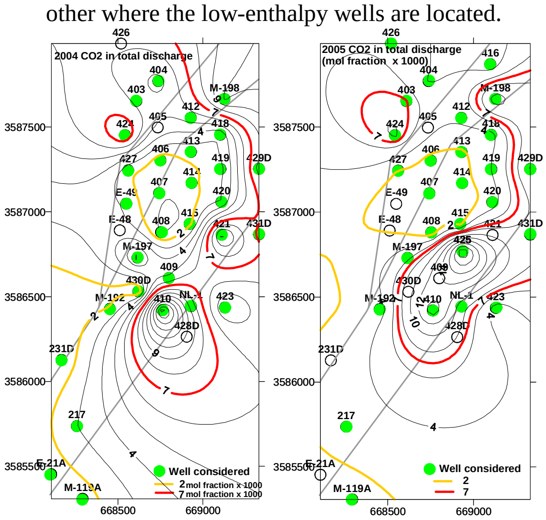

Figure 10: 2004 and 2005 distributions of total discharge CO_2 for CP IV wells.

CO_2 increases towards the northeast part to the well M-198 where the higher value was observed, 10 ‰ molar. In the northwest part, in the well 424 values of 7 ‰ molar are seen. As expected, the higher CO_2 values are located in the zones where important boiling processes occur (*southern block*). For 2005 CO_2 tendencies seem to be as those for 2004 but no data were available for wells 231D, 409, 421, 428D, 430D and E-49 to confirm this.

3.3.5 Total Discharge δD

In Figure 11 the 2004 and 2005 distributions of total discharge δD for CP IV wells are given. As seen in the figure, in 2004 the more depleted δD values are found around wells 406 and 407 while δD increases from this part towards any other direction in the sector.

The more enriched δD values are found in the southwest part of CP IV between the well M-192 and the other CP II wells. The δD behavior resembles that found for enthalpy. In 2005 the tendency seems to follow that for 2004 but it is seen that the area affected by the entry of lower temperature fluids has become larger, now affecting an important number of wells.

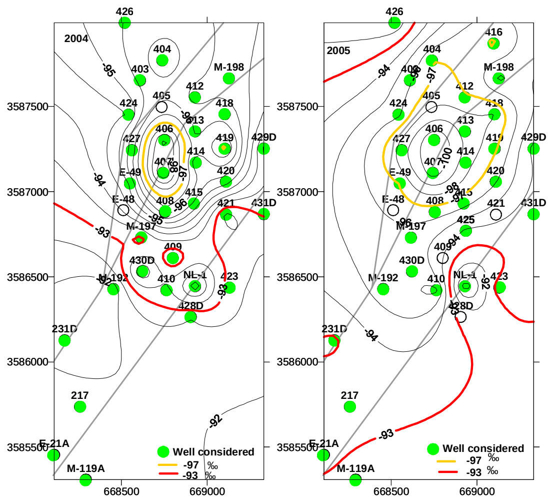

Figure 11: 2004 and 2005 distributions of total discharge δD for CP IV wells.

In Figure 12, a δD vs $\delta^{18}O$ diagram of CP IV wells for 2004 data is given. A mixing line has been identified which suggests the dilution of the reservoir fluid by another lower temperature fluid with an estimated isotopic composition of -14.5 ‰ for $\delta^{18}O$ and -111 ‰ for δD (Portugal et al, 2006). In the figure it is seen that a good number of wells are being affected by this shallower entry, located in the area of the wells 406 and 407.

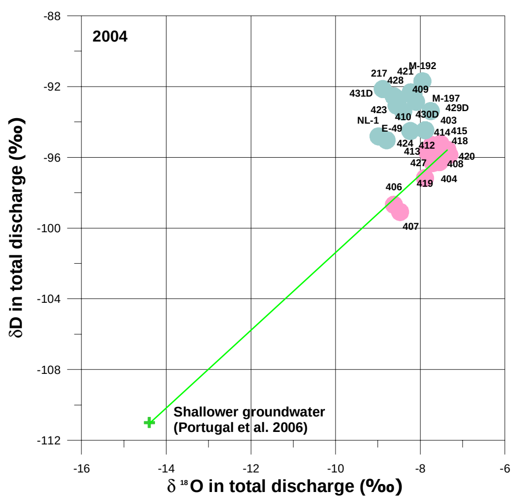

Figure 12: δD vs $\delta^{18}O$ of total discharges from CP IV wells according to 2004 data.

4. CONCLUSIONS

The analysis of chemical, isotopic and production data of 28 CP IV wells allowed the main reservoir processes related to exploitation to be identified. The Fault H divides the CP IV sector into two zones with different characteristics. From wells 429D, 420, 409 and 410 to the east-southeast (southern block) the wells produce high-enthalpy, very low chloride concentrations and relatively high CO_2 and δD. In contrast, from wells 419, 415 and 430D to the west-northwest (northern block) the wells produce low-enthalpy, high chlorides and low CO_2 and δD. The southern block wells respond to exploitation with enthalpy increases that indicate the development of important boiling processes with steam condensation. Some of these wells produce slightly low pH fluids that have affected well casings. The northern block wells respond to exploitation in a more complex ways regarding southern block wells. Processes such as pressure and mass flow rates decreases, boiling, entry of lower temperature fluids to the reservoir and short-term pressure and mass flow rates increases were identified in wells. Among them, the entry of lower temperature fluids to the reservoir is the process that seems to rule the behavior of an important number of CP IV wells: 406, 407, 408, 412, 413, 414, 415, 419 and 427.

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