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Reservoir Processes Inferred by Geochemical, Stable Isotopes and Gas Equilibrium Data in Cerro Prieto, B.C., México

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ABSTRACT

Based on hydrogeochemical, stable isotopes data and the chemical equilibrium of the Fischer-Tropchs reaction (Giggenbach methodology), the interaction of the aquifers, and the reservoir process were studied. Additionally, gas equlibria methods involving Fischer-Tropsch-Pyrite-Magnetite; and Fischer-Tropsch-Pyrite-Hematite-Pyrite-Magnetite reactions also were used in order to define if these approaches may be applied to evaluate reservoir temperature and mass steam fraction in the new Cerro Prieto IV area.

Boiling process was identified for CP-III, while excess steam is found absent in CP-II. Instead, a deficit of vapor is seen, particularly in the W part of CP-II and in the SE part of CP-I. These facts may be related to the evaporated brine injection and the entry of the groundwater. The distribution of temperature calculated by tccg shows a thermal gradient of the beta fluid that increase in east direction, where CP-II temperatures are higher than CP-III.

Gas equlibria methods (involving Fischer-Tropsch-Pyrite-Magnetite; and Fischer-Tropsch-Pyrite-Hematite-Pyrite-Magnetite reactions) were applied in some selected producing wells from four areas under exploitation. The results show good correlation for both equilibria methods; however Fischer-Tropsch Pyrite-Magnetite reactions provide the best estimation of the physical reservoir parameters. The main processes found for Cerro Prieto IV area are lateral vapor contribution and the inflow of hotter and deeper fluid with high liquid saturation.

1. INTRODUCTION

The Cerro Prieto geothermal field has been extensively studied by the Comisión Federal de Electricidad (CFE) and by many scientists. This has enhanced the knowledge of the systems. The exploitation of the reservoirs and the brine injection, as well as the infiltration of groundwater, has caused that the wells produce mixture of fluids and that the systems become highly hydrodynamic. Therefore, it is important to apply different methods to determine the reservoir processes.

Non-condensable gases composition is mainly used to identify reservoir processes in vapor-dominated reservoirs; however, it has been also effective in those reservoirs that become vapor dominated after large-scale exploitation or in those reached by injected fluids. The method developed by D´Amore and Truesdell (1985) has been applied by several

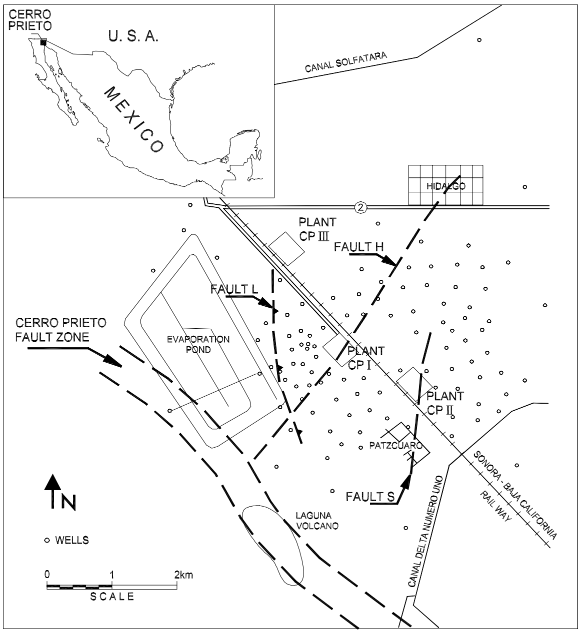

Figure 1: Location of Cerro Prieto geothermal field and the main geological structures.

authors (D´Amore and Truesdell, 1995; Siega et al., 1999; Barragán et al., 2000) in vapor dominated reservoirs.

The theory has been thoroughly described in D´Amore (1992), Siega et al., (1999); Barragán et al., (2000). Using gas chemical reactions, which are assumed to be in equilibrium at reservoir conditions, and the chemical composition measured at the discharge of producing wells was found to be in good correlation with temperature (**t**) and excess vapor (***y***) in the reservoir.

Two correlations were applied in Cerro Prieto: the Fischer-Tropsch (breakdown of methane)-Pyrite-Magnetite and Fischer-Tropsch-Pyrite-Hematite, in order to define if these reactions can determine the equilibrium between these gaseous species of wells from northeast part of the field (CP-IV), which are distinguished to produce high vapor rate.

This work presents also a brief overview on the changes that have occurred in the reservoirs using isotopic (^{18}O and deuterium) and chemical data, as well as the results of applying the two gas-correlations

2. CERRO PRIETO GEOTHERMAL FIELD

The Cerro Prieto Geothermal Field (CPGF) in Baja California is located in the southern part of the Salton Trough about 20 miles south of the United States-Mexico border. It is contained mostly in sandstones and shales of the Colorado River delta. Figure 1 shows the location of the CPGF. At present, for administrative purposes four areas have been recognized and the total installed capacity is 720 MW (Gutiérrez and Rodriguez, 2000). CP-I at the west of the field, CP-II at the southeast, CP-III at the north and CP-IV at the northeast. There are three reservoirs developed in sandstone and sandy shale units that are fed by fluids rising from fractures, (Lippmann et al., 1991). The alpha reservoir in the west part of the field is the shallowest and was the first to be exploited. It is found at depths between 1000 and 1500 m. The deeper beta reservoir extends underneath the entire area of the Cerro Prieto (about 15 km^2) at depths between 1500 and 2700 m with temperatures higher than those found in Alfa reservoir. The gamma reservoir is the deepest, it occurs below 3300 m. Exploitation and development of the field has been conducted by CFE, which has carried out extensive studies.

2.1 Geological and hydrologycal setting

Tectonically, the Salton Trough-Gulf of California area is a zone of transition between the divergent boundary of the East Pacific Rise and the transform boundary of the San Andreas Fault system.

The sediments at Cerro Prieto were deposited mainly in alluvial, deltaic, estuarine and shallow-marine environments during Pliocene to middle Pleistocene times **(**Halfman et al., 1984). The sediments are classified in two units A and B, both overlying a granodioritic basement. Unit A consists of clay, silt, sands and gravel; considered as unaltered unconsolidated sediments. Unit B, below unit A, consists of shale, siltstone and sandstone. Sediments of unit B are considered to have become indurated by compaction, cementation and metamorphic reactions. The contact between the A and B units approximately corresponds to the first occurrence of hydrothermal minerals.

The hydrological model developed by Halfman et al., (1984, 1986) is based on geophysical, lithological and temperature well logs studies, and describes the subsurface fluid flow under natural state conditions. This model shows that geothermal fluid circulates from east to west, vertically through faults and horizontally through a permeable stratum (Lippmann et al., 1991). At the present, in spite of the intense exploitation in the west part a low portion of this hot fluid mixing at shallow strata with groundwater (Portugal et al. 2004).

2.2 Hydrothermal Mineralogy

The early alteration mineral study in the original three zone of Cerro Prieto were carried out by Elder et al.(1979, 1981). While in Cerro Prieto IV the hydrothermal mineralogical study (CP-IV) was carried out by Izquierdo et. al., (2001). According to this study rock alteration in the area is close to 40 % with respect to primary minerals, therefore hydrothermal alteration was defined as high rank and moderate intensity. The rocks are terrigineous being shales more abundant than sandstone and the mineralogy quite similar to all over the field. Minerals identified in the clay fraction are: Na-smectite, Ca-smectite, illite, chlorite and scarce interstratified minerals. Minerals like quartz, plagioclase and amphibole were also identified. Optically calcite, quartz, epidote, illite, chlorite, smectites, wairakite, pyrite, amphiboles, ion oxides (hematite and magnetite) and scarce biotite were recognized. So, the main mineral associations observed in altered rock are: Calcite-illite-epidote-chlorite; -quartz-chlorite; -epidote-wairakite; -epidote-amphibole and wairakite-epidote-pyrite. These mineral assemblages show that the temperature in the zone was between 250 ºC and 300 ºC.

2.3 Fluids Geochemistry

Being a dominated liquid reservoir, the CP-IV wells produce a mixture of fluids at the surface conditions. The liquid fraction from studied wells has a chemical composition characteristic of geothermal brine. According to the Piper classification the CP-IV brine can be defined as the sodium-chloride type. Apart of these major elements, content of potassium and calcium are high, while lithium, boron and sulfate content is very low. Stable isotopic composition ($\delta^{18}O$ and δD) for the same fluids at the discharge are in the range of –89.8‰ to –96.7‰ for deuterium and –7.3‰ to -9.4‰ for oxygen-18. The stable isotopes indicate that the natural recharge to the reservoir consists of groundwater from the alluvial aquifer located in the west part of CP-IV area. The main gases for CP-IV are CO_2 (91 w %), H_2S (4 wt. %) and CH_4 (3 wt. %) and together represent over 98 wt. % in dry basis.

3. METHODOLOGY

Personnel of the Instituto de Investigaciones Eléctricas (IIE) collected steam and liquid samples. The steam was sampled from production separator after one or two stages of steam separation under controlled conditions. Liquid was sampled from weirbox at atmospheric pressure. Chemical and isotopic analyses were made in the IIE laboratories. Staff of the CFE conducted sampling and analysis of gases.
The "**t**" was calculated by using the "ccg" geothermometer (Nieva and Nieva, 1987), and the silica geothermometer (Fournier and Potter, 1982) and "***y***" was calculated by the SCEXVAP routine of the EQQYAC program; which uses Giggenbach methodology (Giggenbach, 1980), modified by Barragan and Nieva, (1989). The method is based on the chemical equilibrium deviation from the Fischer-Tropsch reaction. The process assumes that chemical equilibrium between CO_2, H_2 and CH_4 occurs.

Fluids chemical composition was calculated to total discharge using steam table data by a computer program that carries out heat and mass balance. Salts effects on thermodynamic properties of water were considered negligible. Chemical equilibrium and isotopic compositions at the reservoir were calculated using the excess-steam values above mentioned applying the EQQYAC program. In this work, experimental fractionation factors of Horita and Wesolowski (1994) for oxygen-18 and deuterium were used.

Gas equilibria for this study deals with the use of the following gas equilibrium reactions namely Fischer-Tropsch (FT)-Pyrite-Magnetite (HSH) and Fischer-Tropsch (FT)- Pyrite-Hematite- Pyrite-Magnetite (HSH2) to calculate "***y***" and "**t**" parameters.

FT: $CH_4 + 2H_2O = CO_2 + 4H_2$

HSH: $H_2 + 2H_2O + 3/2FeS_2 = 3H_2S + 1/2Fe_3O_4$

HSH2: $5/4H_2 + 3/2FeS_2 + ¾\ Fe_2O_3 + 7/4\ H_2O = 3H_2S + Fe_3O_4$

4. RESULTS

4.1 1999-2000 Cerro Prieto Features

The Figure 2 depicts the contours map of the tccg values showing the temperature distribution of producing wells of beta reservoir. According to the tccg distribution, higher temperatures are found in the SE and NE of the field. While lower temperatures are observed in west direction, where wells M-90, E-49, M-132 and M-123 are located and in the CP-III northwest area. Wells E-25, E-49 and E-43, located in the NE area of the field, show low tccg values with respect to the thermal tendency in the area. Figure 2 shows a dashed line from NE to SW, close to the line, wells M-160 and E-15 are located showing low tccg values. Tccg data show that the well producing of alfa reservoir are the coolest fluids (towards SW and W direction).

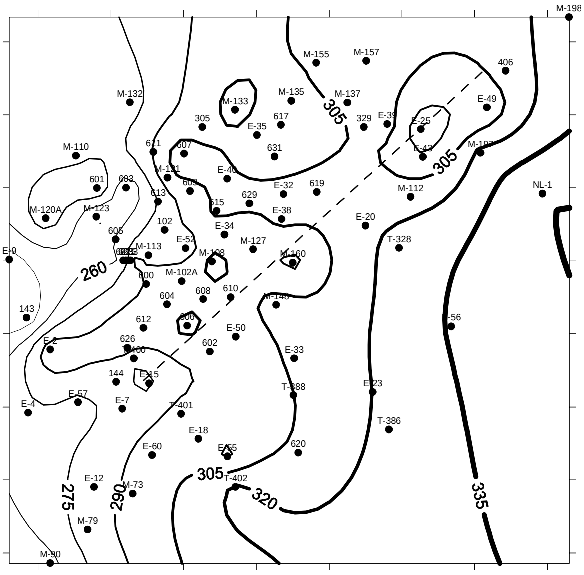

Figure 2: Isotherms of tccg for wells producing of the beta reservoir.

Beta reservoir temperatures calculated by the silica geothermometer shows a different tendency respect to tccg. According to the silica geothermometer the higher values are on a fringe NE-SW direction. While the lower values are in the west and in the east of the field. However, it is clear that the temperatures from the silica geothermometer are lower than those from the tccg.

The occurrence of boiling in CPIII is evident by the excess steam calculated for fluids from producer wells from beta reservoir. Calculated values suggest that in this zone, intense boiling occurs as calculated for 1990 by Truesdell et al., (1992). In the NE part of the field, it is located another boiling zone particularly for fluids from wells M-197, E-49 and E-46 (Figure 3). While in the SE area of the CP-I and the W part of the CP-II a deficit of vapor occur. This event seem to be related to the injection of evaporated brine in the south part of CP-I and the entry of the groundwater.

4.2 Isotopes Description

Stable isotopes fluids data have proved to be an excellent tool in Cerro Prieto. The physical process has been detected thanks to the availability of the oxygen-18 and deuterium data from last decades. The CFE through the IIE carries out a annual program of sampling and measurement of this isotopic species. The stable isotopic values of the reservoir fluids show a dispersion of 10 units in oxygen-18 and 47 units in deuterium. Figure 4 shows a δ^{18}O-δD diagram where reservoir isotopic composition of all producing wells of the field was plotted. Isotopic composition of injection waters and groundwater from shallow aquifers were also plotted. Figure 4 shows the range of fluid isotopic values in the early stages of exploitation.

The range is similar to the values of fluids from deepest well. This is an indication that there is no interaction with light waters at depths below 2900 m from beta reservoir. Deviation of initial values is observed in the fluid from shallow wells from alpha and reservoir, which is due to two processes: a) natural recharge of groundwater to the reservoir and b) injection of concentrated brine (by evaporation) has been discussed (Truesdell et al., 1992; Rodriguez 2000). Figure 4 shows these processes.

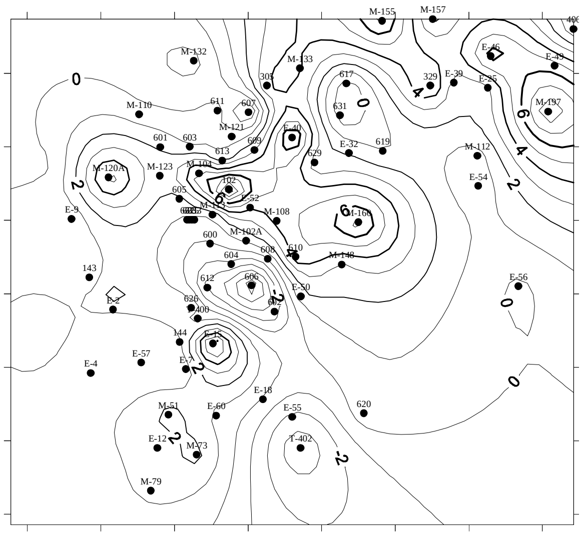

Figure 3: Excess-steam contours for fluids from well producing of beta reservoir.

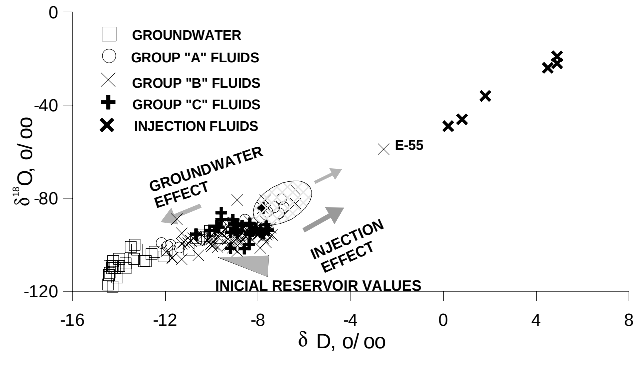

Figure 4: δ^{18}O-δD diagram showing geothermal fluids, injected waters, and groundwater in Cerro Prieto field (1999). The groups A, B and C refer to the producing wells of alpha, beta and deepest wells of beta respectively.

The isotopic composition of fluids from alpha and beta reservoir (open circle and light cross) is moved towards light values similar to those of the groundwater of the area. This is an indication of the mixing of hot reservoir fluids and groundwater from the shallow aquifer (groundwater effect, Figure 4). Mixing is the result of natural recharge induced by exploitation of the field. This process is still not observed in deep fluids of the beta reservoir, particularly in some wells located in CPII. The injection effect in the system is also shown in Figure 4. Injection water with heavy isotopic values (due to superficial evaporation) causes a shift of isotopic values of fluids from alpha and beta reservoir. A remarkable effect of deep injection in the SE of CP-I is on the well E-55 fluid. Where an enrichment of isotopic fluids is observed. This inflow injection water seems to affect the fluid of wells E-50 and E-33.

Injection is carried out in two fronts at different depth. The deepest is in the SE portion of the system trough two injector wells influencing fluids of beta reservoir. While shallow injection is carried out in the NW of the field.

The Figure 5 shows $\delta^{18}O$ composition lines of total discharge measured in 1997. Injection wells are located in the NW portion of the system, where is expected an influence of injection fluids. However, oxygen-18 values do not show any effect due to injection. Only a small enrichment in the fluid of wells 301, 302 and M-11 is noted. While near to wells E-16A and E-6 the injection effect is more evident.

The effect of injection on fluids of wells T-402, E-18 and especially in well E-55 is showed in the Figure 5. This influence had been noticed in 1995 (Portugal and Verma, 1995) although not so clear. In Figure 5 anomalous zones with fluids of light isotopic composition are observed. One of them is located in the NE part of the field; it includes wells E-41, E-37, E-43, E-26, -39 and E-25. The fluid of these wells has oxygen-18 values between –11.7‰ and 9.7‰. In contrast to values for neighbour wells whose average oxygen-18 value is –7.9‰. Another dilution zone is in the central part of the field (wells M-127, M-160 y M-148) with oxygen-18 values between –9.4‰ and –10.2‰. Discontinuous lines in Figure 9 suggest that the fault system (Fault H) proposed by Halfman et al., (1984).

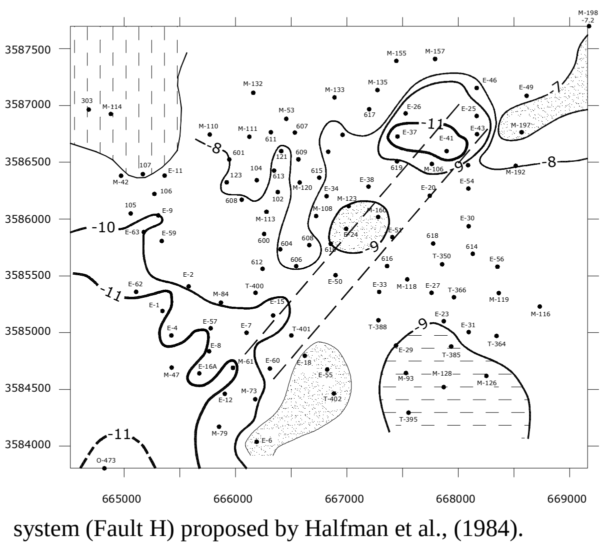

Figure 5: Distribution of the oxygen-18 (‰) in the total discharge in Cerro Prieto in 1997.

The distribution of oxygen-18 values for beta reservoir wells producing is showed in the Figure 6. In the same figure, influence of deep injection zone is observed mainly in well E-6 on the E-55 fluid. Injection in the SE area (well 0473 not shown in the figure) seems that does not have influence on the fluid of near wells. Instead, isotopic changes in the same zone are observed due to the natural recharge to the system.

4.3 Gas Equilibria

The Figure 6 shows the producing wells selected for this work. Figure 7 shows the FT-HSH and FT-HSH2 grids diagrams for CP-IV wells and some selected wells from the other areas of Cerro Prieto. In Figure 7a, excess and deficit of vapor events are shown. Data points of the wells plot on and close to the single-phase liquid line and most of them with negative ***y*** values (-0.1% up to -1%). 614 and 624 wells (Cerro Prieto II) plot outside the grid. Furthermore, M-192 and M-197 wells (CP-IV) that plot outside the diagram yield inconsistent ***y*** values. The values of temperature and excess steam for most of the wells are in the range from 230°C to 330°C and between 0.1% and 25% are estimated by this gas equilibria method. Higher values for both (***y*** and T) reservoir parameters were found for 403, 420, NL-1 M-198 and M-200 CP-IV wells; which may indicate lateral contribution of steam with strong local accumulation of gas. The CP-IV values of these parameters are in agreement with those calculated by cationic geothermometers (t_{nkc} and t_{ccg}) and by FT equilibrium (Barragán and Nieva, 1989) respectively.

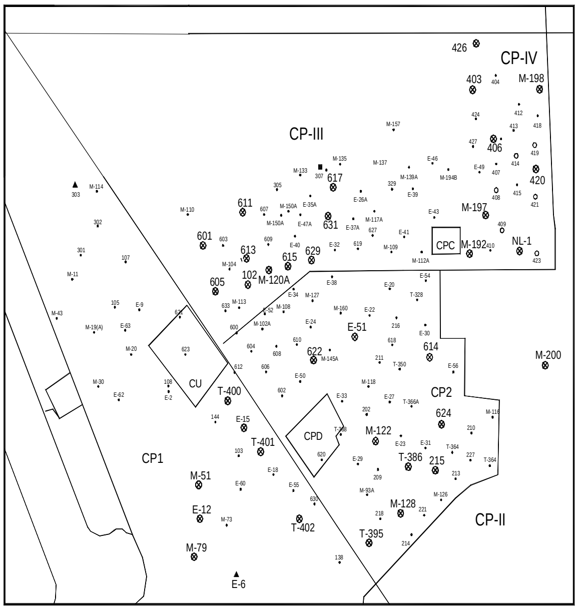

Figure 6: Location of the producing wells selected for this study.

Figure 7b shows data on the HSH2 diagram. As is seen, all of them plot inside the grid, nevertheless both cases of excess and deficit of vapor prevails. The distribution of the data points in FT-HSH2 grid is very similar than FT-HSH; however, slightly low reservoir temperature and also slightly high ***y*** values were estimated. Therefore, FT-HSH2 gas equilibria reactions seem to give good characterization for the data used in this study. The temperature estimations are in the range of 230°C to 315°C, in agreement with those given by mineral assemblages.

5. CONCLUSION

According to the tccg values, temperature increases as function of depth, up to 350ºC. Shallow wells have average temperature of 250ºC, while deeper wells have temperatures between 295º C and 318º C (producing wells from beta reservoir). tccg in CP-II are higher than CP-III. Thermal gradient of fluids of beta reservoir has E-W direction. There are well defined areas within the influence zone of fault H having higher temperatures. The thermal gradient of the beta fluid show increase in east direction. In the case of shallow geothermal fluids (alpha reservoir), cooling is observed in the recharge zone; due to the contact with groundwater. The distribution of temperature values calculated by the silica geothermometer, shows decreasing in west and east direction. The higher temperature values are in a fringe in NE-SW direction. An important boiling process occurs in the CP-III zone, same as shown for 1990 by Truesdell et al (1992), while in CP-II excess steam is absent. Instead of a deficit of vapor is seen, mainly in the part W. A similar event is found in the SE part of CP-I probably due to evaporated brine injection and the entry of the groundwater.

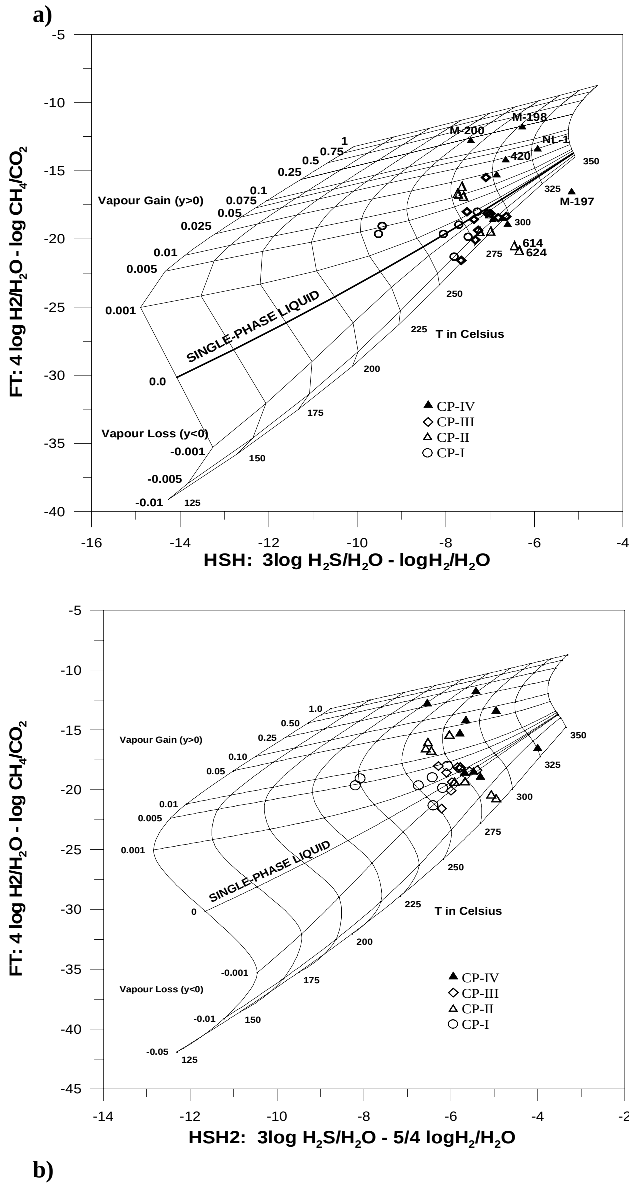

Figure 7. a. FT-HSH grid diagram; b. FT-HSH2 grid diagram.

The range of isotopic values of oxygen-18 and deuterium in the Cerro Prieto fluids has not changed notably in the last five years. On the contrary, a change has been noticed in the influence zone of groundwater and injection waters. The shallow injection front located in the NW zone show values close to 7.5‰. While the deep injection front in the SW area show considerable influence on nearest wells, especially in the fluid of well E-55. It is worth to mention that the fluid of some wells located in this zone has not been affected by such fluid. Instead, entering of groundwater of lighter isotopic composition is observed. The presence of light isotopic composition fluids at NE of the field is more evident in 1999; showing an extension along the dilution fringe discussed in 1997.

In Cerro Prieto, both gas equilibria methods can be applied to characterize the fluids from producing wells. FT-HSH2 gas equilibria give consistent **t** values with respect to the mineral assemblage temperature reported previously and all data points plot inside the grid. While both physical reservoir parameters (**t** and ***y***) estimated by FT-HSH are in good agreement with those estimated by cationic geothermometers (t_{nkc} and t_{ccg}) and FT equilibrium, compared to the values estimated by FT-HSH2 method.

The high excess vapor estimated for 403, 420, M-200, NL-1 and M-198 in Cerro Prieto IV may be due to the inflow of the lateral vapor contribution. In contrast, negative ***y*** values and high reservoir temperature estimation for M-197 fluid seem to be result of the inflow of hotter and deeper fluid with high liquid saturation.

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