



Characterization Methodology for Analysis in Neighboring Productive and Nonproductive Zones of Los Humeros Geothermal Field

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The study focused on the analysis of two neighboring zones in the Los Humeros geothermal field (LHGF), each one with different characteristic behaviors. A characterization methodology which can be used in geothermal reservoir engineering was designed and applied to study the zones. The static temperature profiles determined in wells located at the studied zone of the field ranged between 300°C and 360°C. From these temperatures, isotherms in the studied area were calculated and these trend to be deeper toward eastern zone of the field. Similarly the thicknesses tend to reduce in this direction. By analyzing the profiles of fluid circulation losses were determined during drilling of wells in this zone, the existence of low permeability in the rock formation was inferred. From the results of transient pressure tests, low permeability was confirmed. A marked difference in the productive characteristics between the wells, in the close neighborhood was also observed. Behavior of wells also shows tendency to increase in their steam fractions, with the exploitation time. The characterization methodology applied to the studied zones, allows identify that there is a reservoir section with low permeability, but with high temperatures the depth increases.

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1. INTRODUCTION

The determination of parameters such as temperature, pressure, formation mineralogy, porosity, rock density, permeability, etc., allows static reservoir characterization to be carried out. And this is used for planning its exploitation designs and programming new areas as of expansion [1,2]. Different techniques such as thermodynamic, physicochemical, geological, geophysical, transient pressure analysis, reservoir engineering, etc., are used in reservoir characterization [3-5]. The main results of reservoir characterization give reservoir size determination, reserves evaluation, initial conditions, exploitation designs, useful life of the reservoir, numerical modelling. Different models have been used to simulate the behavior of fluids inside the reservoir under different sets of conditions and to find the optimal production techniques that will maximize the exploitation. [6-8] have used the petrophysical properties and the physicochemical parameters as basic techniques for reservoir studies. They created an interdisciplinary high resolution geosciences model that incorporates and integrates geological and reservoir engineering information, since pore to basin scales. Well data, production data, the reservoir simulators etc., are useful tools for extrapolating parameters characteristics, away from existing wells [9].

This study focused on LHGF, which is one of the four geothermal fields currently operated by CFE in México. It is located at the border of the states of Puebla and Veracruz in central-eastern México (Fig. 1) about 220 km east of México City. Table 1 shows the main characteristics (mean depth, steam production, steam fraction, and electric generation) of the geothermal fields in México operated by CFE. LHGF is the third place of electric generation in México, whose characteristic is fluid production of high enthalpy [10] and low permeability rock formation [11-13]. A comparison of some of the features related with production of Mexican geothermal fields, operated by CFE, is also given in Table 1 [14, 15]. Generally, the producing wells in LHGF show temperatures as high as 300°C at depths greater than 2000 m. The zone studied in this work is the central and south-western section of the LHGF. The wells drilled at central-eastern area of the field are unproductive. However, it is surprising that the wells drilled in its neighboring

zones located at northern, western and south side resulted in being productive.

The drilling operations started since 1981, and during the exploration stage for the expansion of the field, the wells H23, H24, H25, H26 and H27 were drilled (Fig. 1). However, none of these wells were productive. Therefore, in this zone of the field, and still to date, no more wells have been drilled. By this reason, all the parameters available during drilling stage of these wells (profiles and distributions of temperature, pressure and circulation losses) were obtained and analyzed in this study.

During drilling, circulation losses were monitored continuously and these were used to identify, at least qualitatively, permeable intervals along the well. Besides, temperature and pressure profiles were taken at different depths. The use of temperature logs at different depths and different repose times and the numerical model application of [16], allows determining the profiles of static temperatures in the well. The pressure logs are used for determining the static level in the well when the reservoir pressure and static pressure after transient effects have disappeared. The aim of this study is to carry out characterization at different conditions of temperature, pressure and permeable intervals in this zone for understanding its behavior and the feasibility of determining its stored energy. In the study zone there are producer wells and non-producers. Thermodynamic and rock formation properties were used for the producing wells, while for non-producer wells, data recovered only during drilling stage were used.

Wells H1, H6, H12, and H39 are producers and are located in a neighboring area at the south west side of the aforementioned zone of non-producing wells. In Fig. 1 the wells locations and the closeness between them can be seen. While producing wells are located at west and south west side, the non-producer wells are grouped to eastern section.

In summary, the technical support for using this methodology is focused for researching the need of understanding different single behavior of wells located too close between them. Due to some of the wells are producer they have more information quantity useful, for reservoir characterization; since the drilling, its heating

Table 1. Data of the productive characteristics of the four geothermal fields operated by CFE in México, showing that LHGF is first place of produced steam fraction and second place of steam production [14,15]

Field	Average values			
	Depth (m)	Steam production (t/h)	Steam fraction(%)	Current electric generation (MWe)
Cerro Prieto	2400	25	0.35	570
Los Azufres	1600	44	0.66	191
Los Humeros	2200	27	0.89	68
TresVirgenes	2050	24	0.25	10

stage, output curves, and production history. However for non producer wells, only are available be used, drilling stage data and with this restriction, it is necessary carry out the characterization.

2. GEOLOGICAL CHARACTERISTICS OF THE ANALYZED AREA

The field was developed within a Quaternary Caldera. Its heat source is the magma chamber that produced a couple of caldera collapses, known as “Los Humeros” and “Los Potreros”. “Los Humeros” Caldera is ellipsoidal with 21 km by 15 km diameters, whose formation was 0.5 Ma ago. “Los Potreros” Caldera is nestled inside the first one, is also ellipsoidal with 10 km by 7 km diameters and was formed 0.1 Ma ago [17]. Geophysical and geological studies [18–20] allow proposing a third collapse-caldera named “Colapso Central”, located into “Los Potreros” caldera, which contains the majority of producing wells.

The zone coincides with the up flow area of the geothermal system and probably with the magmatic chamber at depth [21].

Based on the rocks intersected by geothermal wells and from a detailed study of drill cuttings from most of them, [22] suggest that the subsurface lithology can be grouped into four Units as shown in Table 2 and the details of these units can be found in [23].

The studied area involves wells located in the central zone of the field, having as boundary structures the “Los potrereros” collapse, the “Mastaloya” fault and the “Las Víboras” fault (Fig. 1).

The lithologic units at LHGF appear intercalated (Andesites, dacites, rhyolites) with chloride alteration. It is, a characteristic in the fluid, generally of low values, in comparison to others, but correlate with high temperatures in this field. It influences in LHGF characterization with high

steam fraction in the fluids, as can be seen in Table 1, and extreme B concentrations, which can be correlated with fluid enthalpy. Taking as objective to indicate chemical behavior in some of the world geothermal fields Table 3 is shown. This exhibits some of the chemical compounds produced in different geothermal fields of the world in order to have a comparison with those of Los Humeros and the sea water [24]. The produced fluids by LHGF are classified as bicarbonate, sulphate and sodium-chloride types, and are oversaturated with silica and calcite [25–27]. Besides the two-phase of the fluid having low salinity [28] there are also signs of high boron present in fluid.

3. PROPOSED METHODOLOGY FOR DATA ANALYSIS

This study focused on the analysis of characteristics of non-producing wells, which are grouped at central eastern zone of “Los Humeros”, finding that at its surrounding there are producing wells. The use of all available information, allows us to carry out reliable correlations between producing and non-producing wells.

For all studied wells, temperature and pressure profiles taken during different standby time periods after drilling stop were used. These measurements can be assumed as initial reservoir conditions. Besides, during drilling, it is a common practice, that circulation losses monitoring in the well are also carried out. From records of fluid circulation losses during drilling, circulation losses in the range of the 50 m³/h were found, at shallow depths. Profiles of circulation losses data were correlated with permeability measurements done by [11]. It is convenient take into account that laboratory tests for permeability determinations were carried out on core samples of the wells, which belong to a limited interval. The knowledge of initial reservoir conditions is useful because it can be used as a reference for comparing the reservoir conditions

Table 3. Comparative values of chemical compounds found in different geothermal fields in the world and in the seawater

Source	Na(ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	Cl(ppm)	B(ppm)
Asal ¹	35000	6500	22000	35	104000	*
Azufres ²	1800	440	40	0.04	3400	420
Cerro Prieto ³	5000	1200	290	0.33	9300	12
Humeros ⁴	1360	2096	1624	0.092	75	1450
Salton Sea ³	54800	17700	28500	49	158000	270
Seawater ³	10500	380	400	1350	19000	5
Reykjanes ⁵	9630	1400	1500	1	18000	9

¹[29]; ²[30]; ³[31]; ⁴[26]; ⁵[32]. *Not determined

Under this consideration, an analytical method which assumes a spherical-radial conductive heat flow in the formation was developed by [35] for estimating temperature that the well would achieve at long repose time. The method assumes a conductive radial flow, ie, conceptually the cooled formation by fluid circulation is treated as sphere of R radius. The mathematical model is given as:

$$T_{ws} = T_i - \frac{m}{\sqrt{\Delta t}} \quad (2)$$

Where,

T_{ws} is the well temperature at different repose times; T_i is the static temperature of the rock formation, and m is given by next expression:

$$m = \frac{R(T_i - T_f)}{\sqrt{\pi\alpha}} \quad (3)$$

Where,

T_f is the fluid temperature in the well after circulation finish; R is the sphere radius thermally affected and α is the thermal diffusivity of the system. Static temperature is obtained from a graph of T versus $(1/\Delta t)^{1/2}$ with m as slope and origin ordinate T_i .

The accuracy of predictive methods is dependent of formation properties. In this work according to [36], we used the long repose times after the well completion. Therefore the measured temperature and pressure, once the well has been closed during this time, can show the natural state of the system which is close to equilibrium.

Data of producing wells taken at surface conditions used the production history, mass flow, pressure, enthalpy, discharge orifice diameter. Through the use of the well flow simulation programs, parameter values at

bottom-hole conditions were calculated, for identifying reservoir evolution.

Under this concept, due to that enthalpy (H) represents the total heat content of a system; in a geothermal reservoir the fluid at saturated conditions, is composed by water and steam phases, which can be expressed as follows:

$$H_T = \frac{W_s H_s + W_w H_w}{W_w + W_s} \quad (4)$$

Where,

W is mass flow, and H is the enthalpy and sub index (s), is referred to steam phase, while (w) is related to water phase. Under this conceptualization, in this work are used the wells production data into a Mollier diagram in order to identify saturation state of produced fluid.

3.1 Analysis Methodology for be Used in any Well Ttype

Proposed methodology used for any well type, are summarized as follows:

- Data selection: (temperature and pressure logs, records of circulation losses during drilling, values of measured permeability in core samples).
- Construction of graphs representing profiles of temperatures, pressures and circulation losses of the wells.
- Determination pressure and temperature at static conditions.
- Comparison of the fluid circulation losses during drilling with permeability measurements to core samples in laboratory.
- Determination of temperature distributions in the study zone by using correlations between wells.

3.2 Analysis Methodology Applied in Producing Wells

- Analyze history production data.
- Compute production at bottom-hole conditions from measurements collected at wellhead, by using wellbore simulators (e. g. WELLFLO and WELLSIM). Details on the physical and numerical models of these simulators are described in [37,38].
- Carry out thermodynamic behavior analysis of the well by using diagrams enthalpy-pressure.
- Define characteristics of parameters distribution (temperature and pressure correlated with permeability) in the study zone with their respective thicknesses capable of heat storage.

4. APPLICATION OF METHODOLOGY ANALYSIS

4.1 Analysis Sequence for Producer and Non-Producer Wells

For temperature logs analysis, the same standby time in wells (36 hours) was used. Profiles of

measured temperatures and circulation losses, of the non-producer wells (H23, H25, H26 and H27), logged during drilling, are shown in Fig. 2. In Fig. 3, profiles of pressure logs at 36 hours of standby of the same wells are shown. It can be seen that there is a linear fit using technique of data regression of the wells.

Profiles of temperatures logged with 36 hours of standby for producer wells (H1, H6, H12 and H39) are shown in Fig. 4. Circulation losses profiles during drilling of these wells in this same graph can be observed. Also, it can be seen in this figure that wells were completed at similar levels (above 400 masl), with exception of H1, which is shallower. Profiles of pressure logs with 36 hours standby, of these wells, are shown in Fig. 5.

Density, porosity and permeability determined in laboratory tests on core samples of some of the wells of LHGF, together with, thermal properties (Diffusivity [K], specific heat, [c]) and, circulation losses with their corresponding thicknesses are shown in Table 4. The results of measurements indicate low permeability (1800 μ D in best case of the well H26).

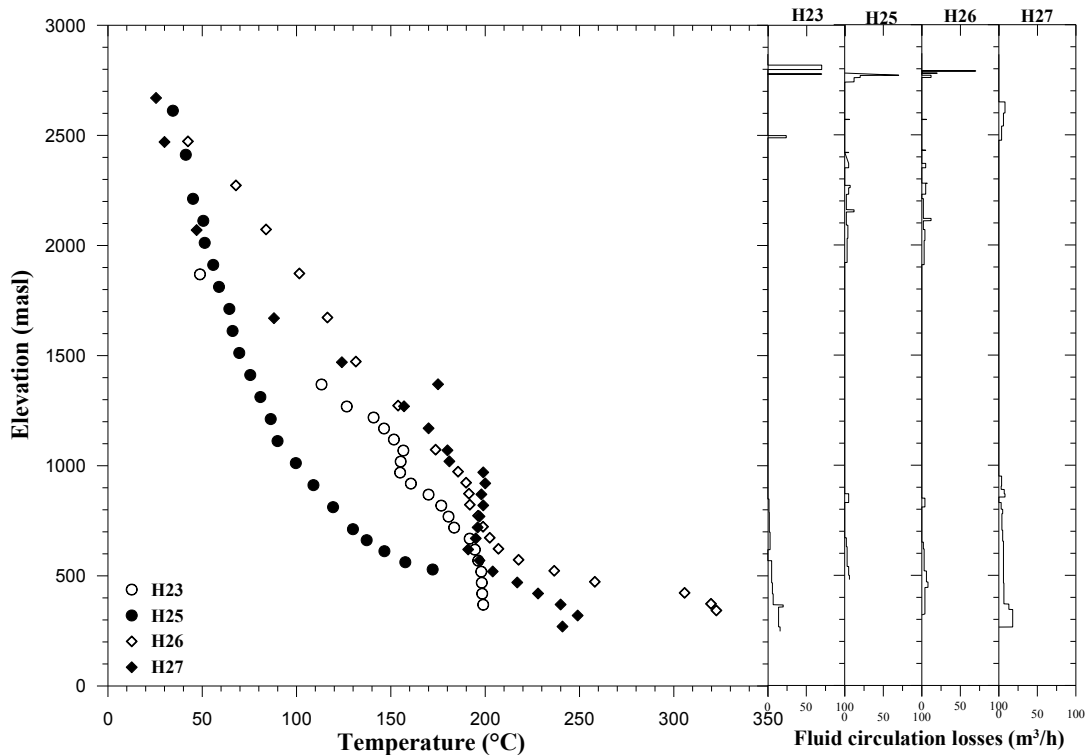


Fig. 2. Profiles showing measured temperatures at 36 hours of standby after drilling stop and circulation losses in wells H23, H25, H26 and H27 of LHGF

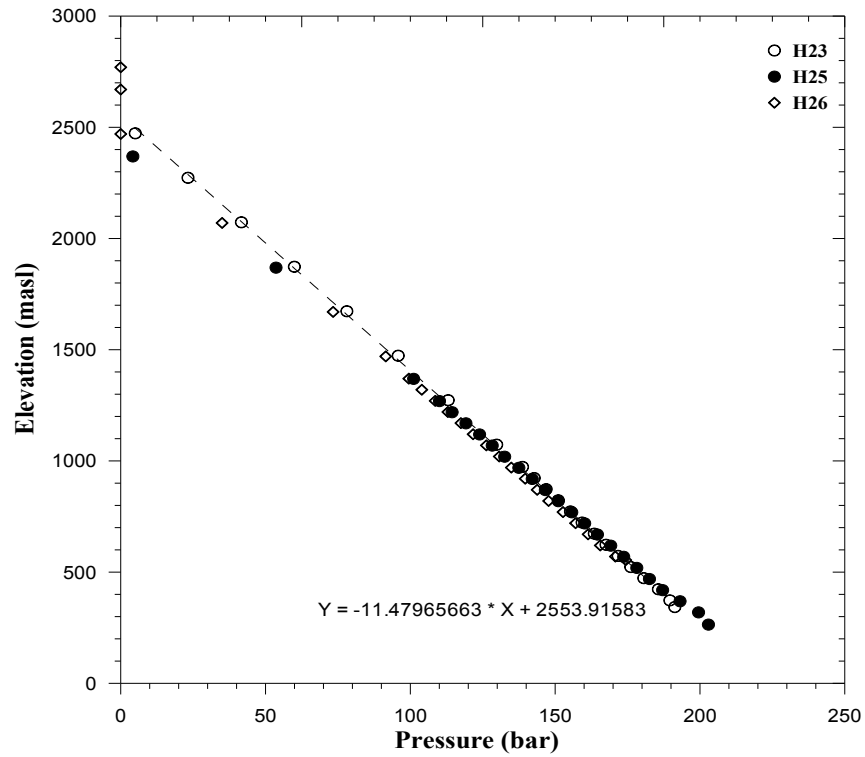


Fig. 3. Pressure profiles in wells H23, H25, H26 and H27 of LHGF showing their fit trends

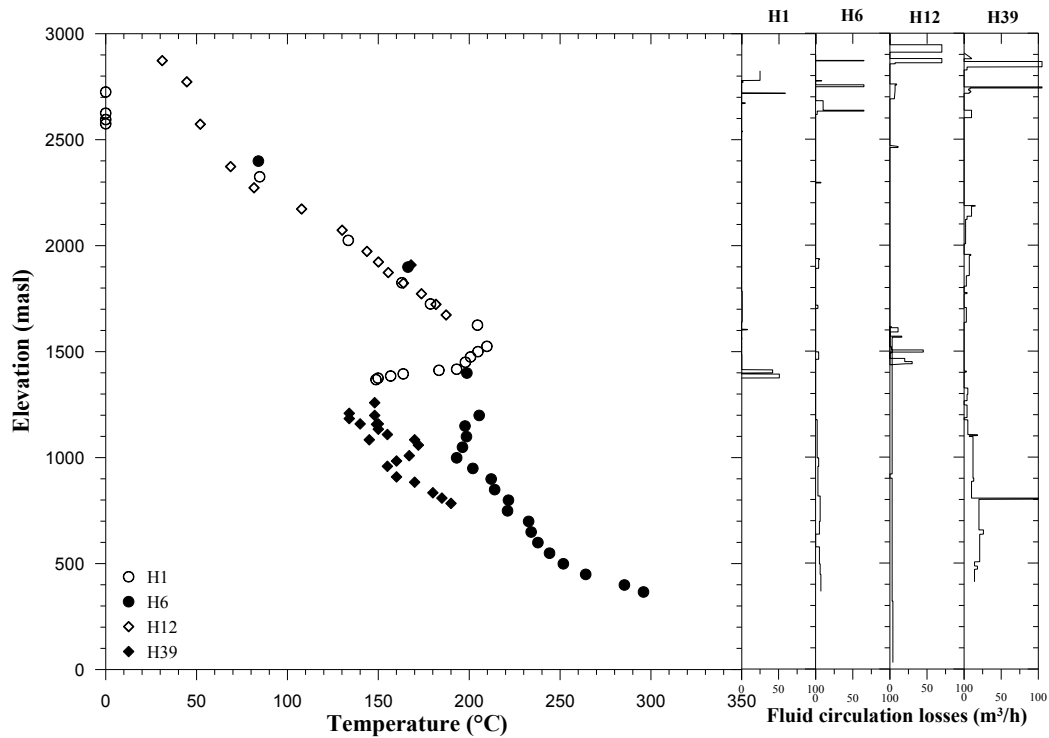


Fig. 4. Profiles showing measured temperatures at 36 hours of standby after drilling stop and circulation losses in wells H1, H6, H12 and H39 of LHGF

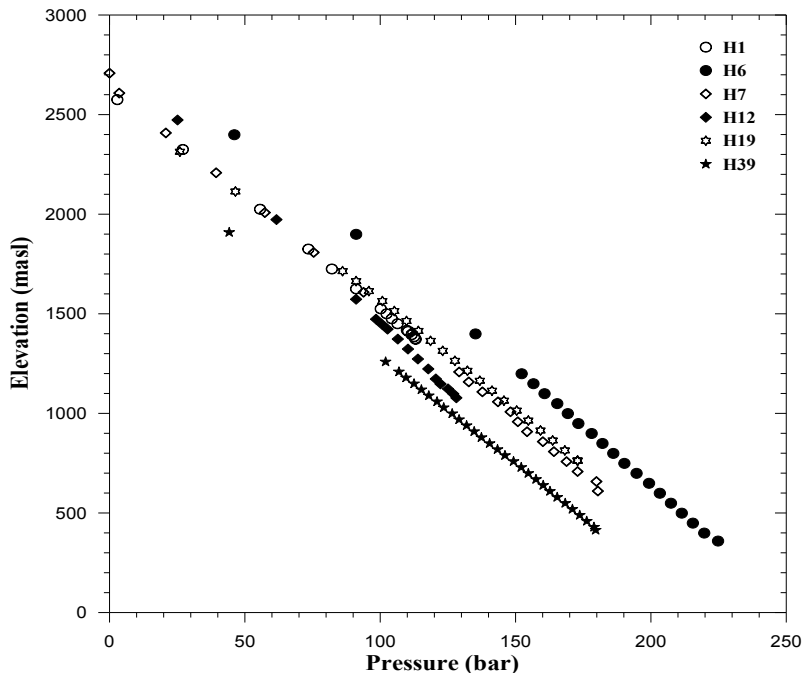


Fig. 5. Pressure profiles of wells H1, H6, H7, H12, H19 and H39 of LHGF showing their trends

Table 4. Measurements results of rock properties [7] of laboratory tests carried out to core samples of some of the lhgf wells, related with thicknesses of circulation losses

Well	Interval masl	ρ_r gr/cm ³	ϕ %	k μD	K [cm ² /s] (10 ²)		c cal/(gr°C)		Circulation losses	
					Dry rock	Saturated rock	Dry rock	Saturated rock	Thickness masl	m ³ /h
H6 ^P									639 - 819	6
H7 ^P									727 - 808	5
H19 ^P	1043 - 1045	2.45	12.5	76	0.4	0.63	0.25	0.28	663 - 854	11
		2.48	11.4	147						
H23 ^{NP}	942 - 945	2.37	13.9	576	0.67	0.68	0.21	0.26	300 - 355	15
H25 ^{NP}	1099 - 1102	2.76	3.4	1					540 - 630	5
H26 ^{NP}	1060 - 1063	2.67	4.5	1800	0.62	0.7	0.23	0.24	470 - 523	5
H27 ^{NP}	1367 - 1370	2.4	10.1	85	0.61	0.67	0.24	0.27	340 - 465	12
H39 ^P									804 - 810	100

^P Producer well; ^{NP} Non-producer well

Although, circulation losses are only a qualitative indication of permeability it can be seen that low values of circulation losses, were observed in the studied wells, except Well H39 with 100 m³/h of circulation loss at 2000 m depth.

4.2 Analysis Sequence for Producing Wells

From measurements of production parameters (pressure, temperature, mass flow rate) at wellhead conditions, and by using simulation

program, values at bottom-hole conditions were calculated, using WELLFLO program [29]. The parameters behavior through the wells operative life is shown in Figs. 6 to 8 using Molliere diagrams. In order to show clear tendency in behaviors, neighbor pairs of wells (H1, H6) (H7, H19) and (H12, H39) were selected.

Additionally, the steam fraction behaviors for each producing well analyzed, were calculated and the results are shown in Fig. 9.

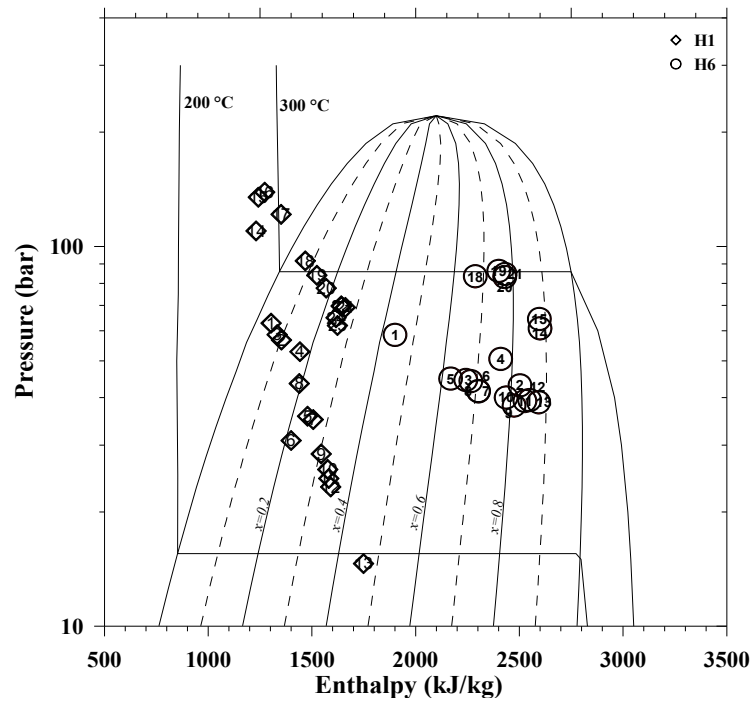


Fig. 6. Enthalpy-pressure behavior at bottom conditions of wells H1 and H6 showing their evolution along their operative life

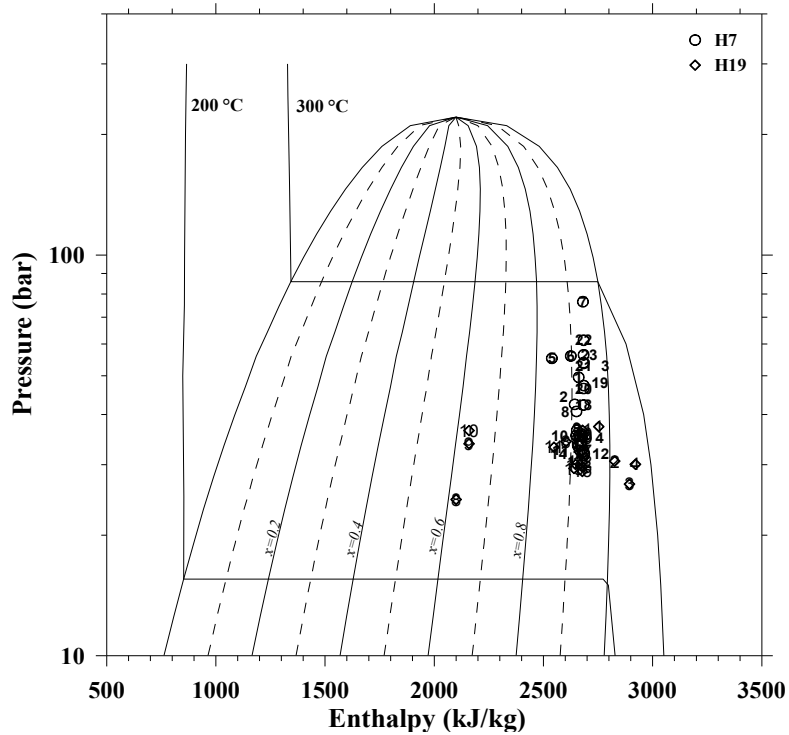


Fig. 7. Enthalpy-pressure behavior at bottom conditions of wells H7 and H19 showing their evolution along their operative life

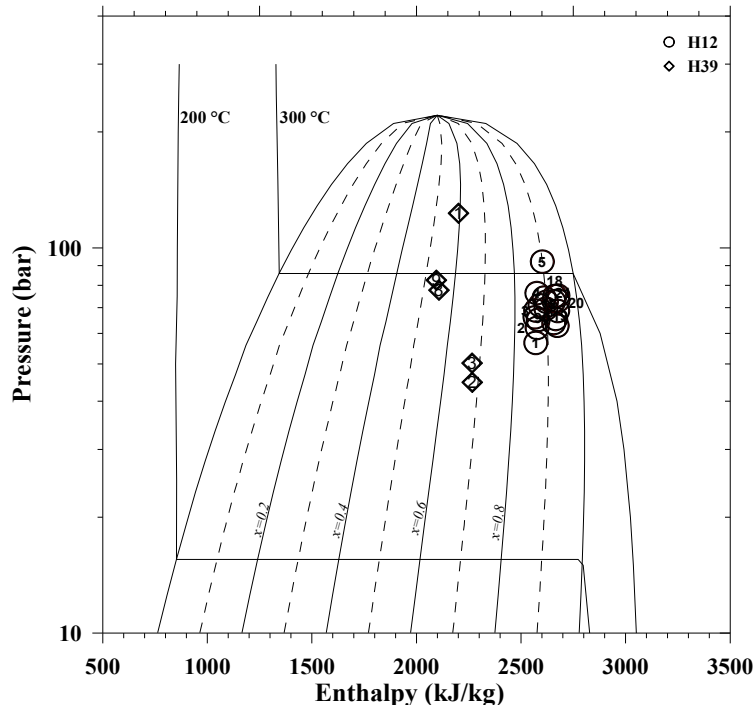


Fig. 8. Enthalpy-pressure behavior at bottom conditions of wells H12 and H39 showing their evolution along their operative life

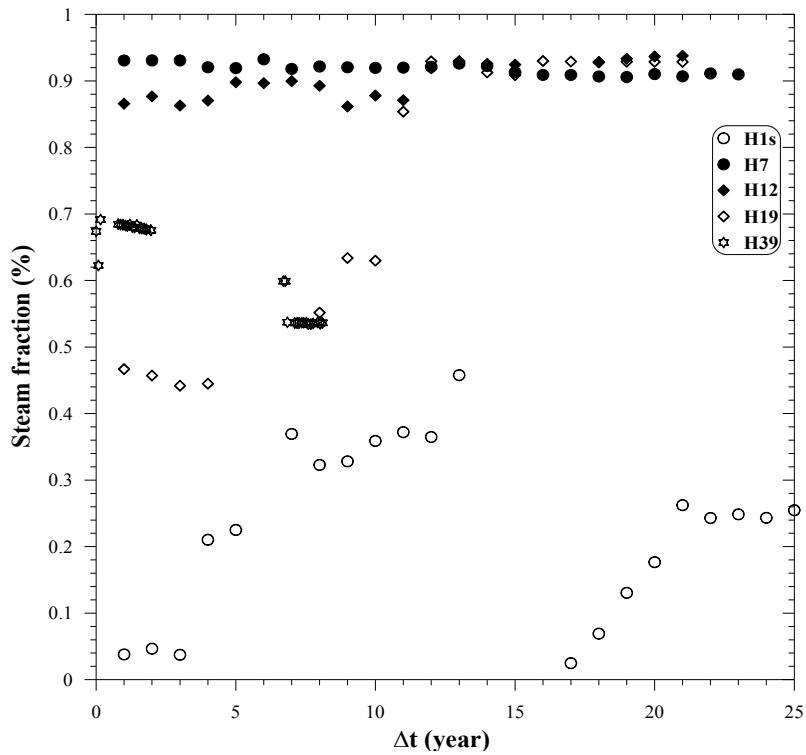


Fig. 9. Behavior of steam fraction at bottom conditions of analyzed wells during their operative life

5. ANALYSIS AND DISCUSSION OF RESULTS

The wells of the field show two zones of circulation losses, one shallower and other one at depth. This last coincides with production zone in the producer wells. The shallower zone of circulation losses in wells does not have any relation with deep geothermal reservoir, due to its thermodynamic behavior.

Using information from pressure logs profiles (Figs. 3 and 5), the bottom pressure at static conditions and location of water static level in each well was determined. A summary of the main parameters (water static level, bottom hole temperatures, feed interval, thicknesses) of both type of wells (producers and non-producers), are shown in Table 5. An interesting approach of this study is that as can be seen in Fig. 1 producing wells are located at west and south west side, while non-producer wells are grouped to eastern section of LHGF. As mentioned before, the LHGF is nested in volcanic rock where the fractures mainly control underground flow, i.e. the major influence is due to permeability, because porosity is too poor or null. Therefore toward the eastern side of LHGF the wells are non producer due to low permeability and that the temperature was measured at more depths as can be seen in same Table 5. However the interest interval, for heat storage, represents the result that relate temperatures up to 200°C with the existence of at least a little of circulation losses (5 m³/h). Thicknesses of rock formation were determined considering temperatures between 200°C, and 300°C, or until its total depth was achieved.

In this analysis, a methodology considering parameters related with production in geothermal reservoirs, such as permeability, temperature and pressure, was planned and applied. In non-producer wells, only drilling data could be useful, but information recovered from producer wells such as mass flow, quality of the produced mass, pressure, enthalpy and its behavior etc., among others are of great importance.

5.1 Permeability and Circulation Losses

In this study, the circulation losses in the rock characteristics were assumed as qualitative. However, it is important to emphasize that circulation losses do not replace permeability data obtained from laboratory measurements or transient pressure tests. During drilling,

circulation losses can be used as indicators to determine the possible drilling stoppage and carry out transient pressure tests and thermodynamic measurements. During drilling, normally great circulation losses at shallow depths in most of wells of LHGF have been detected nevertheless, these do not have relation with geothermal reservoir. This shallow zone of circulation losses (in some cases up to the 50 m³/h) is located between 2770 and 2800 masl.

A significant remark is that except in the Well H39, at deep, the circulation losses in most wells of LHGF, are lesser than 50 m³/h. The circulation losses in producer wells involved in this work can be considered in two average horizons: 1450 masl (H1 and H12) and 800 masl (H6, H7, H19 and H39). The low circulation losses are as a result of the low permeability of the rock formation.

Permeability values obtained in core samples by [7] vary between 0.98E⁻¹⁵ to 1.8E⁻¹² m². The mean values of capacity index (kh) determined from transient pressure tests are in the range of 0.15 to 0.52 (E⁻¹²) m³ [8]. Capacity indices determined from transient pressure tests carried out after thermal stimulation in some of the wells of LHGF vary between 1.2 to 3.1 (E⁻¹²) m³ [9]. At deep, the interval permeable is short in wells H1, H12 and H39; a little high in H6 and H19 and higher in H7. In non-producer wells, the deep zones showing some circulation losses are of average lengths of 350 m, except H25 (averaging 25 m).

The rock formation properties are the backing for any reservoir because it facilitates the inlet of fluid recharge which is useful for maintaining its useful life. But entry of fluid is only possible through permeability existence. The low permeability detected in these wells impacts on the appropriate conditions for the flow in the reservoir besides the absence of recharge.

5.2 Temperatures

Thermodynamic parameters are useful tools for understanding behavior of a geothermal zone and in this study the static temperatures at bottom of the studied wells were determined. The mean static temperature of wells located in the neighboring zones of non-producer wells is 320°C (H1, H7 and H19). The mean static temperature of wells located to south side (H6, H12 and H39) of this same zone is 333°C. However, in respect of the non-producing wells

Table 5. Determined parameters in the producing and in non-producing wells in the studied zone of LHGF

Producer wells				
	Static level(masl)	Bottom hole temperature(°C)	Feed interval (masl)	Thickness (m)
H1	2592	320	1400 - 1630	230
H6	2586	360	495 - 1395	900
H7	2506	320	510 - 1720	1210
H12	2619	330	1390 - 1600	210
H19	2730	320	550 - 1300	750
H39	2356	310	505 - 760	255
Non producer wells				
H23	2553	290	370 - 690	320
H25	2420	265	550 - 575	25
H26	2470	360	320 - 700	380
H27	2520	280	300 - 700	400

H25 and H26 extreme limits in static temperatures of 265°C and 360°C were observed respectively. While static temperatures determined in Wells H23 and H27 are 290°C and 280°C respectively.

It can be observed that temperatures tend to be deeper toward eastern side of the LHGF. Similarly if it is assumed that the isothermal superfacies between 200°C and 300°C represent a potential zone of heat storage, it is feasible to determine useful thicknesses in the reservoir. However according to temperature behavior these thicknesses tend to be smaller at eastern side of the field. In wells located at eastern side, no were logged temperatures more than 250°C.

5.3 Pressures

The water static levels determined in producer wells are located between 2500 and 2700 masl except Well H39 (2350 masl). While in non-producer wells, these static levels are in the range of 2420 to 2550 masl. Average values of static pressures in producer wells were determined as 150 bars at 700 masl; and 180 bars at 350 masl in the zone of non-producer wells. In the 25 years continuous operation at north and west of central zone, the bottom flowing pressures decreased from initial value of 80 toward 45 bars. At the south zone, diminution in pressures from initial value 80 to 55 bars was found.

5.4 Enthalpy

Behavior of produced fluid by wells of LHGF is characterized by high enthalpy, which averages

up to 2300 kJ/kg, exceptin Wells H1/1D (1300 kJ/kg). Changes in production parameters (pressure, enthalpy, steam fraction) of wells located in the study zone, during operation stage, can be annotated as follows: At north and west of central zone (Wells H7 and H19); the average enthalpies varied from 2600 to 2800 kJ/kg, and steam fraction from 0.9, until to achieve superheat conditions. The studied wells of south zone (H6, H12 and H39) show increases in enthalpy in the range of 600 kJ/kg (from 2000 to 2600 kJ/kg), and steam fraction from 0.6 to 0.95. An important observation in this is that production parameters behavior of the Wells H1/1D along 12 operation years differs from the other field wells. Wells H1/1D indicates a decrease in its bottom pressure from 90 to 25 bars, an increase in its enthalpy from 1000 to 1300 kJ/kg, and steam fraction, and saturated liquid to 0.4.

6. CONCLUSION

A characterization methodology for geothermal reservoirs containing producing areas, neighboring to non-producing zones was designed and applied. The analysis carried out through proposed methodology application, allows us to identify characteristic behaviors of a heterogeneous system, such as LHGF. Taking into account producers and non-producers wells, the analysis methodology was carried out using measured data according to the wells type. Through applied analysis methodology, it was shown that temperature distribution in zones of a heterogeneous system can be determined. In this case, in the zone of the producer wells are

320°C and in the zone of the non-producing wells are 280°C. A practical use of methodology results is thermodynamic parameters distribution can be used to take decisions for establishing development projects for each zone. In this case, it was identified that temperatures tend to be deeper towards the eastern side of LHGF. Applied methodology allows us to identify pressure drawdown during operative stage of the field which can be used for establishing field management or expansion plans. Another practical use of characterization methodology is that it allows us to identify reservoir thickness with heat storage. In the case of LHGF, its central-eastern side combines low permeability with high temperature whose results indicate heat storage at deeper.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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