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# Identifying the Behavior of Thermodynamic Parameters Measurements in a Geothermal Reservoir

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## ABSTRACT

A study of thermodynamic (temperature, pressure) measurements logged at completion stage of wells of Los Humeros geothermal field, Mexico, were carried out. A prominent feature is that some temperature profiles show a particular behavior, in some cases with thermal regression. Because this field is located in a volcanic environment, we applied static reservoir characterization techniques to identify both the continuity of rock formation and the influence of structures on thermodynamic parameters of this reservoir. For this study, we used information obtained during the drilling and completion stages of the wells. Although the information corresponds mainly to thermodynamic measurements and transient pressure tests, these correlate with fluid circulation losses and lithological profiles. Through the processing of the thermodynamic measurements, we obtained gradient profiles of temperature and pressure. The analysis used in the completion stage allows one to determine the thermodynamic parameters of the reservoir at initial conditions and identify the thickness of the rock formation that, in some cases, could be used for exploitation. A special behavior we observed is particular trends in the profiles of the thermodynamic variables of each well after completion. Some of these peculiarities are thermal regressions with different temperature decreases, different lengths and depths. After selecting the profiles with similar behavior, we identified that these correspond to wells that group geographically by region although the lengths of the profiles and the magnitudes of temperature reduction are different. These results can be used to make decisions about the right time to carry out production tests, which are useful for determining best exploitation designs. Similarly, these thermodynamic analyses can be the technical basis for making decisions on the best depth of completion and for selecting the thickness of exploitation that assures the productivity of future wells.

## 1. INTRODUCTION

In the majority of the cases, the reservoir rocks are highly variable in their properties. The heterogeneity of reservoir matrix may be classified in two main categories. The first is the lithological heterogeneity and the second is the spatial rock variability, which is related to variation of rock properties from one point to another in space. This is due to different deposition condition and different occurrence histories related with time.

The reservoir characterization should provide the main parameters of the fluid flow modeling. Some of these parameters are the rock and reservoir fluid properties such as, porosity, permeability density, viscosity, pressure, temperature, chemical composition among others. Besides it is important to take into account the same variation of them through the reservoir.

Thermodynamic parameters of the reservoir are useful technical tool for its characterization however as mentioned before, must be correlated with all available information for describing it properly.

During drilling are monitored continuously the circulation losses, these data are useful for construction of losses profiles, which are used for identify, at least qualitatively, permeable intervals along the well. Even though "circulation losses" is a known expression during drilling stage, this term is used for indicating the difference between fluid volume injected and the recovered at each depth. Besides, along the drilling stage, different depths are scheduled for logging profiles of temperature and pressure. Through the use of temperature logs at different depths and different stabilization times and applying different analysis techniques were determined the profiles of static temperatures (Garcia-Gutiérrez et al., 2002; Arellano et al., 2003) in the well.

Similarly is not easy to have all indicators for taking decision about the best depth for well completion. An optimal thickness found in the well is that which, combines permeability with thermodynamic conditions for fluid boiling. It is important to emphasize that circulation losses are only a qualitative indication of permeability whose thickness is determined from transient pressure tests. However during drilling operation the only qualitative indicator for permeability existence in the rock formation is the circulation losses record. So, combining thickness existence with fluid losses and high temperature, it is possible take decision for drilling stop, and for carrying out transient pressure tests which help to decide its best well completion thickness.

The pressure logs are used for determining the static level in the well, the reservoir pressure and static pressure, after transient effects have disappeared. The aim of this study is to achieve a characterization about the different conditions of temperature, pressure, permeable intervals in studied zone for understanding its behavior in order to expand applicability of this methodology to fields with similar behavior. Due to in this study zone exist producer and non-producer wells, were used dynamic and static data for producers, while for non-producer wells only were used data recovered during drilling stage.

Parameters are logged since the well drilling stage and are useful for defining appropriate its completion and mechanical design for its production pipes. Each detail during this stage is very important for achieving successful in the well; by this reason next list enunciates but not restricted any other subject-matter which would help a good well completion.

- Drilling speeds.
- The inlet and outlet temperatures of the drilling fluids.
- Chemical sampling of fluids and gases that come out with the circulation of the drilling fluid.
- Sampling (meter by meter) of the perforation cuttings for further analysis.
- Mineralogical control.
- Lithology control of the well (each meter), for the construction of its column.
- Record of circulation losses of drilling fluids.
- Temperature and pressure profiles, logged approximately every 400 meters, using resting times series of 0, 6, 12, 18, 24 and 30 hours. The objective is to determine the profiles in undisturbed state and the static pressures and temperatures to be used in the numerical models of the reservoir.
- Injection tests when the target depth is reached in the well, to analyze them by means of pressure transient techniques and determine the petrophysical characteristics of the reservoir area.
- If the well presents thermodynamic characteristics of production, enable it with its surface facilities, valves, pipes, silencer, measuring instruments (manometers, thermometers, and sampling holes) to make a discharge test to different openings and develop the initial characteristic curve of the well production.
- During the production test, take samples of the fluid produced at each orifice change, for its chemical characterization.

Between all of these parameters the thermodynamic measurements play a main role. Temperature and pressure measurements are conducted during the wells drilling and are used for determining its profiles distribution along their depth.

The series of pressure-temperature logs, together with all the parameters that have been determined allow identifying the characteristics of the well to make an appropriate definition on its best range thickness for exploitation. .After the well drilling reaches the intervals of interest, transient pressure tests are carried out.

## 2. THEORETICAL BACKGROUND

In geothermal energy, sufficient reservoir permeability is essential for exploiting heat resources. Reliable prediction of permeability and in consequence flow rate in a deep geothermal reservoir is difficult because subsurface data frequently are limited. Since fracture density often increases around fault zones, fault-related reservoirs have become prime targets for exploration (Bauer J., 2018).
The temperature and pressure are measured once the well has been closed for some time and these measurements show the natural state of the system which is close to equilibrium. The length of this process varies and the determination of the initial state often requires some interpretation. The water temperature at equilibrium correlates with the temperature in the rock and the temperature process that is determined is therefore called the rock temperature profile.

Each drilling stop at different depth in wells is used for taking measurements temperature along their depth with 6, 12, 18, 24, 30 and 36 hours of standby. Using these data and applying Horner method, static temperature is calculated for each drilling stop. The profile of static temperatures of each well was determined using linear interpolation between depths of those calculated values. A combined analysis of temperatures, pressures and rock properties, gives an approach about heat and thermal energy stored. In this work were used depths of isotherms of 200 and 300 °C for estimating a thickness in each well. This thickness is useful for determining the capability of thermal energy in the studied zone mainly where in the non-producer wells are located.

The disturbance on the temperature of the rock formation around the wellbore produced by the drilling process has been analyzed by different authors (Jaeger, 1961; Bodner and Sharp, 1988; Horne, 1995; Eppelbaum et al., 1996; Kutazov, 1999; Verma et al., 2006: Cermak et al., 2008, among others). Changes in temperature are affected by several parameters and technical practices such as the duration of drilling fluid circulation, the temperature differences between the rock formation and the drilling fluid, thermal diffusivity of formations and drilling techniques.

Ordinarily the different static temperature determinations assume that the difference in thermal properties between the drilling mud and rock formation is negligible. Although this would be a conventional assumption even for interpreting bottom hole temperature surveys, when the circulation periods are small the different methodologies should be used with caution.

The lithological profile of the well is needed because each sample recovered during drilling is used for thermal conductivity coefficient determination according to rock formation type. Sometimes, the heterogeneity of the rock signifies the possibility of finding thin vertical barriers that may or may not extend across the field. The temperature gradient can be determined directly from measured data and are useful for identifying open thickness to rock formation. The pressure gradient can be determined similarly and through temperature correlation is used for calculating fluid density at each depth interval. Pressure data can provide information about reservoir continuity and during reinjection operation on the effectiveness of this program. When such pressures are plotted as profiles for well-to-well comparison, one striking feature that could emerge is the great variation in pressures, both laterally and vertically (Bayoumi et al., 2017). This fact could be correlated to existence of different hydraulic systems, provoked by the structures of rock formation. However in formations that appear to be discontinuous, pressure uniformity suggests that the reservoirs are, in fact, continuous or connected. Characterization for geothermal reservoirs with high temperature is a special matter due its thermodynamic behavior, in this sense Abidin et al. (2009) and Mines (2016), developed methodologies for evaluation rock of a high-temperature reservoir (HTR). Other studies such as of Shook (1999; 2001) at The Geysers, California, are focused to distinguish the difference between a normal vapor-dominated reservoir and the high-temperature conditions found below it. Studies carried out by Huang et al. (2015) on geothermal zones of high temperature and low permeability indicates large heat transfer areas between the flowing fluid and the surrounding formation.

## 3. FIELD ANALYSIS

This analysis methodology was applied using thermodynamic measurements in wells of Los Humeros geothermal field (LHGF) which show particular characteristic due that is nested in volcanic system. This is the reason for the anisotropic behavior of the rock formation shown through behavior of field wells. The LHGF is the third producer field in México, after Cerro Prieto (570 MWe) and Los Azufres (220 MWe), (Gutiérrez-Negrín L. 2019). It is located at the border between the states of Puebla and Veracruz at central-eastern México (Figure 1) at about 220 km to east of México City. The field is inside the Los Humeros volcanic caldera which lies at the eastern end of the Mexican Volcanic Belt (Ferriz and Mahood, 1984).

A map of LHGF location with their drilled wells and the main structures is shown in the same Figure 1. Through application of the analysis of thermodynamic characteristics behaviors after well completion, were identified particular behavior in each well profiles. However after selection of profiles with similar trend, it was found that these, are related with each well location. These results can be used for taking decisions for determining the appropriate time for carrying out production tests.

Some of the logged parameters during drilling stages of the well are summarized in a representative graph, similar to that shown in Figure 2. From this graph the technical staff can be see correlation between thermodynamic properties, lithology, rock properties and mechanical well completion, which is useful for taking decisions on its behavior.

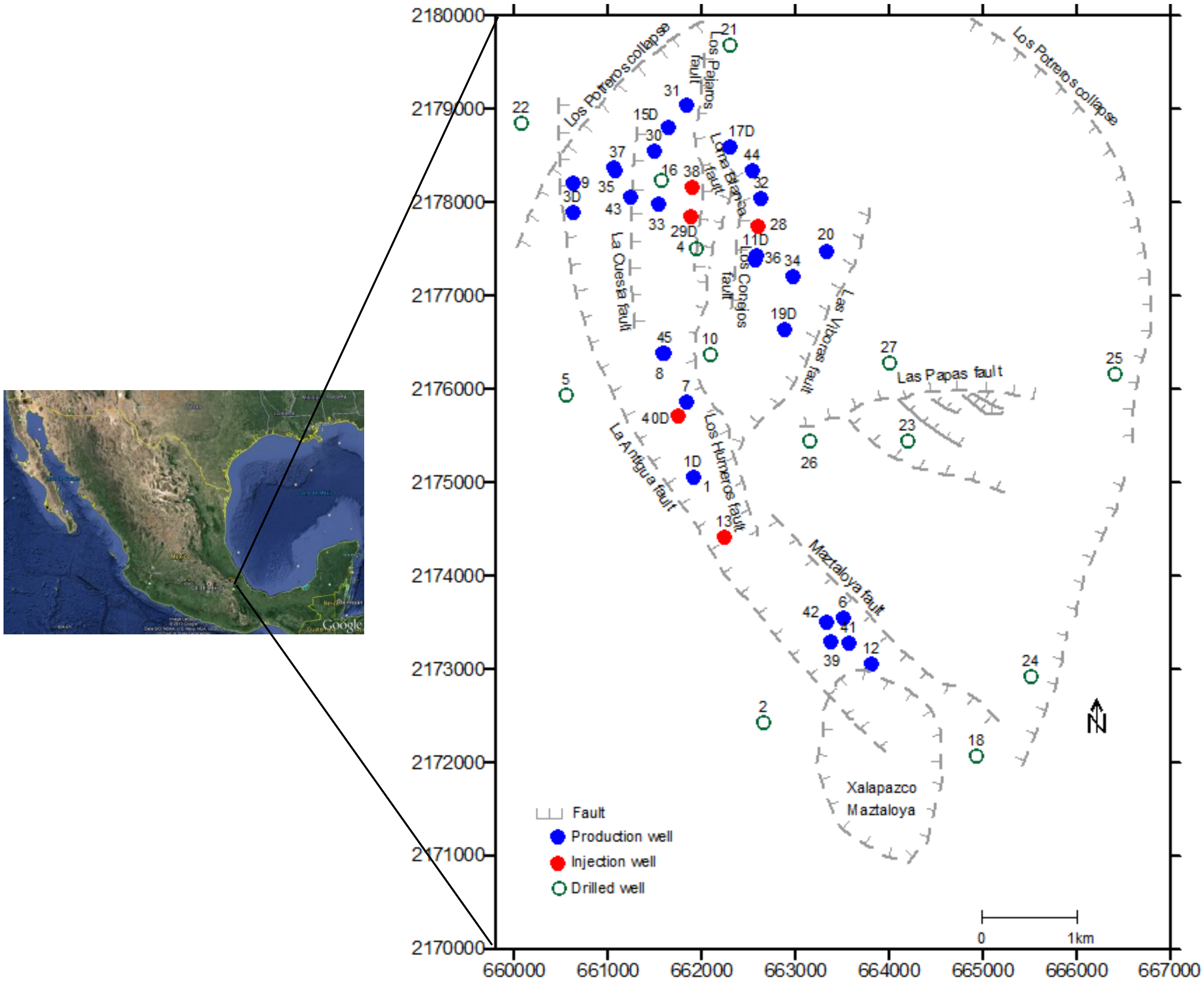

**Figure 1: Map of LHGF location with drilled wells and main structures.**

The measured temperature and pressure once the well has been closed for some time after its completion could be correlated to natural state of the system and be considered close to equilibrium. The length of this process varies and the determination of the initial state often requires some interpretation because does not could be possible to carry out the thermodynamic measurements. The water temperature at equilibrium correlates with the temperature in the rock and the temperature process that is determined is therefore called the rock temperature profile.

Detailed reservoir information is essential to the reservoir engineer in order to analyze the current behavior and future performance of the reservoir. Pressure transient testing is designed to provide the engineer with a quantitative analysis of the reservoir properties. A transient test is essentially conducted by creating a pressure disturbance in the reservoir and recording the pressure response at the wellbore, i.e., bottom-hole flowing pressure $p_{wf}$, as a function of time.

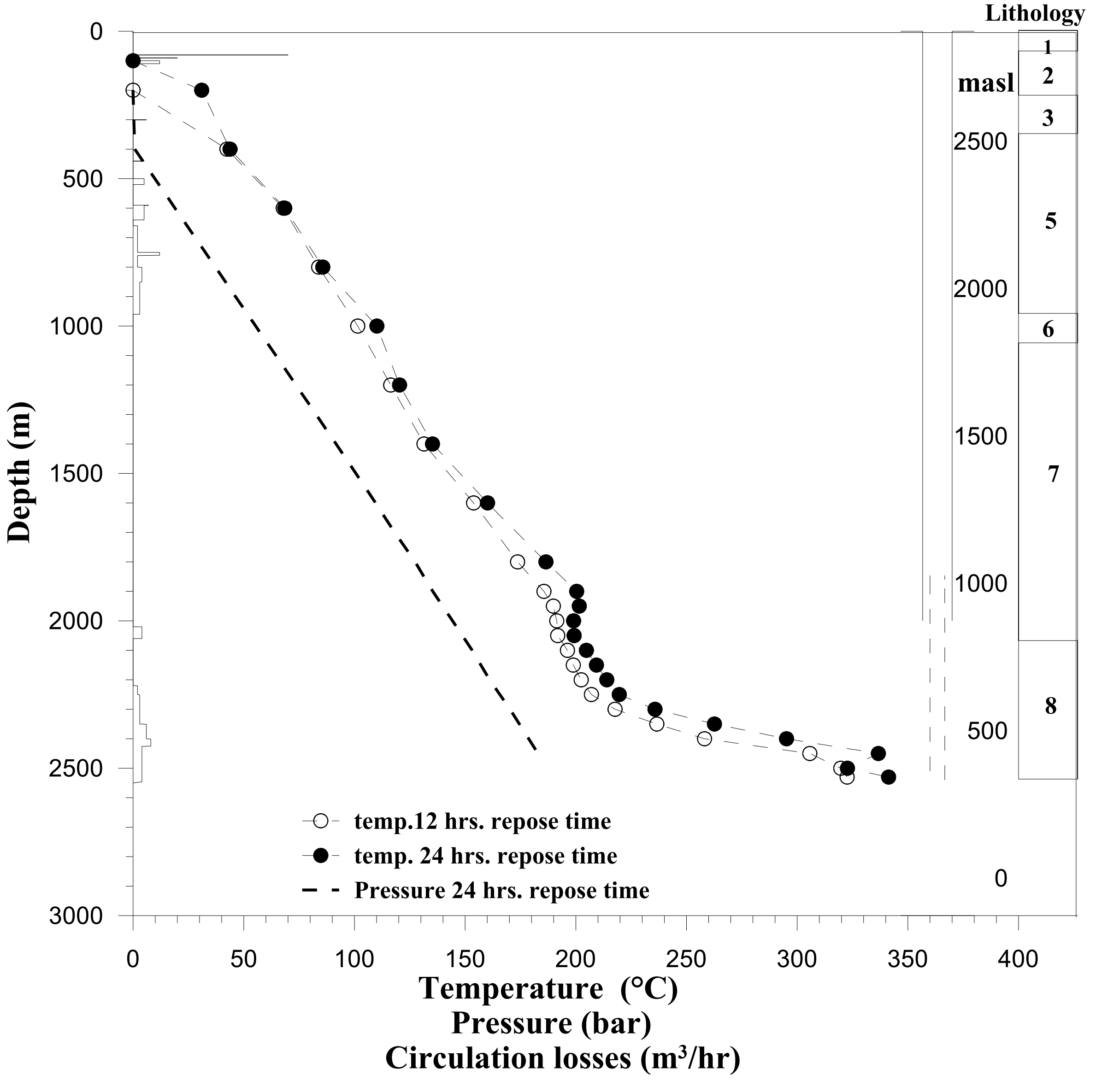

**Figure 2: Correlation of different well information, recovered during its drilling and completion stage.**

Description of the lithologic units found during drilling of LHGF wells, are as following (Viggiano and Robles, 1988; Cedillo, 2000):
Lihologic Unit 1: Pumices, basalts, andesites, rhyolites
Lihologic Unit 2: Lithic tuffs.
Lihologic Unit 3: Vitreous ignimbrites
Lihologic Unit 4: Andesites and ignimbrites
Lihologic Unit 5: Augiteandesites
Lihologic Unit 6: Vitreous tuffs
Lihologic Unit 7: Hornblende andesites
Lihologic Unit 8: Basalts

In some of the wells, were found at depth: Intrusives (granite, granodiorite and tonalite) and metamorphic rocks (marble, skarn, hornfels).

Thermodynamic measurements (temperature, pressure) mainly carried out during drilling completion stage were used for correlation analysis. From measured parameters, its corresponding gradients along the well profiles were determined. Besides these analyses the whole correlation involves the circulation losses during drilling and, lithology identification. Even though the static temperature calculations allows identify temperatures near to undisturbed state, in this work were used temperature measurements at well completion stage. Used measurements correspond to logging series carried out with 6, 12, 18, 24 and 30 hours of repose time which are used for applying the different methods of static temperatures. However in some cases logging of 30 hours did not developed due to technical decisions of field operators. Therefore it had been taken care for using measurements with same repose time in wells; in this case it was observed that loggings of 24 hours are common.

The advantage for using measurements with these repose times is due that can be identified the thermodynamic behavior of the well along its profile and the influence of different formation strata. This analysis technique is applicable to profiles both temperature, pressure and their respective gradients, besides allows identify feed zones and is useful for defining exploitation thickness.

The first approach for a general diagnosis involves develop a graph of temperature profiles logged with same repose time in the wells. Analysis was focused according to each zone of LHGF and the north zone is the major density of drilled wells, so, graphs of Figures 3, 4 and 5 show temperature profiles of such wells. Wells numeration corresponds to its order of drilling; by this reason in Figure 3 appear temperature profiles of the more ancient wells and in Figures4and 5, of the more recent wells. Same graphs were carried out with pressure profiles logged at same repose time. The obtained results show disordered profiles distribution of such parameters. While some wells show temperature regression along its profiles, some others show conductive behavior and others definitely show profiles with temperatures less than 200 °C.

As a first analysis it was identified that some of the wells show temperature regressions along their profiles. While that wells with temperatures less than 200 °C, were correlated with those located at the boundary of geothermal zone. However, in spite of showed disorder in graphs it was possible to identify some tendency in profiles of some of the wells. From this manner, were identified that from Figure 3 profiles of wells H3, H9 and H22 show particular trend. Under this observation were grouped temperature profiles according to each particular trend and was constructed Figure 6, which shows temperature profiles of wells with similar trends mainly related to thermal regression at identical depths.

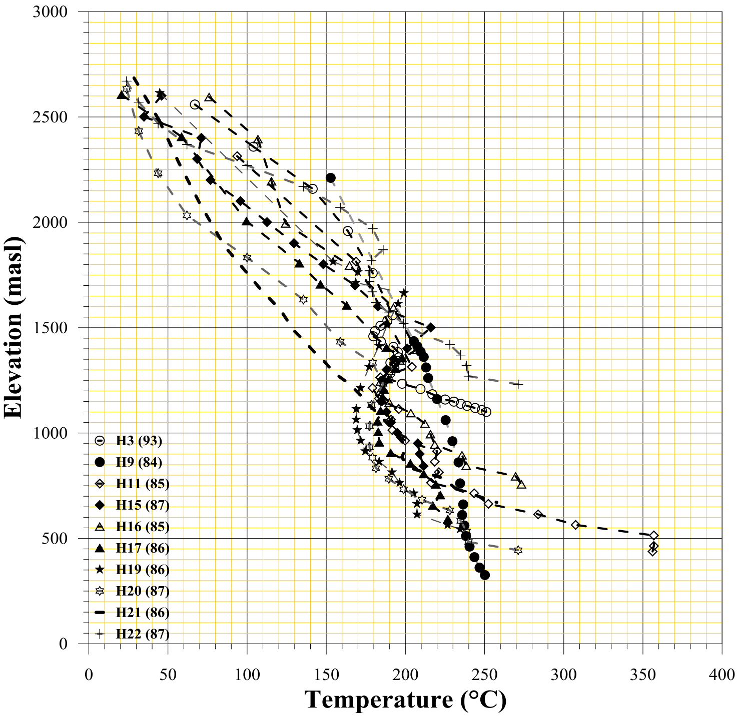

**Figure 3: Temperature profile of north zone wells of LHGF, drilled at initial stage of life field (1984-1987).**

In this study were classified three main blocks at north zone (western, central and eastern) of LHGF. A clearly behavior of compartmented case is that of wells located between “Caiman” and “Nueva” faults (wells H11, H17, H19 and H21) which, except H21 show similar trend in temperature profiles. Well H21 is located at north of "Colapso Central" and this would be the reason for its different, temperature profile, respect to others of this sector, the matter is that its temperature profiles, does not show any thermal regression. Besides, according to all the characteristics shown by the well H21 leads to assume that is out of the geothermal reservoir. It can be seen similarity of temperature profiles with thermal regression, and their relative level where it occurs, shown in Figure 6.

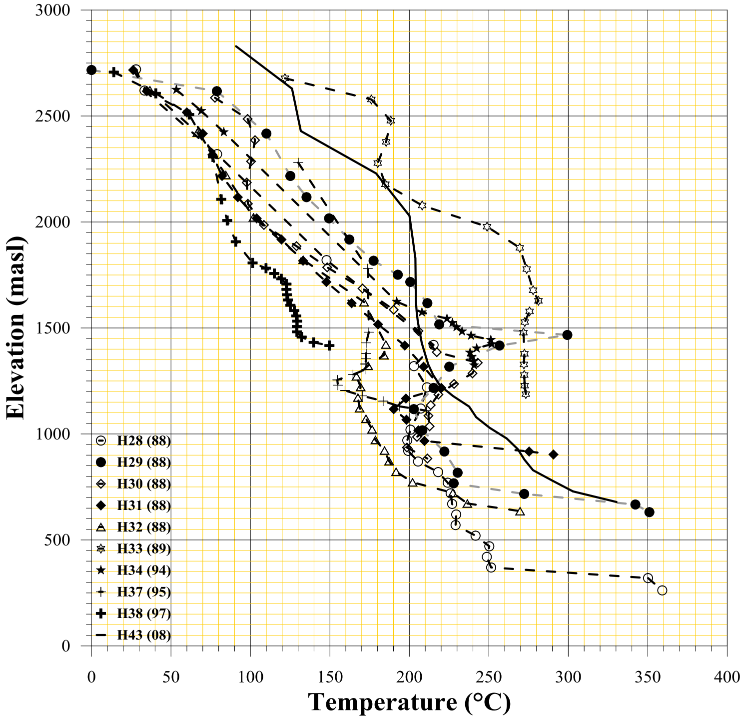

Figure 4: Temperature profile of north zone wells of LHGF, drilled at intermediate time, of the field life (1988-1997).

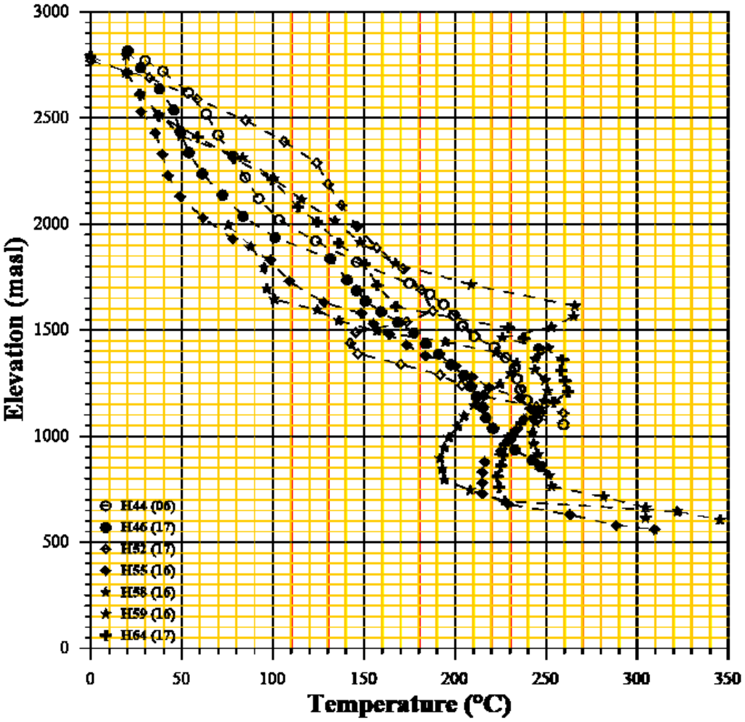

Figure 5: Temperature profiles of wells located at north zone of LHGF which were drilled between 2016 and 2017.

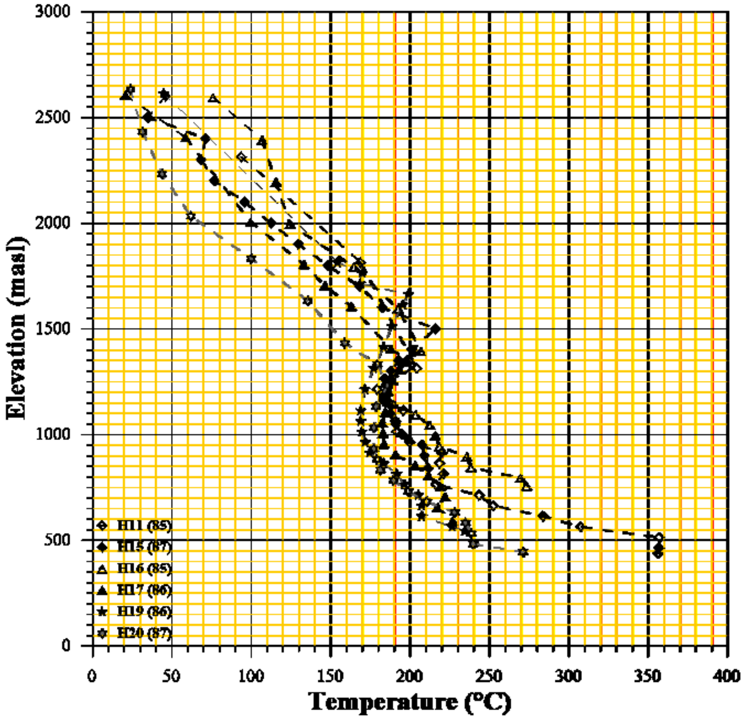

**Figure 6: Graph showing similar trends in thermal regression at similar depth levels of drilled wells of north zone at initial stage of LHGF life.**

However, as an example of different thermal procedure, were extracted those temperature profiles that no agree with general behavior of the wells. In this way, in Figure 7, temperature profiles of wells H3, H9, H21 and H22 which do not indicate any possible correlation with the another wells, are shown. It can be seen that temperature profile of well H3 shows two intervals of temperature regression with lengths no more than 100 meters at upper levels than of wells generality.

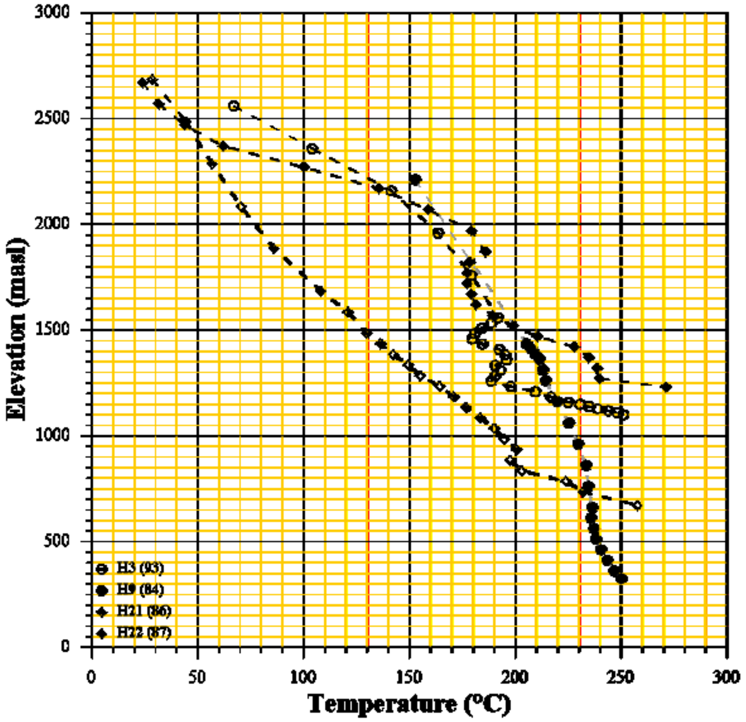

**Figure 7: Graph showing temperature profiles of LHGF north zone wells, drilled at initial stage, whose behavior differs from those which show temperature regression at similar levels depth.**

In similar way to temperature analysis, also were analyzed pressure profiles, taking into account the drilling order, were grouped the wells in north zone of LHGF according to their drilling year. Through simple analysis of wells graph which were drilled at initial stage of field, Figure 8 shows pressure profiles of wells H3, H9, H11, H15, H16 and H17. From this, it can be seen that excepting wells H9 and H16, all of them coincide to about same point of static level. Behavior of well H16 is related with a heating early because at depth the slope of the pressure line decreases, i.e. fluid density is lesser than of a water column with temperature still without heating. In the case of well H9, as can be seen in Figure 8, it can be identified that it has a light interval feed between 500 and 650 masl and other between 1750 and 1850 masl.In order to identify pressure profiles behavior and corresponding static levels location were combined measurements of wells drilled at initial stage and those after ten years, whose graphs are shown in Figure 9.In both cases can be identified that static level is located in the order of 2600 masl. The keep up of static level can be explained due to field continuous exploitation started at about middle of the analysis period and would be consider that still there is not highlight drawdown.

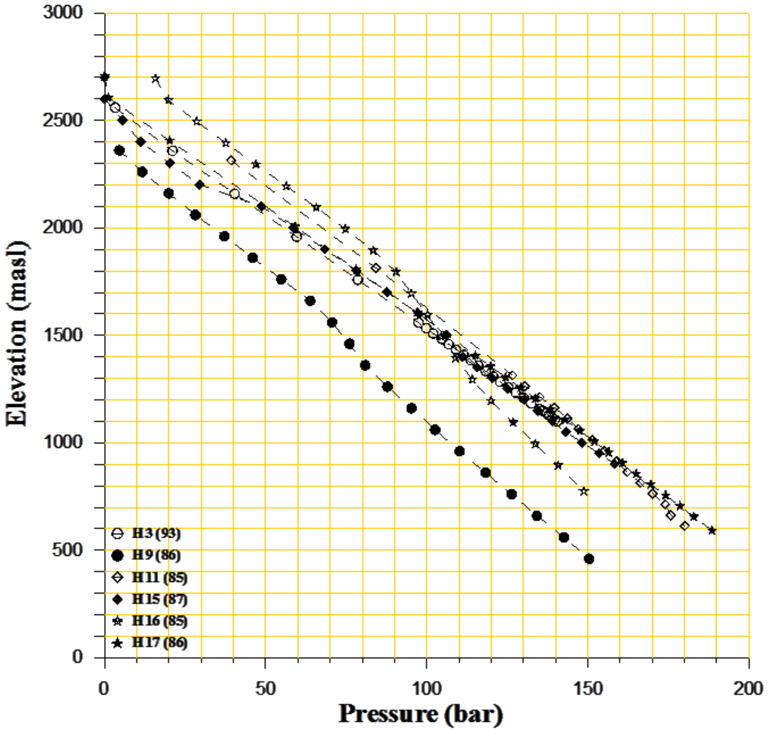

**Figure 8: Measurements pressure taken in wells drilled at initial stage of LHGF life, showing in the majority (excepting wells H3 and H9) the same trend of static level location.**

During production stage is not easy to carry out thermodynamic measurements because the difficult for introducing logging tools in the well due to mass flow rate. The alternative for knowing bottomhole conditions is to use wellhead measurements and then through a wellbore simulator program can be calculated bottomhole parameters values. Under this technique it can be analyzed thermodynamic evolution of wells during exploitation stage and so, in this work examples of obtained results in two of the LHGF wells are shown. Well H1 is located at central zone of LHGF and another; well H6 is at south zone of the field and flow simulation results are shown in a Mollier´s diagram of Figure 10.

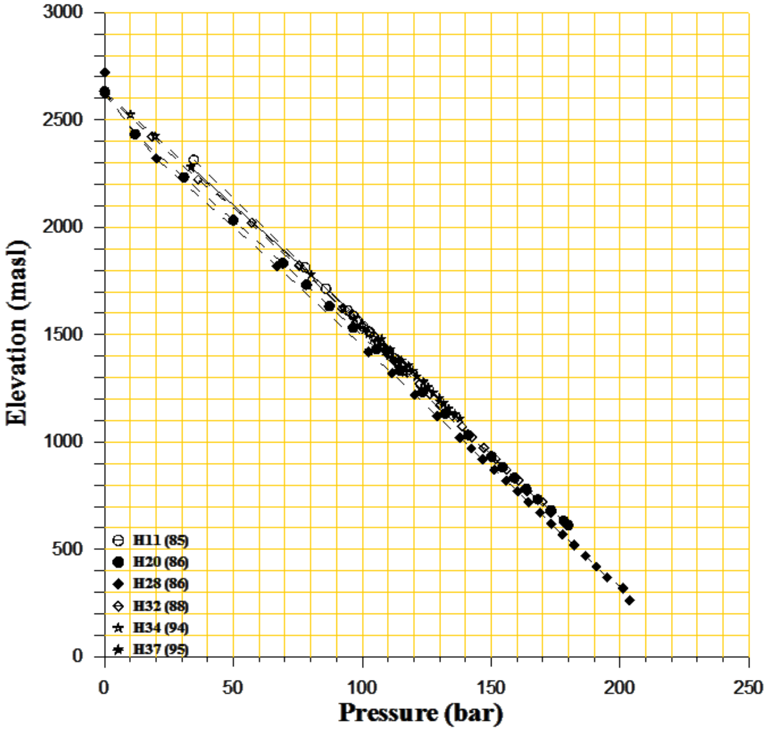

**Figure 9: Wells pressure measurements, combining stage of its drilling, both at initial stage and after ten years of LHGF life, which show in the majority (excepting wells H3 and H9) the same trend of static level location.**

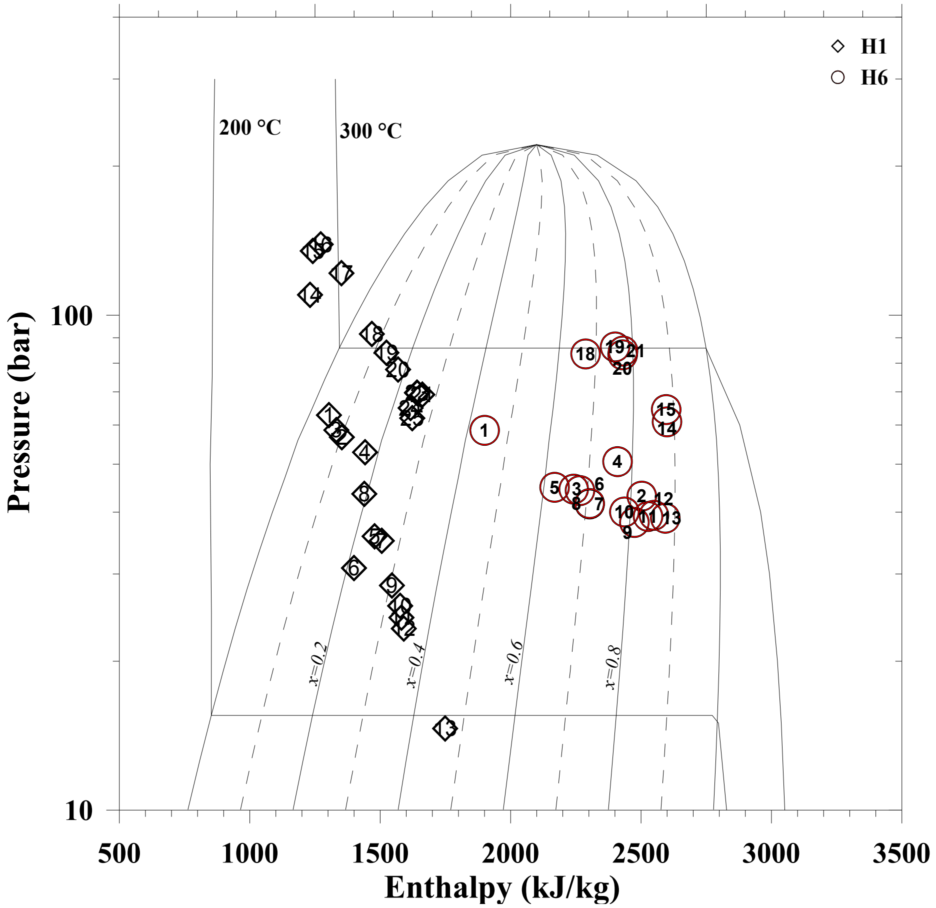

**Figure 10: Enthalpy-pressure-temperature behavior at bottom conditions of wells H1 and H6 showing their evolution along their operative life.**

From Mollier diagram of last figure, it can be seen that while well H1 in its two production stages show a quick decrease in temperature and pressure, its enthalpy increases slightly. Even though, enthalpy increases in this well, steam fraction of produced mass remained in no more than 0.4 in quality. By other hand, well H6, respect well H1, shows less decrease in both pressure and temperature, with a slightly enthalpy increase. Steam quality fraction of well H6 varies along its operative life from 0.65 to 0.9.

## 4. DISCUSSION

It is important to emphasize that circulation losses do not replace permeability data obtained from laboratory measurements or transient pressure tests. The low circulation losses are a consequence the low permeability of the rock formation. Permeability values obtained in core samples by Contreras et al., (1990) vary between 0.98E-15 to 1.8E-12 $m^2$. The mean values of capacity index (kh) determined from transient pressure tests are in the rank of 0.15 to 0.52 (E-12) $m^3$ (Torres, 1995). 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) $m^3$ (Sánchez-Luviano et al., 2015). Even though circulation losses at shallow depths are representatives of good permeability, at bottom did not logged. However it is feasible to identify that feed zone can be correlated with lithologic unit 7.

It was taken special care for using measurements logged at similar period times before the field would starts its dynamic state due to exploitation stage. By this way, from temperature logs profiles of wells H11, H15, H16, H17, H19 and H20 shown in Figure 6, it can be identified thermal decrease at similar depths, between 1250 and 1500 masl. Besides, taking into account that thickness between 200 and 300 °C represent a potential zone of heat storage, it is an indicative feasibility for determining useful thicknesses for exploitation in the reservoir. However according to behavior of analysis carried out these thicknesses tend to be smaller at eastern side of the field, besides, in wells located at this section, no were logged temperatures more than 250 °C.

Through simple analysis of wells graph which were drilled at initial stage of field, Figure 8 shows pressure profiles of wells H3, H9, H11, H15, H16 and H17. From this figure, it can be seen that excepting wells H9 and H16, all of them coincide to about same point of static level. Behavior of well H16 is related with a heating early because at depth the slope of the pressure line decreases, i.e. fluid density is lesser than of a water column with temperature still without heating. In the case of well H9, as can be seen in Figure 7, it can be identified that it has a light interval feed between 500 and 650 masl and other between 1750 and 1850 masl.

The water static levels determined in the majority of the producer wells were located between 2600 and 2650 masl except Well H39 (2350 masl). While in non-producer wells these static levels are in the rank from 2420 to 2550 masl. Average values of static pressures in producer wells were determined in 150 bars at 700 masl; and 180 bars at 350 masl.

The field heterogeneity highlights similarly in characteristics of production performance, showing differences in thermodynamic behavior of wells belonging to same field. According to shown analysis example, it is clear that while the well H1 in a field zone behaves with steam fraction less than 0.5, other one well, trend to high quality steam fraction. Besides, it would seem that production parameters in the well H1 zone decrease with magnitude major than in the zone where is located the well H6.

## 5. CONCLUSIONS

From records of fluid circulation losses during drilling of these wells, at shallow depths, only were found that fluctuating in the order of 50 $m^3$/h of lost fluid.

The analysis carried out in studied zones of LHGF need to be ordered according to heterogeneity in wells behavior. This heterogeneity leads to identify, through behavior of some wells the presence of compartments, due to recovered data show that two wells located too close at minor distance of their drainage radii, have different characteristics.

Through results correlation of temperature static calculated in Los Humeros wells, it was found that at east zone of LHGF temperatures are deeper.

Through methodology of static characterization, of thermodynamic parameters, used in LHGF it can be identified, reservoir initial conditions which can be assumed as reference level, before its evolution starting due to continuous exploitation stage.

The use of thermodynamic analysis is a technical useful tool for defining with more certainty exploitation thickness in future new drillings.

From the analysis carried out it can be determined for LHGF, water static levels, bottom hole temperatures and pressures, feed intervals and thicknesses of formation.

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