***Method Article***

# Thermal Behavior Analysis of Geothermal Systems under the Influence of Rock-Formation Structures

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## ABSTRACT

As part of the reservoir static characterization technique, behavior analyses of some of the obtained variables during the drilling and completion stages of wells of the Los Humeros Geothermal field (LHGF) are shown. It was used information obtained during both, the drilling and completion stages of the wells. The base information used data are those from thermodynamic measurements (temperature, pressure) and fluid circulation losses profiles. The determination of reservoir thermodynamic parameters initial conditions together with the analysis used at the completion stage allows identifying the thickness of the rock formation which in some cases be used for exploitation. The anisotropy of the rock formation shown through the heterogeneous behavior of the field wells is related to its volcanic environment and structures. Through the application of the analysis of thermodynamic behavior after well completion, were identified individual behavior profiles in each of them. However, after the selection of profiles with a similar trend, it was found that these, are related to location of each well. The particular behavior of some of the LHGF wells is used to identify compartments existence in the system which influences both, rock formation continuity at depth and geological structures that impact in fluid flow and its thermodynamic parameters. The found parameters during drilling wells are the technical sustain for taking decisions on its best completion depth. This information also is useful for selecting the thickness which must be exploited, in order to assure wells productivity. Through the different analyses applied in LHGF, besides obtaining reservoir static characterization can be identified that the geological structures influence its behavior.

*Keywords: Renewable energy; geothermal systems; temperature profiles; thermodynamic behavior; geological structures; permeability; heat source.*

## 1. INTRODUCTION

Geothermal is a great renewable energy source that is continuously replenished by natural processes (heat source and water recharge). It is important to note that a geothermal resource is part of a complex geological system where some crucial parameters such as lithology, faults, fractures, stress field, diagenesis, rock mechanics and fluid chemistry play an important role. Other important parameters are the porosity and permeability domains, the fluid flow (lateral and vertical), the temperature distribution and the overall reservoir behavior during injection and production. High-temperature geothermal systems are characterized by containing energy of high-quality, and are usually located in volcanic zones, which may influence the reservoir and its geological structural features that contribute to a sustainable phase for the exploitation of these resources. A method for calculating the effective thermal conductivity of moist capillary-porous materials used in wall partitions was proposed [1, 2]. This proposed methodology was developed based on the theory of generalized conductivity and geometric modeling of the structure.

The integrated characterization of high-temperature geothermal systems is a technical term commonly used for determining reservoir initial conditions and their evolution from a life cycle perspective [3-10]. It involves static and dynamic characterizations of the geothermal reservoir under exploitation conditions. The static characterization is generally focused to identify reservoir initial conditions, which may be assumed as reference level for the future exploitation conditions. The reservoir characterization is one of the most used tasks for identifying the geometrical dimensions of a reservoir, the petro physical rock properties, the evaluation of reservoir reserves, the initial thermodynamic conditions, among others which contribute to estimate reservoir natural condition. The reservoir at initial conditions involves characteristics of its rock and fluid.

In petroleum and geothermal systems, the amount of the recoverable energy and the technique for its extraction depend primarily on the accuracy of the integrated (static and dynamic) reservoir characterization, which are usually referred as the first and second stages of the geothermal reservoir life [11]. To achieve this goal, it is necessary to determine the heat source, the petrophysical rock properties, and the hydrologic feed source with accuracy. The integrated characterization plays an important role for establishing the exploitation management programs as well as the feasible and sustainable growth of a geothermal field [12-20].

In the first stage given by the static reservoir characterization, the methodology leads to the identification of blocks, which drive to a compartmented behaviour of the reservoir. The determination of reservoir thermodynamic parameters together with the petrophysical properties of the rock by considering the initial exploitation conditions lead to define the exploitation thickness. Results of geological, geophysical and geochemical studies obtained from the exploration stage are also useful for carrying out the static characterization. The well drilling and completion is a stage that provides the opportunity for obtaining a reliable knowledge of direct reservoir properties. The drilling velocity, the fluid circulation losses, the inlet and outlet temperatures of the drilling fluid, the lithology (defined from the drilling cuttings recovered) are also used for determining the characteristics of rock-formation that are crossed by the wells [4]. Reservoir compartmentalization is primarily detected from the observation of some thermodynamic and geological properties, such as temperature, pressure, lithology discontinuities both areal and vertical distributions. Fractures and faults are common features of many reservoirs in volcanic systems. They create traps, serve as conduits of fluid flow and can behave as barriers or baffles. Naturally fractured reservoirs consist of fractures in formations and only fractures contribute to flow and storage. The rock matrix has almost zero permeability and porosity [5]. The variation of thermodynamic parameters in a geothermal reservoir can be monitored using temperature and pressure logs whose heterogeneous behavior may be originated by some geological structure barriers [6]. In some geothermal systems, the depletion and the underground crossed-flow between the well and reservoir occur due to the presence of these geological barriers which may act as semi-permeable channels that can effectively create a compartmentalized reservoir [7]. An important issue that must be considered during the well drilling stage is to have a better understanding of the initial thermodynamic state of the reservoir, which also has an important contribution to the geothermal systems. To obtain this important knowledge, thermodynamic measurements must be performed at different well depths by considering the behavior of the rock-formation during drilling. These pressure and temperature measurements are usually conducted during well completion and before the exploitation stage, and are used for identifying conditions at undisturbed state of the geothermal system [8]. Rock-core samples are also collected during the well drilling and completion for determining some petrophysical properties. The experimental determination of petrophysical properties are complex and costly lab tasks. As these core samples correspond to some strata or short sections of the lithological column, their main limitation is that cannot be used as a generalized property for the entire well. Among other technical tools available for inferring indirectly the rock properties is the well-known analysis of transient pressure tests, which are generally carried out during well drilling completion stage. All these thermodynamic and geological characteristics are integrated for validating the existence of a geothermal reservoir.

In the second stage of the reservoir life cycle, after exploitation started, the magnitude of disturbances requires to be studied as a suitable technical tool for performing the dynamic characterization of reservoirs. The performance behavior, the well productivity decline, the thermodynamic evolution, the extraction effects of the fluids, the remaining geoenergy reserves and the useful life are particularly analyzed.

In this work, the fundamental concepts of static and dynamic reservoir characterization were applied to the study of the high-temperature geothermal system of Mexico (Los Humeros geothermal field, LHGF), [21-23]. This type of geothermal reservoirs is nested in volcanic rock formation with heterogeneous geological structures, which are characterized by a low permeability and a lack of porosity. These geological volcanic structures exhibit low permeability values ranging from $10^{-20}$ to $10^{-16}$ $m^2$ [9, 10], which are significantly different to those values found in sedimentary formations (e.g., the case of Cerro Prieto geothermal field) [24]. The aim of this study is to introduce techniques helping to identify static characterization related to reservoir initial conditions which can be assumed as a reference level, before its evolution starts.

Distribution at subsurface and at deep of geological structures is one of the factors for permeability appearance in geothermal reservoirs, which majority are located in volcanic systems. Heterogeneity of volcanic systems is one of their characteristics, which does not guarantees continuity of formation strata through the reservoir, also including hydrocarbon fractured systems. In geothermal systems, tectonic of volcanic formations is characterized by absence of primary porosity and low permeability, which occurs in the fissures between the structures blocks. During drilling of geothermal wells, it has been found existence of abnormal behaviors in measured pressure and temperature, such as variation in gradients as depth function.

The correlation between wells and their pressure-temperature data together induce reliable evidence about the reservoir heterogeneity or its continuity. In some areas where lithology appears to be discontinuous, pressure uniformity distribution could suggests that the reservoir are in fact, connected. In contrast, in other areas where lithologic units can be correlated more easily, large pressure variations suggest reservoir discontinuity, or at least greatly reduced lateral permeability. The different trend of pressure data in each well could be evidence of geological structures influence on the reservoir [25].

## 2. THEORETICAL BACKGROUND

Geological structures have influence in heterogeneous behavior in rock formation and in their domain parameters. However, distribution of geological structures along the field results in compartments, some of them communicated through a permeable barrier [26, 27]. The fissures between geological structures create a permeable way which allows underground flow and helps for defining the cells in the mass conservation modelling, for each rock block component [28, 29].

It was carried out demonstration [30] that a material balance simulator can be used with pressure histories from well tests in compartmented oil reservoirs to identity geological structures. Due to geologic structures influence in underground flow these may be modeled as either sand filled, shale filled or water, bodies. Geo Scientific disciplines, allow one to quantify the effect of geological variability on future reservoir performance [31]. The understanding of geologic controls (such as structures, faults, barriers) allows identify behavior of some of the reservoir parameters [32].

Some authors [33] carried out studies using diaphragm walls as an analogy manner of geological structures and obtained that the presence of significant groundwater flow and activating the whole length of the diaphragm wall, both affect positively the thermal exchange. Moreover, the type of the considered thermal load is found to have a direct impact on the thermal performance of diaphragm walls. [34] coupled thermo-hydro-mechanical (THM) model to investigate the combined effects of thermal perturbation and in-situ stress on heat transfer in two-dimensional fractured rocks. The calculation of the effective thermal conductivity of a heterogeneous volume was performed [35, 36] using a homogenization technique, based on an energy method. This numerical model has been applied to packed beds which can be used to simulate volcanic rock formation.

Analysis of temperature and pressure behavior, within several thermodynamic parameters takes a main role in geothermal systems. Characterization methodologies are technical tools which have been applied since petroleum engineering start and; from beginning of geothermal engineering, these techniques have been adapted for be using in its different stages. Temperature behavior as one of thermodynamic parameter takes a main role in geothermal systems and the technique used in petroleum reservoirs was adapted to geothermal reservoirs. Under this way classical method of [37], is used for static temperature determination from temperature logs at different times of repose after drilling has been stopped. Characterization for geothermal reservoirs with high temperature is a special matter due its thermodynamic behavior, in this sense [38 - 40], developed methodologies for evaluation rock of a high-temperature reservoir (HTR). Other studies such as of [41, 42] 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 [43] on geothermal zones of high temperature and low permeability indicate large heat transfer areas between the flowing fluid and the surrounding formation. Phenomena associated with geothermal modeling are described by [44, 45]. Application of different conversion functions for the correction of thermal conductivity and study of the impact on the resultant temperature and heat flow prognoses for a synthetic, along 2-D geological cross sections were carried out by [46].

The main features associated to a geothermal reservoir are: a basement, a seal cap, heat source, permeability and water recharge, are described [47]. For a displacement in a hypothetical homogeneous medium, the rate of distortion and spreading is zero, however, as the heterogeneity increases, both increases [48]. The essence, of heterogeneity study is focused to identify the features that impact the system performance. The existence of faults and throws mark the difference between sealing and leaking each layer differently [16]. Heterogeneity of geothermal reservoirs is mainly due to its volcanic origin which is the cause of great variations both in physical and thermodynamic properties of the rock system [5].

Since drilling stage, the temperature distribution of fluids depends on several factors such as: depth, thermal conductivity of drilling fluid and the rock, drilling fluid flow rate, inlet temperature, and temperature gradient of rocks. Conductive heat transfer process appears in the well and can be identified along temperature logs taken at different repose time interval. Normally both conductive and convective heated reservoirs could contain hot water in liquid phase. Analysis of temperature logs to study relationship between thermal conductivity and porosity in well of Reykjavik (HS-36) was carried out by [39]. The results obtained show that thermal conductivity decreases with increasing porosity. They proposed that relationship between thermal conductivity and porosity is close to the harmonic average theoretical equation, whose expression is:

$$\frac{1}{K} = \frac{\emptyset}{K_w} + \frac{(1-\emptyset)}{K_r} \tag{1}$$

where K is thermal conductivity (W $m^{-1}$ $°C^{-1}$); $K_w$ is thermal conductivity of water and $K_r$ is thermal conductivity of rock matrix and $\phi$ is the porosity (as fraction).

To date, the commonly used temperature determination methods are down hole measurement method, simple estimation method and computer simulation method, however direct measurement represents reservoir state of best manner. The main task is to know heat transfer behavior in the rock in order to define the time at which pseudo steady state is achieved. This is useful for taking temperature measurements which could be assumed as representative of the reservoir. Even though measurements of thermodynamic parameters are carried out at different depths and different repose times, during drilling stops, in general, repose times are not enough for achieving pseudoesteady state conditions. Under this situation is that were designed predictive numerical methods. One of the most common is the line source solution known as Horner method [48]. This is a traditionally used method for static temperatures determination, based on line source concept for heat transfer extrapolation to infinite time. The representative numerical model is:

$$T_{ws} = \; T_i - m \log \frac{t_c + \Delta t}{\Delta t} \tag{2}$$

where $t_c$ is the circulation time before repose time start; $\Delta t$ [h] is the repose time; $T_{ws}$ [°C] is the well temperature at different repose times; $[(t_c + \Delta t)/\Delta t)$ is the Horner dimensionless time; $T_i$ [°C] is the static temperature of the rock formation. The methodology uses a graph of $T_{ws}$ [°C] versus $[(t_c + \Delta t)/\Delta t)]$ for obtaining a line with slope m; and ordinate to origin with $T_i$ [°C] value. However it was found this method underestimates the temperature of the rock formations for circulation times too very short [49].

By other hand an analytical method which assumes a spherical-radial conductive heat flow in the formation was developed by [40] for estimating temperature that the well would achieve at long repose time. The method assumes a conductive radial flow, i.e. the cooled formation by fluid circulation is treated as sphere of R [m] radius. The mathematical model is given as:

$$T_{ws} = T_i - \frac{m}{\sqrt{\Delta t}} \tag{3}$$

Where m is given by next expression:

$$m = \frac{R\,(T_i - T_f)}{\sqrt{\pi\alpha}} \tag{4}$$

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

Temperature and pressure logs during drilling and warming stage of Hverahlid field were analyzed by [42]. After drilling, 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 [41].

Thermodynamic gradients (pressure, temperature, fluid density) along wells profiles are some of the practical application results. Methodology for identifying thickness open to formation through the known technique as heating index was applied by [50-52]. This is the thermal gradient as time function determined from temperature measurements along each depth of well profile. In this methodology are used temperature measurements logged at two different repose time in the well after drilling job stopped. The cooldown effect provoked by drilling fluid, can be identified in the thickness with some permeability will show temperature decrease. However in those thicknesses without permeability temperature drawdowns do not appear. This technique allows identify qualitatively permeability presence. Even more, if the cooled thickness shows temperature increase with repose time, this fact could help to identify that this thickness is permeable and with heat feed. However, if its behavior does not show any temperature increase during repose time, equivalent to heating lack, then, it could be inferred that this thickness is not of geothermal characteristics.

Another qualitative evidence of permeability is the fluid circulation losses during drilling, because under its existence, the job could be stop for verifying this, through thermodynamic logs and transient pressure tests. The results analysis of these transient tests allow obtaining heating index profile, rock properties petrophysical determination as porosity ($\phi$) [dimensionless], permeability (k) [mD], drainage radius ($r_e$) [m], static pressure ($p_e$) [Bar], skin effect (s) [dimensionless]. Another method for determining petrophysical rock properties are through laboratory measurements to core samples, however these are only representatives of local thickness.

## 3. METHODOLOGY APPLIED TO A GEOTHERMAL FIELD

México contains more than 4200 thermal manifestations along its territory and to date has five geothermal fields under exploitation, four of them belonging to CFE, operated by “Gerencia de Proyectos Geotermoeléctricos” and other one, operated by Private Investor “Geodesa”. The map of Figure 1 shows general location of these geothermal fields making a close up of LHGF for highlighting its wells and the mains structures identified by geological surveys.

The LHGF is the third producer field in México, after Cerro Prieto (570 MWe) and Los Azufres (220 MWe). 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 [53]. The field is inside the Los Humeros volcanic caldera which lies at the eastern end of the Mexican Volcanic Belt [51]. LHGF is located near the limit with the Sierra Madre Occidental province, according to [54].

This field is typified as a reservoir of high enthalpy in its production, but low permeability and low mass flow production [55]. Its thermodynamic characteristics are one of the arguments to be classified as a "super hot" geothermal system. Due to be nested in volcanic rock formation, high variation in both formation characteristics and their parameters has been found. Through correlation of this whole behavior, the main presumption is focused that structures domain underground flow.

The blocks arrangement, in LHGF, influences in reservoir structure resulting in one or more compartments, however each one in communication with its neighboring, through a permeable path. Due to reservoir heterogeneity, each well has a single lithological column and this characteristic is influence factor on its behavior [19, 23]. For LHGF thermal properties were defined from the rock formation taking into account lithological Group and its identified Unit.

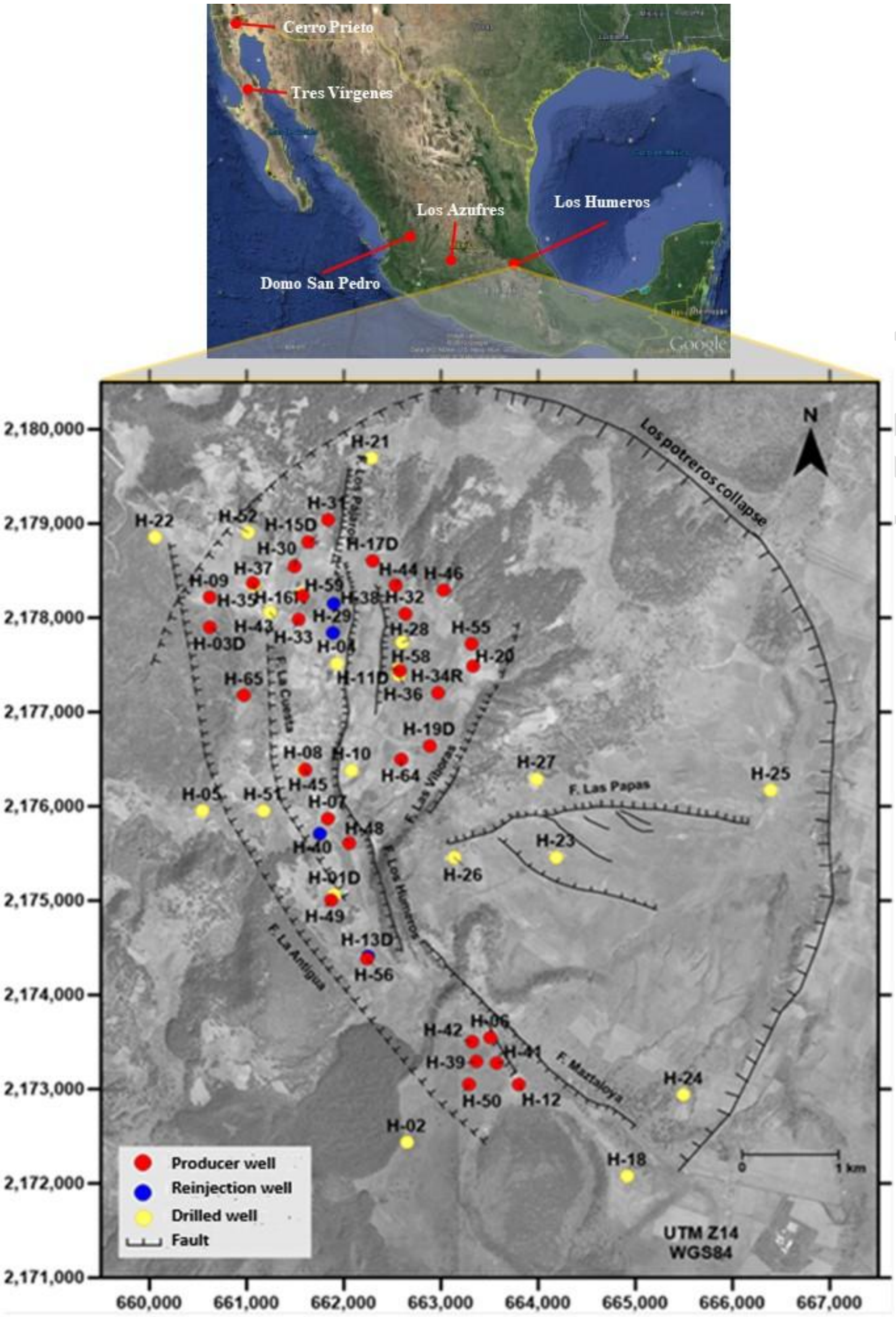

**Fig. 1. Locations of geothermal fields, to date operating in Mexican Republic, with a close-up of LHGF showing wells and the main identified geological structures.**

Different authors [44, 47] have studied and identified along LHGF development, lithological Units. However the last modification and description of lithological groups and corresponding Units was carried out by [52], which are shown in Table 1.

**Table 1. General lithological characteristics found during drilling in Los Humeros wells, related with lithological groups, its Units, rock type and formation age [44, 47, 52]**

| Lithologic Group | Lithologic Unit | Description | Age | Geological Era | Depth (m) |
|---|---|---|---|---|---|

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| I. Post Caldera Volcanism | 1. pyroclasts | Tuffs, pumices, some alluvion | < 0.003 Ma | Quaternary ( < 0.06 Ma) | 0- 230 |
|  | 2. Post caldera lava flows | Rhyodacites, andesites, basaltic andesites, olivine basalts lava flows | 0.05 - 0.003 Ma |  |  |
| II. Caldera volcanism | 3. Los Potreros caldera volcanism | Zaragoza ignimbrites, rhyodacitic flows (0.069 Ma) | 0.069 Ma | Quaternary | 230-890 |
|  | 4. Intercalderas volcanism | Rhyolitic and obsidian domes, Faby tuff and andesitic-dacitic lava flows | 0.074 - 0.07 Ma | Quaternary | 890-1250 |
|  | 5. Los Humeros caldera volcanism | Xaltipan ignimbrite, andesitic, rhyolitic lavas | 0.164 Ma | Quaternary | 1250-1690 |
| III. Pre-caldera volcanism | 6. Upper precaldera volcanism | Rhyolites, dacites, andesites, tuffs and basalts | 0.693-0.155 Ma | Quaternary | 1690-1790 |
|  | 7. Intermediate pre-caldera volcanism | Pyroxene andesites, mafic andesites, dacites | 2.61 Ma - 1.46 Ma | Pliocene-Early Quaternary | 1790-1900 |
|  | 8. Basal pre-caldera volcanism | Hornblende andesites, dacites | 10.5 - 8.9 Ma | Miocene | 1900-2030 |
| IV. Basement | 9. Basement | Granites and schists, limestones and shales, granitic intrusions | 15.1 - 190 Ma | Paleozoic to midle Miocene | 2030-2500 |

### 3.1 Characterization of thermodynamic parameters behavior

The LHGF topography is irregular and the wells-head varies between 2800 and in some cases as far as 2900 masl. Therefore, for parameters profile analysis elevation data were used in order to have equal levels in the comparison criteria. Thermodynamic measurements (temperature, pressure) mainly carried out during drilling completion stage of the wells were used, because represent unperturbed state. From these, were determined the respective gradient profiles in the wells. Besides these analyses the whole correlation involves the circulation losses during drilling and, lithology identification. From previous historical behavior of the LHGF is clearly identified that the field can be partitioned in three main sectors: North; Central and South. As a first approach for a general diagnosis were graphed temperature profiles logged with same repose time in the wells. Graphs were constructed according to zone where the wells are located. The zone with density major of wells is the north zone, so, graphs of Figure 2 show temperature profiles of these.

### 3.2 Temperature analysis

Wells numeration corresponds to its order of drilling; by this reason in Figure 2 appear temperature profiles of the more ancient wells. Excepting measurements of the well H3, majority logged temperatures were carried out between 1984 and 1987 years. In Figure 3 temperature profiles of drilled wells at north zone at intermediate time are shown, whose measurement date varies between 1988 to 1997 years, excepting H43 (2008).

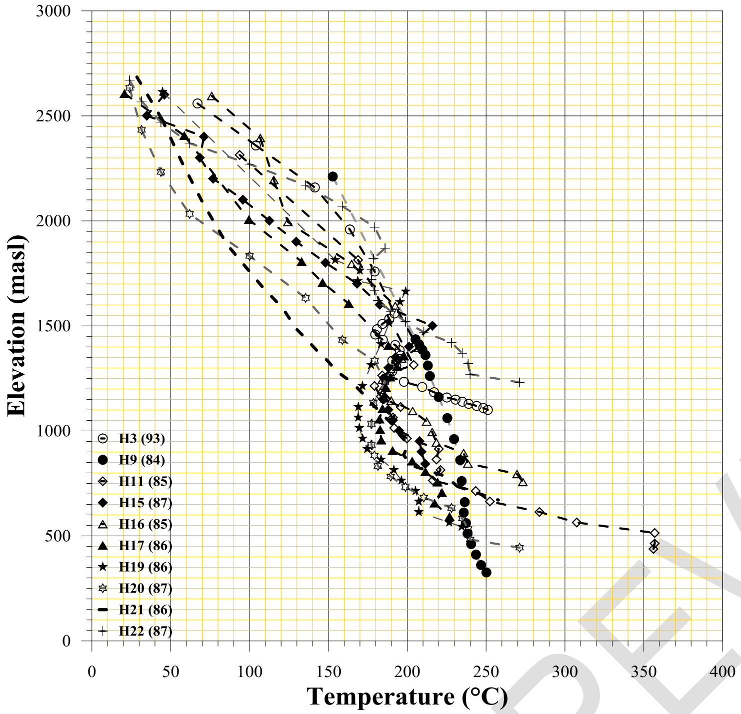

**Fig. 2. Temperature profiles of north zone well of LHGF, drilled at initial stage of field life (1984-1987)**

In a third stage of temperature measurements analyses in LHGF were associated those drilled between 2016 and 2017 years, which are shown in Figure 4, excepting well H44 (2006).

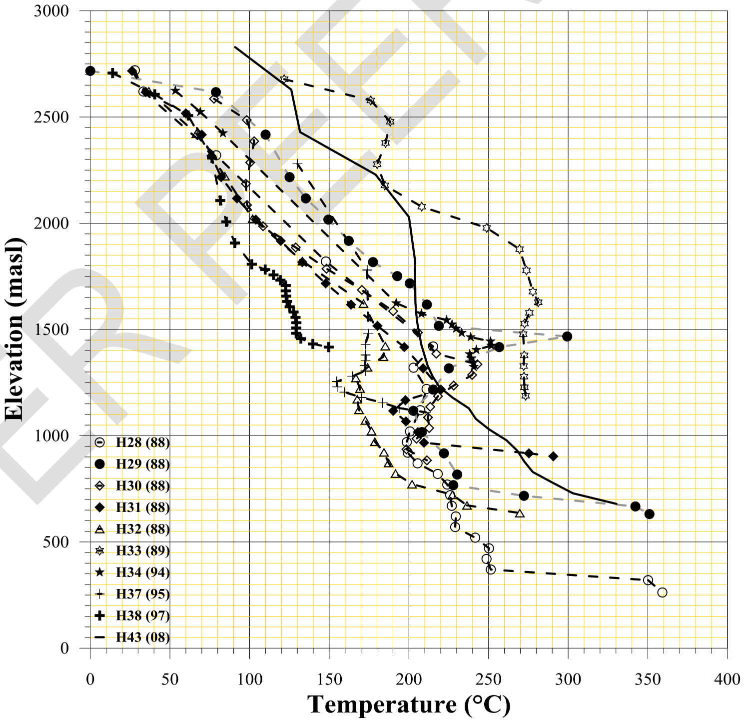

**Fig. 3. Temperature profile of north zone wells of LHGF, drilled at intermediate time, of the field life (1988-1997)**

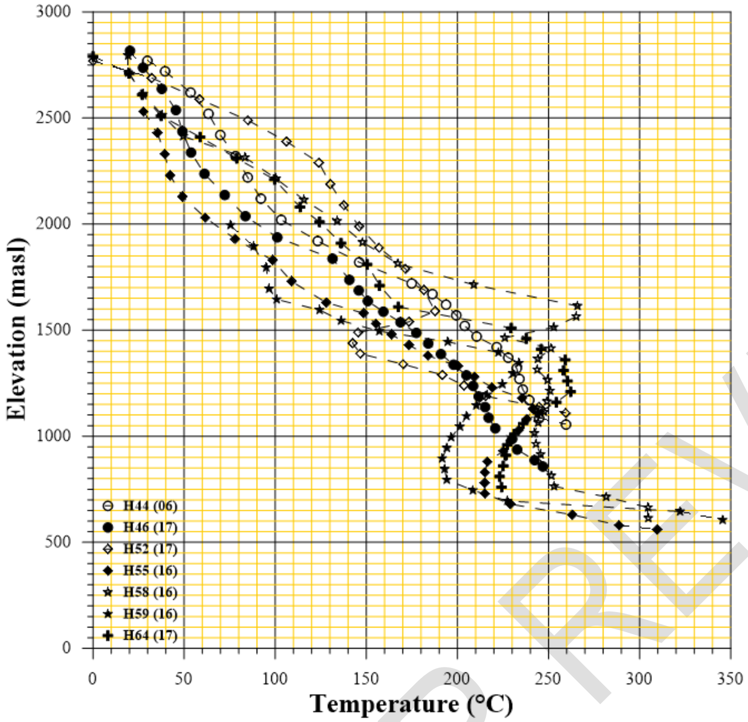

**Fig. 4. Temperature profiles of wells located at north zone of LHGF which were drilled between 2016 and 2017 years**

General observation in relation with the different measurement stage is that the graphs show disordered profiles temperature distribution. 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.

Using profiles of Figure 2 were excluded wells H3, H9, H21 and H22 which show differences to those wells appearing in this figure. Therefore, in Figure 5 it can be identify particular characteristics in temperature profiles of wells, which show similar trends mainly related to thermal regression at analogous depths. While in Figure 6 temperature profiles of wells (H3, H9, H21 and H22) which do not show any possible correlation are shown. It can be seen that temperature profile of well H3 shows two intervals of temperature regression with lengths no more than 100 m at upper levels than of wells generality.

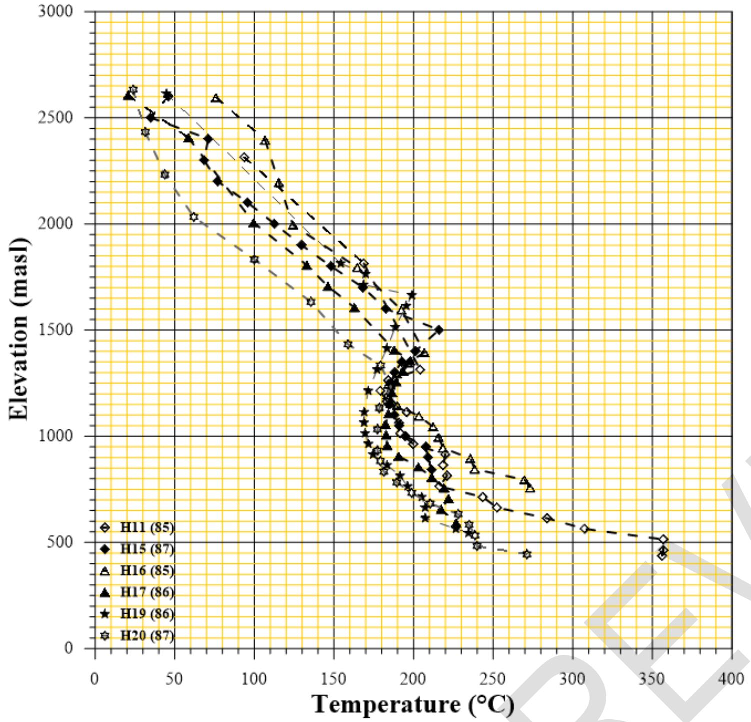

**Fig. 5. Graph showing similar trends of thermal regression at similar depth levels of drilled wells of north zone at initial stage of LHGF life**

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 that located at the bound of the geothermal zone. However, in spite of showed disorder in graphs it was possible to identify some tendency in profiles of some of the wells. Under this observation were grouped temperature profiles according to each particular trend.

Along this study were found individual behaviors of wells which allow identify three main blocks at north zone (western, central and eastern) of LHGF. A clear behavior of geological structures influence is that of wells located between “Los Pájaros” and “Las Víboras” faults (wells H11, H17, H19, and H21) which, except H21 show a similar trend in temperature profiles. It can be seen similarity of temperature profiles with regression, and their relative occurrence level, shown in Figure 7. Well H21 is located at the north of "Colapso Central" and this would be the reason for its different temperature profile, respect to others of this sector. The highlight is that its temperature profiles show a little thermal regression of only 3 °C, as can be seen in Figure 8, at 6 and 24 hours of repose time. Besides, according to all the characteristics shown by this well (H21) leads to assume that is out of the geothermal reservoir. In Table 2 are shown different thermal regression with their corresponding thicknesses found along profiles of these mentioned wells.

Another representative behavior of thermal regression is given by wells drilled in recent years after about 20 years of continuous exploitation having as common characteristic that are located in the corridor located between “Los Pájaros” and “Las Víboras” faults. These wells are H55, H58 and H64, whose temperature profiles are shown in Figure 9. The corresponding values associated with thermal regression (levels, thickness and temperature decrease) are shown in Table 3. The highlight of both Figures 7 and 9 and Tables 2 and 3, is that levels are common and thermal regression are in similar range of temperature decrease. It can be seen from Figure 9 that well H58 shows three levels of thermal regression, however, the location deeper is correlated with the other two wells.

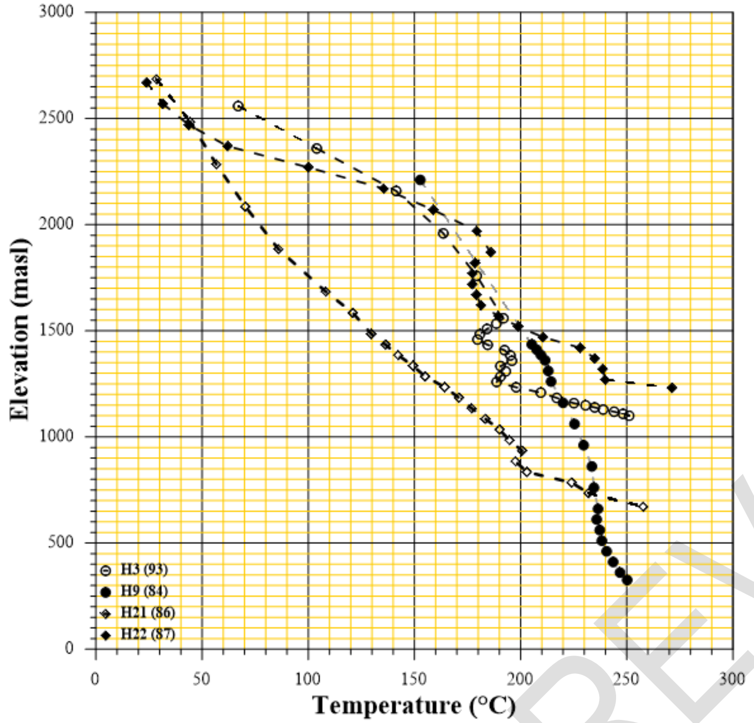

**Fig. 6. Graph showing temperature profiles of LHGF north zone wells, drilled at initial stage, whose behavior differs from those which show temperature regression at similar levels depth**

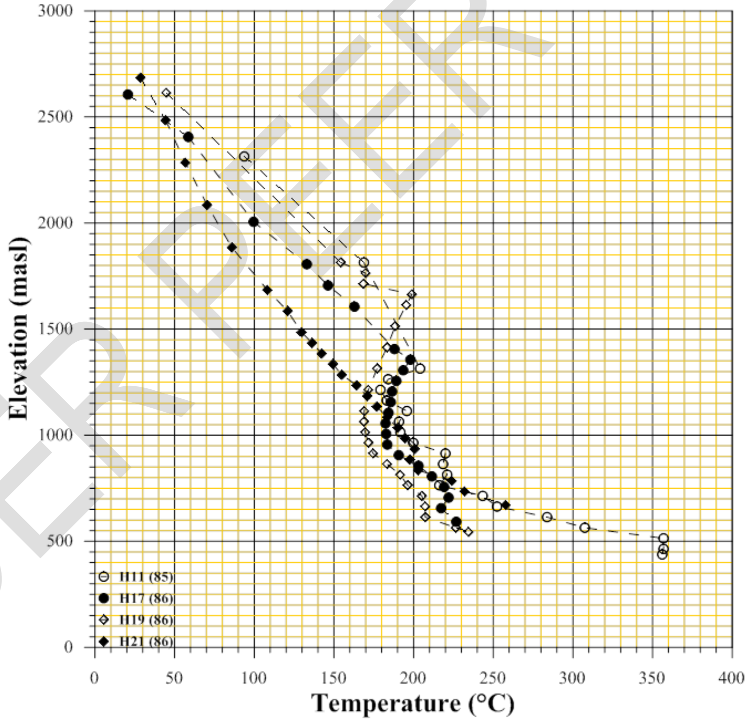

**Fig. 7. Graph showing temperature profiles of LHGF north zone wells, drilled at initial stage and located in the corridor between "Los Pájaros" and "Las Víboras" faults**

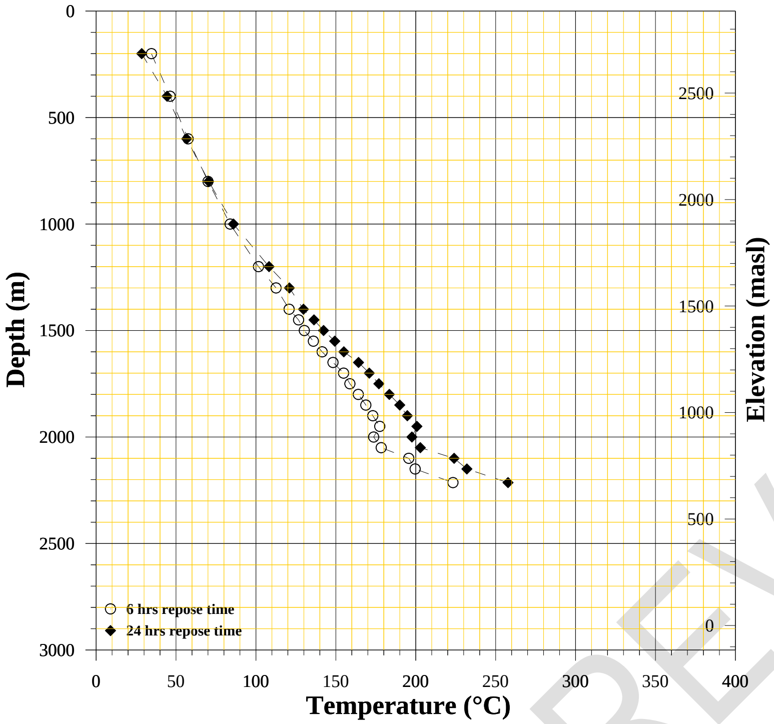

Fig. 8. Temperature profiles of well H21 at 6 and 24 hours of repose time, measured during its drilling completion stage

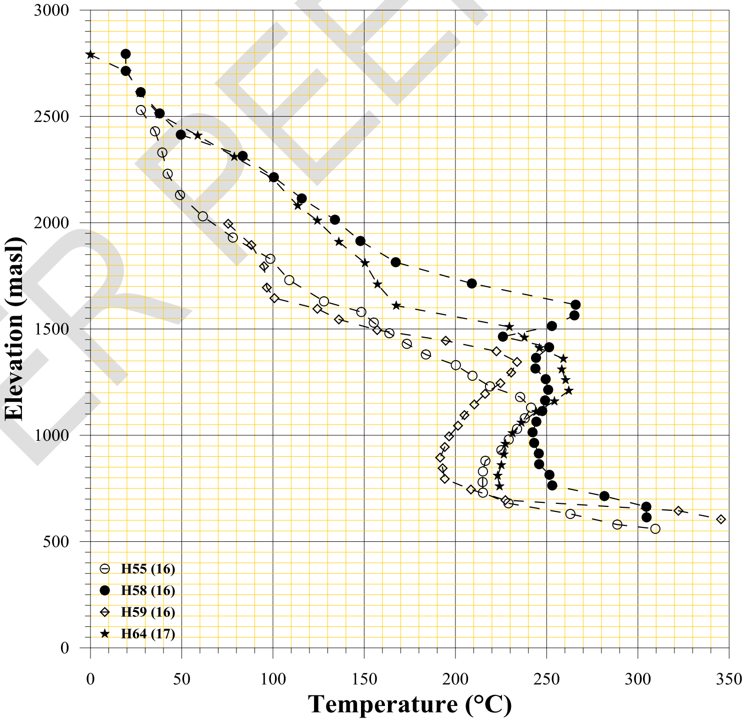

Fig. 9. Graph showing temperature profiles of LHGF north zone wells, drilled more than twenty years after exploitation, located in the corridor between Los Pájaros" and "Las Víboras" faults

**Table 2. Evaluation of thermal regression, associated with corresponding thicknesses and levels of wells located between “Los Pájaros” and “Las Víboras” faults, at north zone of LHGF**

| Well H11 | | | |
|---|---|---|---|
| masl | Temperature (°C) | ∆h(m) | ∆t(°C) |
| 1314 | 204 | 100 | -25 |
| 1214 | 179 | | |
| Well H17 | | | |
| masl | Temperature (°C) | ∆h(m) | ∆t(°C) |
| 1356 | 198 | 300 | -16 |
| 1056 | 182 | | |
| Well H19 | | | |
| masl | Temperature (°C) | ∆h(m) | ∆t(°C) |
| 1664 | 199 | 550 | -30 |
| 1114 | 169 | | |

**Table 3. Evaluation of thermal regression, associated with corresponding thicknesses and levels of wells located between “Los Pájaros” and “Las Víboras” faults, at north zone of LHGF, which were drilled after more than twenty years of continuous exploitation**

| H55 | | | |
|---|---|---|---|
| masl | Temp (°C) | ∆h(m) | ∆t(°C) |
| 1130 | 241 | 400 | -26 |
| 730 | 215 | | |
| H58 | | | |
| masl | Temp (°C) | ∆h(m) | ∆t(°C) |
| 1614 | 266 | 150 | -40 |
| 1464 | 226 | | |
| 1414 | 251 | 100 | -7 |
| 1314 | 244 | | |
| 1214 | 251 | 200 | -9 |
| 1014 | 242 | | |
| 895 | 192 | | |
| H64 | | | |
| masl | Temp (°C) | ∆h(m) | ∆t(°C) |
| 1210 | 262 | 400 | -39 |
| 810 | 223 | | |

It is feasible to identify that thermal regression of the three wells appears at similar levels, even though in each well the thickness is single. The well H11 shows lesser thickness, H17 shows lesser thermal regression and well H19 located more at south, show higher thermal regression and thickness length.

### 3.3 Pressure profiles behavior

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 10 shows pressure profiles of wells H15, H16, H30 and H31. These wells are located in the corridor bounded by geological structures of “La Cumbre” and “Los Pájaros” faults. From this figure, it can be seen that all of them coincide to about same interval of static level (between 2450 and 2250 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 11. In both cases can be identified that static level is located in the order of 2600 masl. The analyzed wells involved in this graph are located between geological structures of “Los Pájaros” and “Las Víboras” faults.

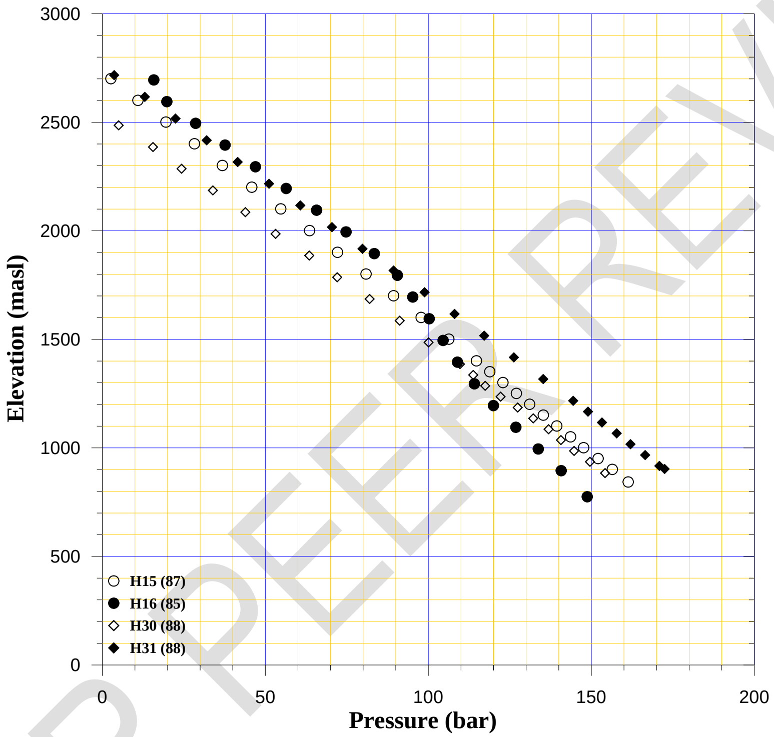

**Fig. 10. Pressure profiles taken in wells, located between geological structures of “La Cumbre” and “Los Pájaros” faults, which were drilled at the initial stage of LHGF life**

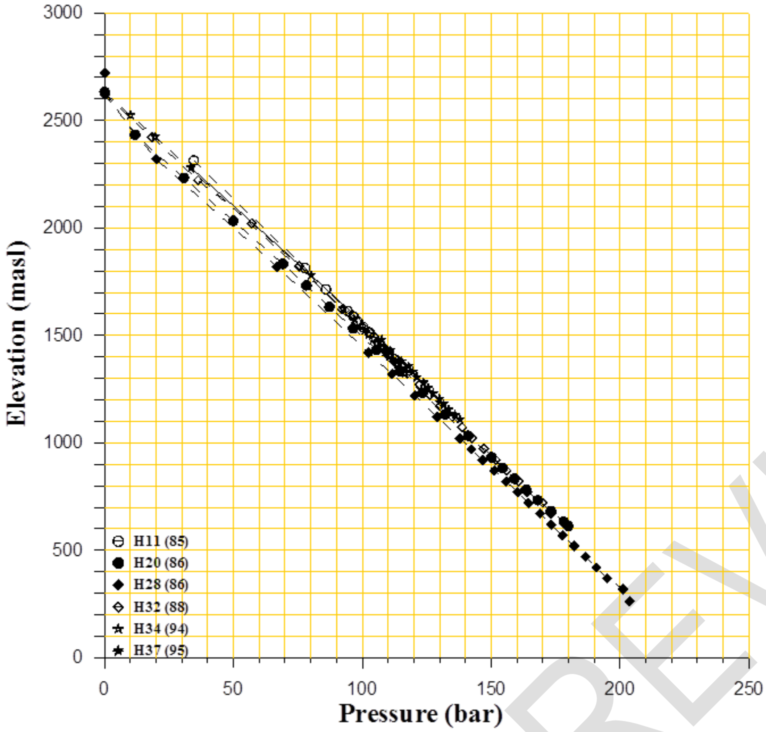

**Fig. 11. Pressure profiles taken in wells located at north zone, having as characteristic that were drilled between the first 10 years of LHGF life**

### 3.4 Correlation with lithologic units and circulation losses during drilling

In spite that wells were drilled at different stages, according to thermodynamic parameters profile behavior, were identified similar trends according their location. So, in order to correlate the previous analyses with physical rock characteristics were incorporated circulation losses recorded during wells drilling. In order to indicate the differences in the behavior provoked by geological structures in wells located in both analyzed zones, in Figures 12 and 13 profiles of circulation losses during drilling, are shown.

The circulation losses during drilling are associated with permeable characteristics of the crossed intervals by the bit, so, these profiles are taken as a qualitative manner of this parameter. The generalized characteristic of the wells is that show an interval of circulation losses upper than 50 $m^3h^{-1}$, between 2700 and 2800 masl, which correspond to lithological Unit 1. However, these circulation losses do not are related to geothermal reservoir. A deep, in the interval of geothermal feed, circulation losses are less than 20 $m^3h^{-1}$. These characteristics are identified in Figures 12 and 13, even though the wells are located under different geological influence zones. Circulation losses profiles of wells located in the sector bounded by “Los Pájaros” and “Las Víboras” faults are shown in Figure 12. While, the circulation losses profiles of wells located in the sector bounded by the geological structures of “La Cumbre” and “Los Pájaros” faults are shown in Figure 13.

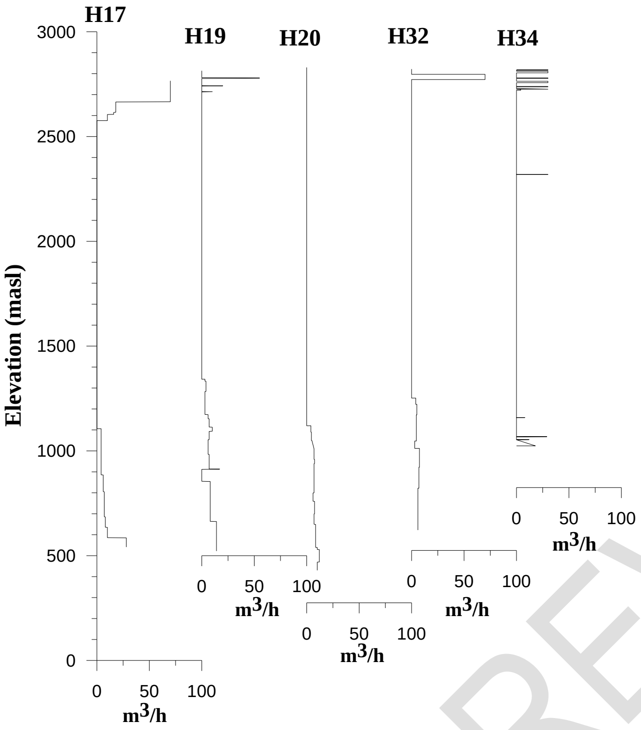

**Fig. 12. Circulation losses profiles, during drilling of wells located in the sector bounded by “Los Pájaros” and “Las Víboras” faults**

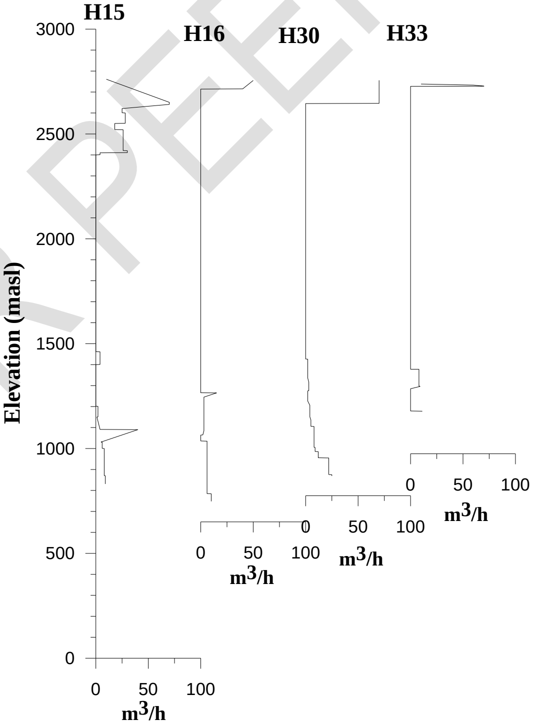

**Fig. 13. Circulation losses profiles, during drilling of wells located in the sector bounded by “La Cumbre” and “Los Pájaros” faults**

## 4. RESULTS AND DISCUSSION

Initially, in this analysis, it was taken special care that temperature and pressure measurements logged, would have the same repose time (in this case, 24 hrs) after drilling stopped. Also, was taken care in the analysis, for grouping those wells drilled according to its drilling contemporaneity. From the analysis of measurements behavior, it was identified initial thermodynamic conditions of the LHGF. The first analysis of temperature measurements shows unordered profiles which do not allow be correlated. Taking into account the curve shape of each well, it had been chosen those with similar trends selecting away from those with different behavior. Through applied methodology were grouped wells with a similar trend. After wells selection with similar temperature profiles, it was identified their thermal regression was, which allows grouping them as can be seen in Figures 5, 7, and 9. It is highlighting that this behavior is related to geological structures which are visible at the surface and therefore they allow assume its continuity at deep.

From temperature logs profiles of wells H11, H15, H16, H17, H19, and H20 shown in Figure 5, it can be identified thermal decrease at similar intervals, between 1250 and 1500 masl. It was taken special care for using measurements logged at similar period times before the field would start its dynamic state due to exploitation.

Due to that not always is enough clear that structures at the surface may have continuity at the bottom, thermal regression identified in wells, could help to explain and clarify the continuity influence of geological structures. Through the incorporation of geologic and lithological information besides the thermodynamic in analysis correlations, it was feasible to group wells with similar temperature profiles, resulting in this similarity can be related to their locations in the field. According to wells locations, it can be identified geological structures presence, so, would be assumed that these structures operate as influence factor becoming as the origin of different formation blocks, resulting in a compartmented behavior of the system.

From the behavior found in this geothermal system, it can be identified that faults and fractures existing profoundly affect the fluid flow. They can either impede or enhance fluid flow dramatically, thereby playing an important role in migration, entrapment, production and in whole recovery process. It was identified that faults and/or fractures create a network, communicate hydraulically with each other, and provide overall conductivity (permeability) of the reservoir. For this field the rock matrix provides overall storage capacity (porosity), however its permeability just provide the conductivity for flow from the matrix into faults and/or fractures. Faults and/or fractures do not form a continuous conductive network; only a limited number of faults and/or fractures may communicate hydraulically with each other. Faults and/or fractures, and matrix provide conductivity, but overall storage capacity (porosity) is in the rock matrix.

However, it is appropriate to use all information types available, besides thermodynamic measurements, which be correlated with the geophysical survey, drilling cutting samples, pressure transient tests, circulation losses, etc., among others. Were chosen wells with temperature profiles with a particular behavior, different to those which exhibit thermal regression, which are shown in Figure 6. From this figure, it can be seen, that temperature measurements of wells H3, H9, and H22 vary in the same value rank (190 – 240 °C) and depth levels (1200 – 1500 masl), even though their temperature profiles are different between them. However temperature profile of well H21 is different, showing low values in relation to the other three wells. First wells resulted with productive characteristics, however, in well H21 not enough permeability, nor temperature, was identified, which would allow at least a little geothermal production.

From this analysis, it can be found anisotropy is present, including neighboring wells located too close. It could be supposed that, in absence of the geological structures, the field would be a homogeneous system and all the temperature profiles of the wells would have an approximate or similar behavior. However, from the analysis carried out, were obtained different trends which induce to assume that LHGF behaves under influence of geological structures existing. Temperature profiles of wells shown in Figures 2 and 3 appear as disorderly trends which are related to system heterogeneity. However, after preliminary analysis of profiles shape, it can be identified similar trends, mainly in thermal regression intervals, as can be seen in Figures 5 and 9.

It was taken care that wells were grouped taking into account their logs would correspond to the same period of time in order to develop this analysis, with the same reference time and identify their initial conditions. A characteristic behavior found in this analysis is that temperature profiles logged in wells show that thermal regression being more remarked in those located nearest to geological structures. This thermal regression is associated with cold fluid entrance through these geological structures. In a subsequent analysis stage, was chosen those wells located at the eastern rock block, between "Los Pájaros" and "Las Víboras" faults. Analyzed wells of this block are, H17, H19, H20, and H21, whose temperature profiles are shown in the graphs of Figure 7. From this figure, it can be identified thermal regression in all wells at similar depths, except H21 whose thermal behavior differs from the wells profiles of this block. This behavior type of the well H21 is related to its location in a marginal section of the reservoir, characterized by low temperature and null permeability.

As can be identified in Figure 10 particular behavior in the different pressure profile trends of the wells of each block was identified, which allow assuming a heterogeneous reservoir. However pressure profile trends of wells shown in Figure 11 indicate mainly similarity and the static level can be located, at initial conditions before any disturbance in the reservoir.

These behaviors, which are different for each analyzed block, allow being correlated with geological structures presence shown in Figure 1.

From LHGF static characterization, the influence of geological structures behavior can be seen through analysis of different parameters, such as lithological and mineralogical distribution, temperature and pressure profiles, petrophysical properties, among others.

From the analysis carried out in LHGF, in the majority of the wells only high temperature is a common factor, however, unfortunately permeability is not a feature of this field. The lack of permeability in the reservoir affects its productive characteristics behavior. Fluid circulation losses during drilling are used as qualitative indicators of permeability existence in the thickness being crossed. It is important to emphasize that, low values of circulation losses at deep, during drilling, are common in the generality of LHGF wells. Another use of the obtained results, related to thermal behavior along the well profile, is focused to taking decisions for determining the appropriate time for flow starting and carrying out production tests.

Reliability of obtained results is supported through interrelation of thermodynamic (pressure, temperature) profiles, circulation losses profiles, temperature, and pressure gradients, and lithology. However, it is important to emphasize that, as long as more information can be used (of the different geosciences disciplines) results certainty, will increase.

## 5. CONCLUSIONS

Correlative analysis of circulation losses during drilling and pressure-temperature profiles during the completion stage are used in this work as a technical tool for determining the initial conditions of LHGF as part of its static characterization.

Correlation of different parameters obtained during wells drilling and at its completion stage in the Mexican LHGF allows identification of the formation properties at an undisturbed state.

In this work, it was applied sequential analysis of the different parameters which contribute to determining the static characterization of LHGF.

It was applied static characterization methodology taking into account control parameters in geothermal reservoirs, whose results allow identify the unperturbed state of LHGF Mexican geothermal field.

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

Thermodynamic profiles behavior of LHGF allows identifying its heterogeneity, which is associated with volcanic rock where is nested.

From the selection of temperature profiles configuration of the wells, were classified those with similar behavior, founding that can be associated with its closeness to geological structures and consequently support the assumption that LHGF behaves under geological structures influence.

Concerning analysis related to fluid circulation losses during drilling the major quantity of lost fluid (about 50 $m^3hr^{-1}$) occurred at shallow depths, while at the depth of the wells only were measured in the order between 4 to 10 $m^3hr^{-1}$. This behavior would be correlated with low permeability in the reservoir thickness.

It was found that geological structures existing nearby wells, impact their thermodynamic measurements, dominating that LHGF behaves as a compartmented system.

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