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An Approach for Characteristics Determination of Initial State in a Geothermal Field

Alfonso Aragón-Aguilar[1*], Georgina Izquierdo-Montalvo[1], Abel F. Hernández-Ochoa[1], Paromita Deb[2], Miguel Ramírez-Montes[3], Siomara López-Blanco[1], Alejandro Arriola-Medellin[4], Dominic Becerra-Serraros[1], Aldo Azoños-Figueroa[1]

[1]Instituto Nacional de Electricidad y Energías Limpias, Reforma 113, Col. Palmira, Cuernavaca, Morelos, México, 62490

[2]Institute for Applied Geophysics and Geothermal Energy, RWTH Aachen University, Germany

[3]Gerencia de Proyectos Geotermoeléctricos (CFE), Alejandro Volta 655, Col. Electricistas, Morelia Michoacán, México, 58290

[4]Instituto Tecnológico de Mérida, Av. Tecnológico km 4.5, S/N, Mérida, Yucatán, México, 97118

*aaragon@ineel.mx

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ABSTRACT

México contains more than 4200 thermal manifestations along its territory. To date five geothermal fields are exploited continuously and electricity generation capacity is in the order of 925 MWe. Four of these geothermal fields are exploited by “Comisión Federal de Electricidad” (CFE) and the other one is exploited by a private investor. Even though the major electrical generation is being produced by "Cerro Prieto" geothermal field, along Mexican neovolcanic belt are located the next two second main fields in México ("Los Azufres" and "Los Humeros"). The anisotropy of the rock formation shown through behavior of these both geothermal fields are related with its volcanic environment. However, highlights that in “Los Humeros” has been found wells with single behaviors with particular characteristics of high temperature (in the rank of 350 °C), including those neighbor, which allows to consider the compartmented behavior hypothesis. Additionally, it has been found, as a general characteristic of field rock formation is its low permeability, influencing in production flow rate and drawdown pressures. Through the use of the analysis of thermodynamic characteristics behavior, after well completion, can be taking decisions for determining the appropriate time for carrying out its production test. It is mainly important, the identification of appropriate thicknesses for be exploited in each well, which represents the aim of having successful results through a producer well with electrical generation capacity. Even though target depths of each well have been designed from geological and geophysical studies, carried out during exploration stages, the drilling is the best way for confirming these. Therefore, in the wells generality, found parameters during drilling, are the technical base for taking decisions on the best completion depth and to select the thickness which must be exploited, in order their productivity assure. Obtained parameters during well completion and before its exploitation start up, are used in this work for static characterization of “Los Humeros” Geothermal field into the GEMex project.

1. INTRODUCTION

Reservoir characterization is useful to identify reservoir geometrical dimensions, physical rock properties, some initial evaluation of reservoir reserves, its initial thermodynamic conditions, among others. This task is focused to identify rock formation thickness with geothermal production capacity. For achieving the objective, it is necessary to identify heat sources, petrophysical rock properties, and hydrologic feed sources. So, reservoir characterization plays an influence role for establishing management programs and feasible growth of the field.

Integrated characterization allows to determine initial conditions (static characterization) of the system, including reserves evaluation and the system parameters (rock and fluid) since the first stage. Both, in petroleum as geothermal and hydraulic systems, the amount of the recoverable energy and the technique for its extraction depend primarily on the accuracy of its characterization in this stage (Bayoumi et al., 2019). Due to natural reservoir condition, these parameters are petrophysics (rock) and thermodynamic (fluid). In the second stage of the operative life after exploitation started, the disturbances magnitude is used for dynamic characterization. During the dynamic characterization, parameters such as performance behavior, productivity decline, thermodynamic evolution, extracted fluid geochemistry, until remaining reserve, and useful life are analyzed.

This work is a part of integrated characterization planned in Work Package Six (WP6) of GEMex Project. According to characteristics shown by the Los Humeros Geothermal Field (LHGF), it is considered a Super-Hot Geothermal System (SHGS). In spite of that, low permeability is prevailing at deep position generally. The methodology applied in this work to static characterization uses information obtained during drilling and at completion stages of the wells. The “Comision Federal de Electricidad” (CFE) is the owner of the LHGF, which is the source of all the information supplied for GEMex project.

This work is focused to show the methodology applied to static characterization of the LHGF. Besides determining initial conditions of reservoir thermodynamic parameters, the analysis used in this stage allows to identify petrophysical properties of the rock, which lead to define exploitation thickness by combining with thermodynamic parameters.

Besides, the well drilling constitutes the base for reservoir acknowledgement because it is a direct window to verify hypotheses constructed during the exploration stage. Under this point of view, it could be said that static characterization involves two information types; one obtained before the well drilling and one obtained during these jobs and well completion until before its exploitation stage. Results of geological, geophysical and geochemical studies during exploration stage are useful for static characterization; however, the well drilling represents opportunity for direct reservoir properties knowledge. Parameters such as drilling velocity, fluid circulation losses, temperatures of entry and exit of drilling fluids, lithology from cuttings recovered, are used for determining characteristics of rock formation that the well crosses (Ahmed, 2001).

An important issue, which must be considered during the well drilling stage, is the acknowledgement of initial thermodynamic state of the reservoir. This plays important role in geothermal systems. To accomplish it, thermodynamic measurements were carried out at different depths according to rock formation behavior during drilling. The development of these measurements is mostly necessary during completion and before exploitation stage. These are useful to identify conditions at an undisturbed system.

It is clear that laboratory measurements applied to core samples are very useful to determine rock properties. However, their main limitation is that they are not accepted as properties generalization of at least profile of the well. This last concept is that core samples are recovered from a short section of the well, and that the characteristics change due to heterogeneous behavior in the case of volcanic formations.

Among different technical tools for determining rock properties in Mexican geothermal fields has been used to analyze transient pressure tests. These are carried out at a well drilling completion stage. They indicate geothermal reservoir presence, i.e., high temperature, thermodynamic conditions, and circulation losses during drilling.

Majority of geothermal reservoirs are nested in volcanic rock formations whose characteristic is its heterogeneity and lack of porosity. These characteristics are different to geothermal fields found in sedimentary formations. However, the common factor, for both system types, is existence of a heat source. The study field of this work is Los Humeros geothermal field (LHGF) located in volcanic rock.

2. THEORETICAL BACKGROUND

Characterization methodologies are technical tools, which have been applied since petroleum engineering started and since geothermal engineering started. Those have been adapted to use in its different life 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 Horner (1951), is used for static reservoir determination from temperature logs at different times of repose after drilling has been stopped. Characterization of geothermal reservoirs with high temperature is a special matter due to its thermodynamic behavior. In this sense, Abidin et al. (2009) and Mines (2016), developed methodologies to evaluate rock of a high-temperature reservoir (HTR). Other studies, such as of Shook (1999; 2001) at The Geysers in California, were focused to distinguish the difference between the normal vapor-dominated reservoir and the high-temperature conditions found below it. Studies carried out by Huang et al. (2015) on geothermal zones at high temperature and low permeability indicate large heat transfer areas between the flowing fluid and the surrounding formation. Toth and Bobok (2017) described phenomena associated with geothermal modeling.

The essence of heterogeneity is focused to identify the features that impact the system performance. The main features associated to a geothermal reservoir are basement, seal cap, high temperature, high permeability and water recharge (Grant et al., 1982). This is a property of the rock that causes the flood front, the boundary between the displacing, and the displaced fluids to distort and to spread as the displacement proceeds (Lake and Jensen, 1991). For a displacement in a hypothetical homogeneous medium, the rates of distortion and spreading are zero, however. As the heterogeneity increases, both the rates of distortion and spreading increase.

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. Since the 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 along temperature logs taken at different repose time interval.

Temperature and pressure logs during drilling and warming stage of Hverahlid field were analyzed by Afeworki (2010). 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 (Landsvirkjun, 2015).

Thermodynamic gradients profiles (e.g., pressure, temperature, fluid density) along wells are some of the practical application results. Aragón et al., (2000) and Izquierdo et al., (2002) used as methodology for identifying thickness open to formation, the known technique as heating index. It is the thermal gradient as time function determined from temperature measurements along each depth of well profile. Temperature measurements are logged at two different response time in the well after drilling job stopped. By heat transfer, the thickness with some permeability will show temperature decrease. However, in those thicknesses without permeability temperature drawdowns do not appear. This technique allows to 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, i.e., warming lack, then, it could be inferred that this thickness is not of geothermal characteristics.

Another qualitative index of permeability is the fluid circulation losses during drilling, because the job could be stopped for verifying this through thermodynamic logs and transient pressure tests. Measurement results allow obtaining heating index profile, rock properties petrophysical determination as porosity (Φ), permeability (k), drainage radius (r_e), static pressure (p_e), skin effect (s). Another method for determining petrophysical rock properties are through laboratory measurements to core samples, however these are only representatives of local thickness.

3. ANALYZED GEOTHERMAL FIELD

To date in Mexican Republic, there are five geothermal fields under exploitation. Four of them belongs to CFE and operated by "Gerencia de Proyectos Geotermoeléctricos", and others are operated by Private Investor "Grupo Dragón". 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 a third produce 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. The field is inside the Los Humeros volcanic caldera, which lies at the eastern end of the Mexican Volcanic Belt (Ferriz and Mahood, 1984). The LHGF is located near the limit with the Sierra Madre Occidental province, according to (Cedillo, 2000; Gutiérrez-Negrín et al., 2010; Izquierdo et al., 2011).

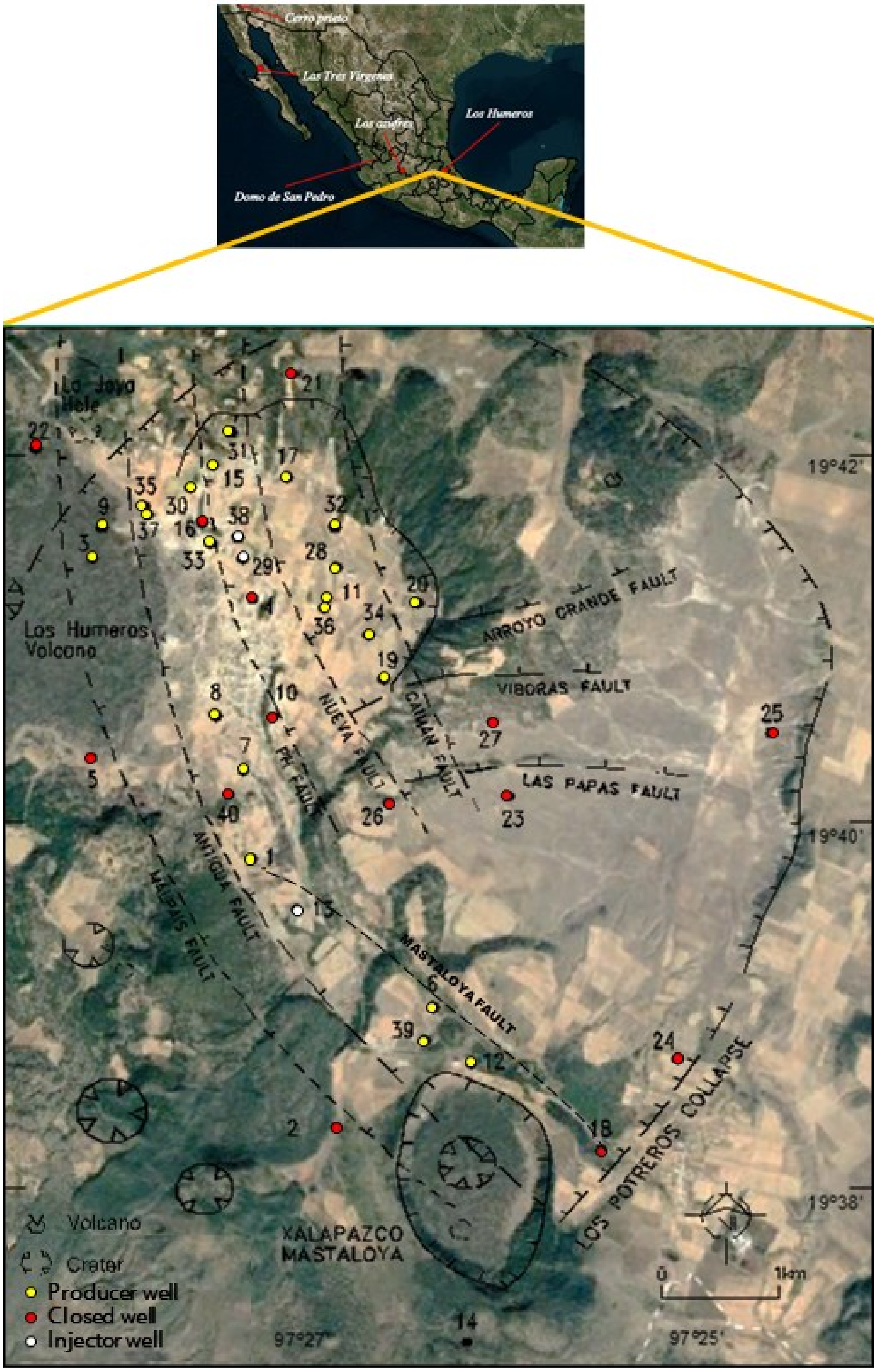

Figure 1: Locations of geothermal fields to date operating in Mexican Republic, with a close up of LHGF, showing wells location and the main identified geological structures.

This field is typified as a reservoir of high enthalpy in its production, but low permeability and low mass flow production (Arellano et al., 2003; Aragón et al., 2017). Its thermodynamic characteristics are one of the arguments to be classified as a "super-hot" geothermal system. 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.

Due to reservoir heterogeneity, each well has a single lithological column, and this characteristic is influent factor on its behavior (Lord and Collins, 1991). For the LHGF, thermal properties were defined from the rock formation taking into account lithological Group and its identified Unit.

Cedillo (1999) studied and identified from cutting samples during drilling wells of the LHGF, different lithological Units. After diverse versions the last modification and description of lithological groups and corresponding Units was carried out by Calcagno et al. (2018), which are shown in Table 1.

Table 2: General lithological characteristics found in Los Humeros wells; related with both lithological groups, its Unit, rock type and formation age.

Lithologic Group	Lithologic Unit	Description	Age	Geological Era
I. Post Caldera Volcanism	1. Pyroclasts	Tuffs, pumices, some alluvion	< 0.003 Ma	Quaternary (< 0.06 Ma)
	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
	4. Intercalderas volcanism	Rhyolitic and obsidian domes, Faby tuff and andesitic-dacitic lava flows	0.074 - 0.07 Ma	Quaternary
	5. Los Humeros caldera volcanism	Xaltipan ignimbrite, andesitic, rhyolitic lavas	0.164 Ma	Quaternary
III. Pre-caldera volcanism	6. Upper precaldera volcanism	Rhyolites, dacites, andesites, tuffs and basalts	0.693-0.155 Ma	Quaternary
	7. Intermediate pre-caldera volcanism	Pyroxene andesites, mafic andesites, dacites	2.61 Ma - 1.46 Ma	Pliocene-Early Quaternary
	8. Basal pre-caldera volcanism	Hornblende andesites, dacites	10.5 - 8.9 Ma	Miocene
IV. Basement	9. Basement	Granites and schists, limestones and shales, granitic intrusions	15.1 - 190 Ma	Paleozoic to midle Miocene

4. ANALYSIS OF PARAMETERS FOR STATIC CHARACTERIZATION

This study used thermodynamic measurements (temperature, pressure) mainly carried out during drilling completion stage. From these, their corresponding gradients were determined along the well profiles. Besides these analyses, the whole correlation involves the circulation losses during drilling and lithology identification. The 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 of the general diagnosis graphed temperature profiles logged with same repose time in the wells. Graphs were constructed according to zones where the wells were located. The zone with density major of wells is the north zone, so, graphs of Figure 2 show temperature profiles of these. Wells numeration corresponds to its order of drilling; by this reason in Figure 2 (A) appear temperature profiles of the more ancient wells and in Figure 2 (B) 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.

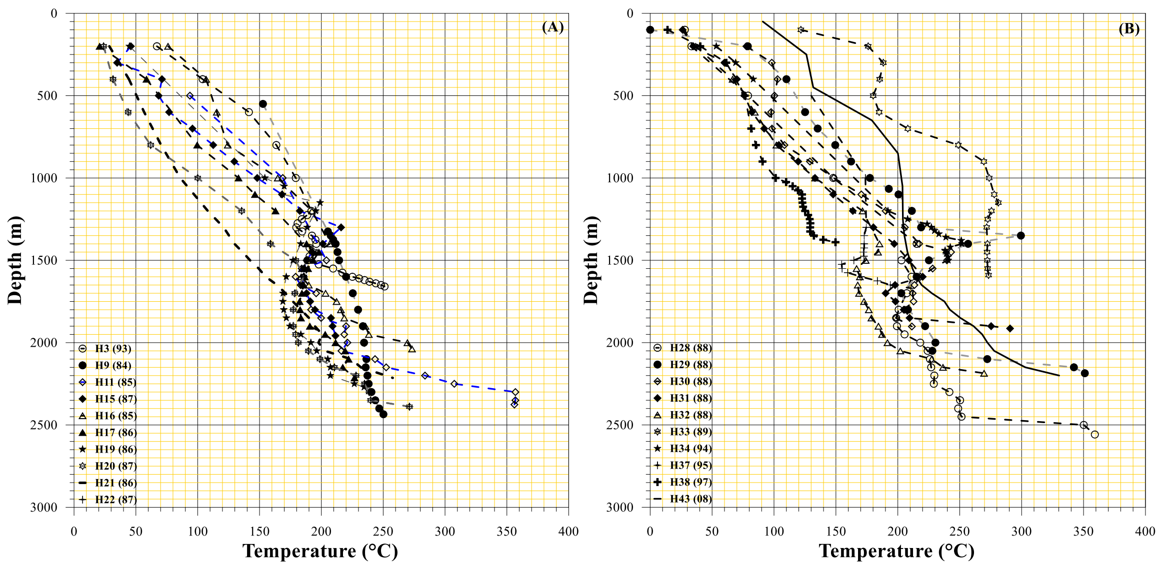

Figure 2: Temperature profiles of wells located at north zone of LHGF (A) involves the more ancient drilled wells, while (B) the more recent wells.

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 boundary 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. As a first case were identified that from Figure 2(A) profiles of wells H3, H9 and H22 show particular trend.

In this study were classified three main blocks at north zone (western, central and eastern) of LHGF. Respect to wells located at western block, from Figure 3 it can be seen that, profiles of H3 and H22 show temperature regression. However, it occurs at different depth to that generality of wells of this sector. Using as reference Figure 1, it can be seen the closeness of both wells to "Malpais" fault, and the different depth, would be associated that well H3 is located in direction of falling this structure. In the block between "Malpais" and "Antigua" faults, are located H3 and H9 wells, however this last behaves of different manner to those of the north zone, because does not show the identified thermal regression in some others. Graphs of profiles correlation of temperature, pressure, circulation losses, thermal gradient, pressure gradient and lithology, are shown in Figures 4 (H3) and 5 (H9).

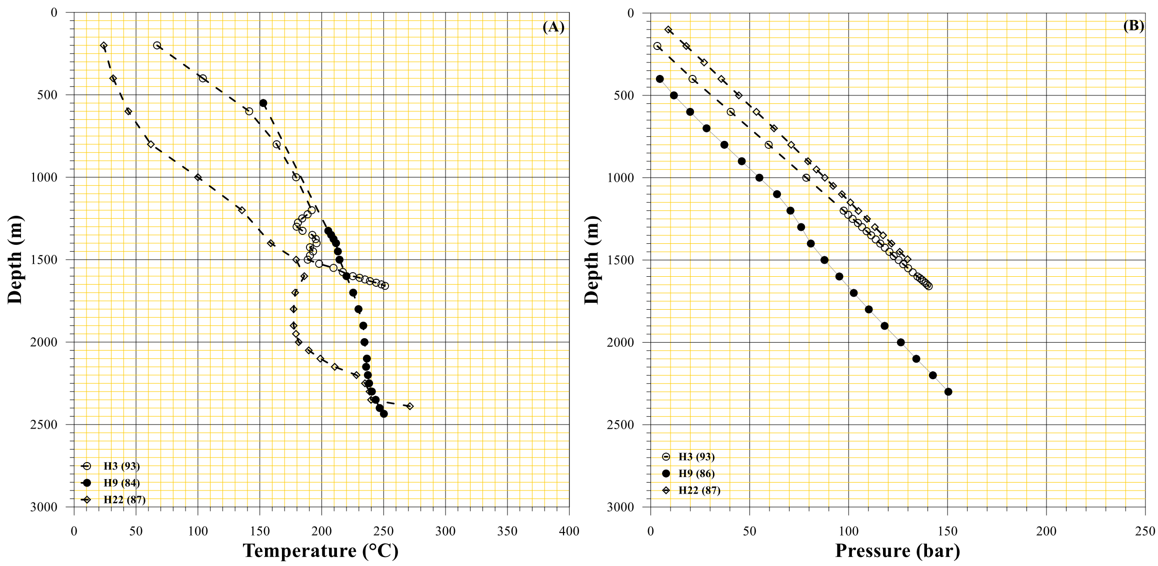

Figure 3: Temperature (A) and pressure (B) profiles of wells located at western block of north zone of LHGF, emerging the different behavior of H9 located more away of "Malpais" fault, respect to wells H3 and H22.

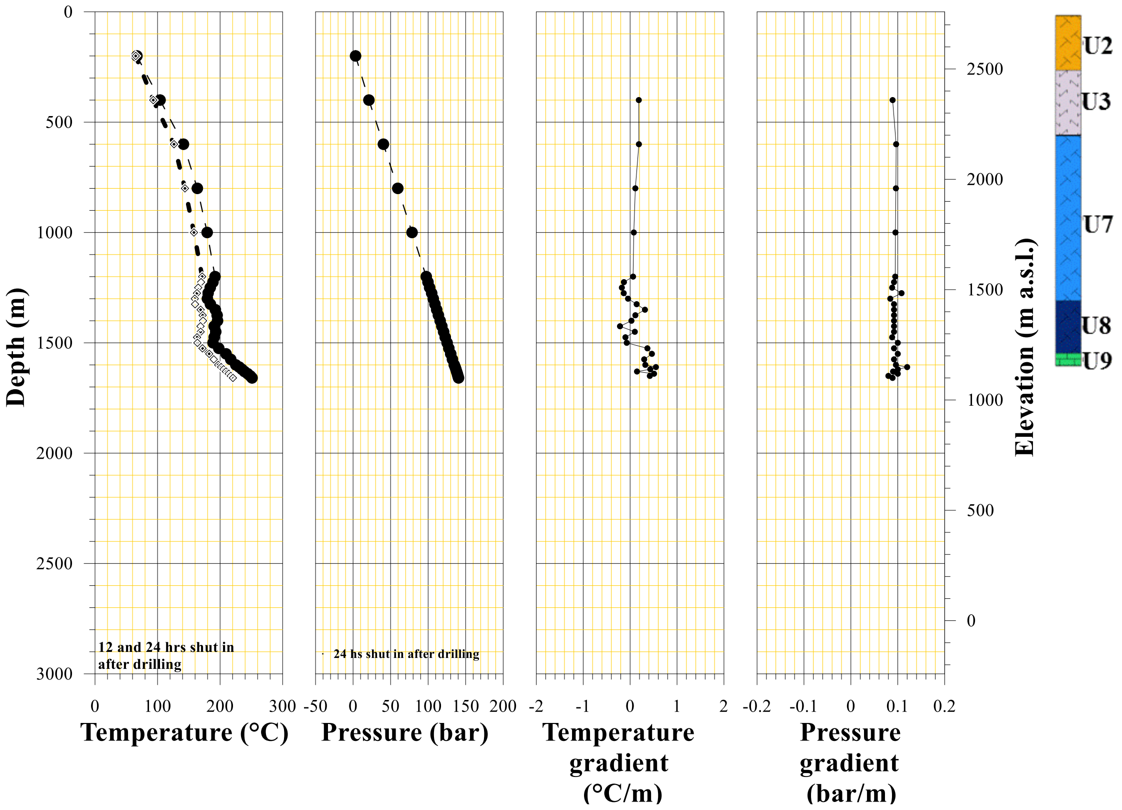

Figure 4: Profiles correlation of temperature, pressure, circulation losses, thermal gradient, pressure gradient and lithology of well H3.

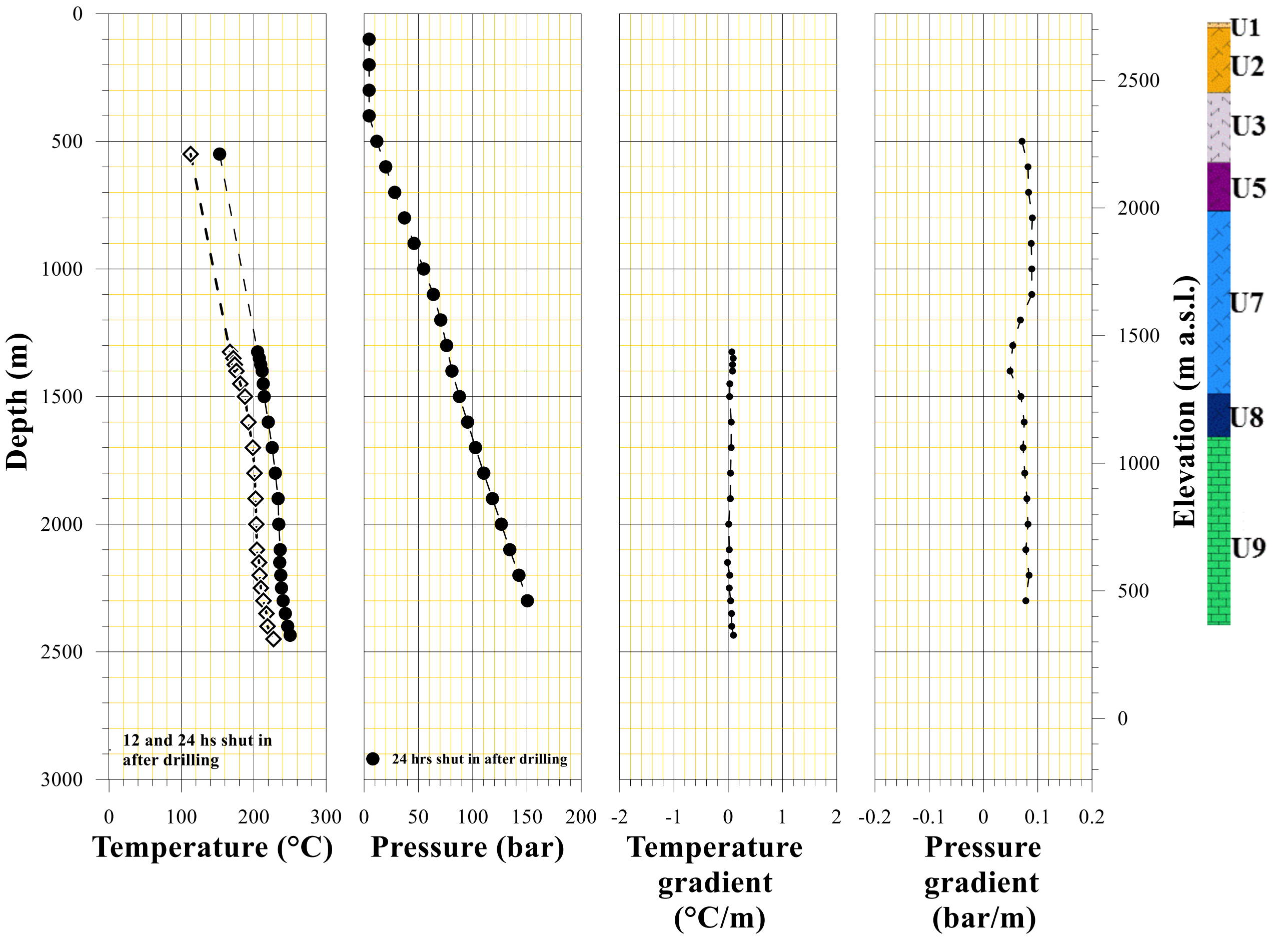

Figure 5: Profiles correlation of temperature, pressure, circulation losses, thermal gradient, pressure gradient and lithology H9.

In a second stage of this analysis, taking into account temperature profiles shown in Figures 2 and using wells position of Figure 1, were chosen those located between "Nueva" and " PH" faults block of the north zone of LHGF. Graphs of Figure 6 show temperature (A) and pressure profiles (B) behavior with same repose time.

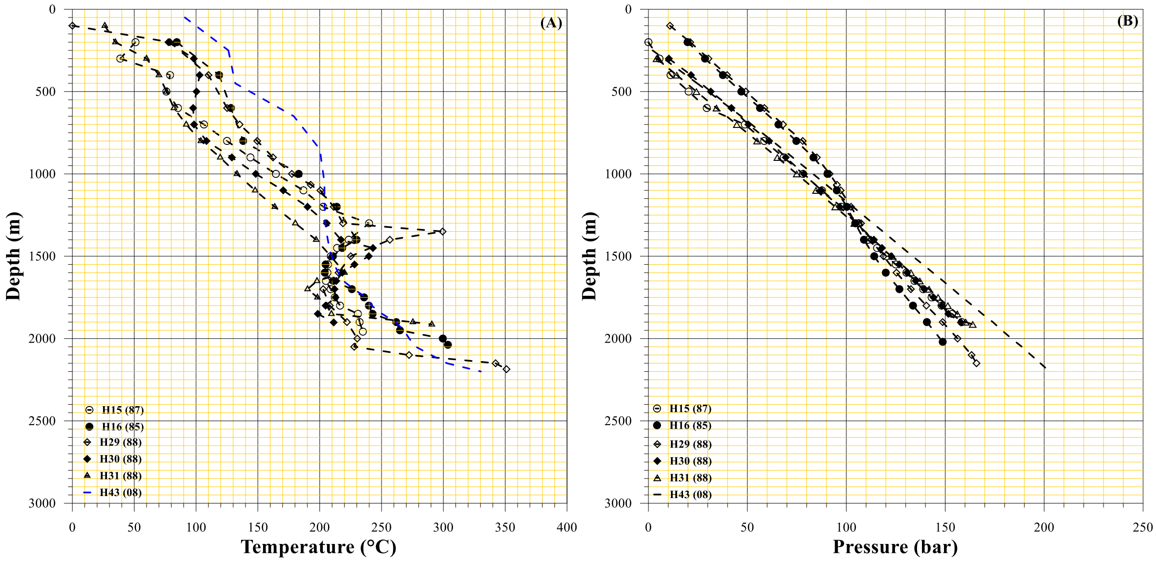

Figure 6: Temperature (A) and pressure (B) profiles, at initial conditions, of wells located at central block of north zone of LHGF.

Special care was taken for selecting that measurements would correspond to same period time, i.e., that the date agrees for initial conditions of the field. Under this idea wells H15, H16, H29, H30, H31 and H43 were analyzed, except this last (H43) the logs of all correspond to same period time. It can be seen from temperature logs profiles, except H43, that all wells show a decrease at similar depths. While H43 temperature profile shows a convective behavior in few repose time hours.

In a subsequent analysis stage of north zone wells of LHGF, was chosen those located in eastern block constituted between "Caiman" and "Nueva" faults. Analyzed wells of this block are H11, H17, H19, H20 and H21, whose temperature and pressure profiles are shown in Figures 7 (A) and (B), respectively. Similarly, to formerly, special care was taken that these thermodynamic measurements were carried out in similar period times.

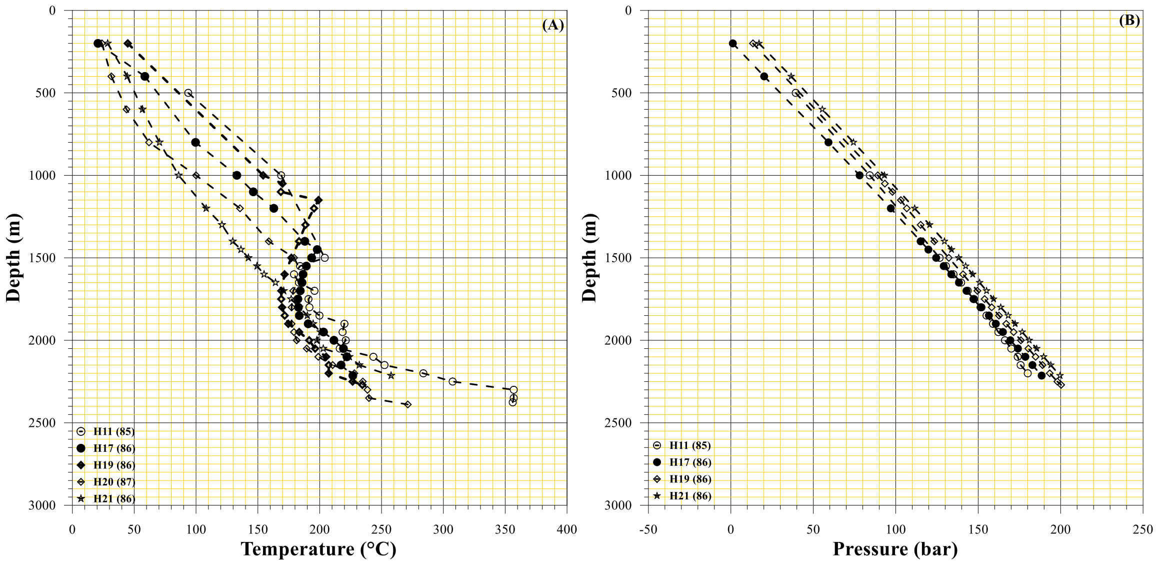

Figure 7: Temperature (A) and pressure (B) profiles, at initial conditions, of wells located at eastern block of north zone of LHGF.

Respect to temperature profiles behavior of wells shown in Figure 7 (A) it can be identified thermal regression in all wells at similar depths, excepting H21 whose thermal behavior differs from those of this block.

Pressure logs taken during drilling and at well completion stage are useful for determining static level location and its correlation with hydrological aquifer. Besides, pressure gradient profiles along the well allow determine thicknesses with hot fluid entrance or contrarily gas inlet. Correlations of these different variables are part of static characterization and at drilling completion stage are useful technical tools for both to design mechanical well completion and for establishing wellbore initial conditions. Similarly, identification of these parameters at initial condition is used for stage of behavior analysis and reservoir modeling. Examples of correlation of profiles of thermal gradient and pressure gradient, with lithology can be used for identify possible fed intervals along the well are shown in Figures 8 (H15) and 9 (H19).

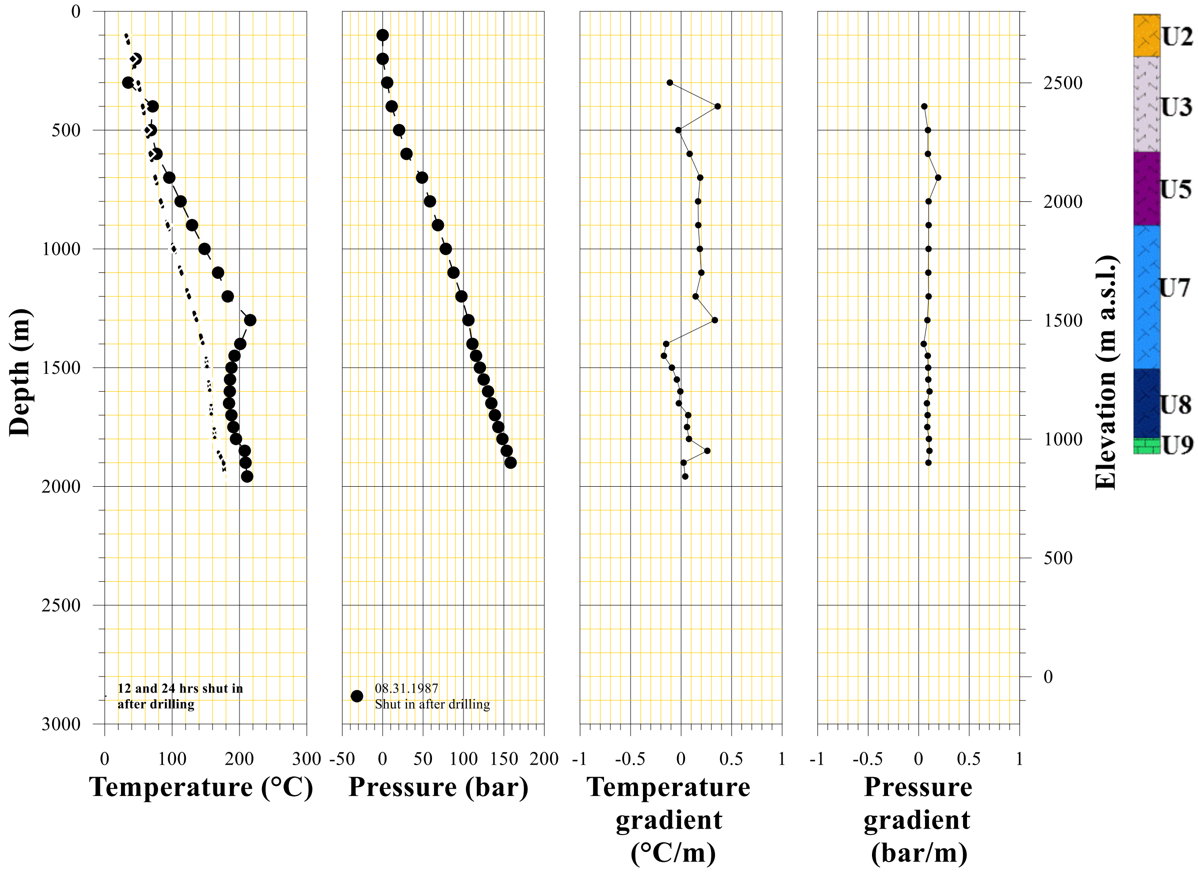

Figure 8: Profiles correlation of temperature, pressure, thermal gradient, pressure gradient and lithology of well H15.

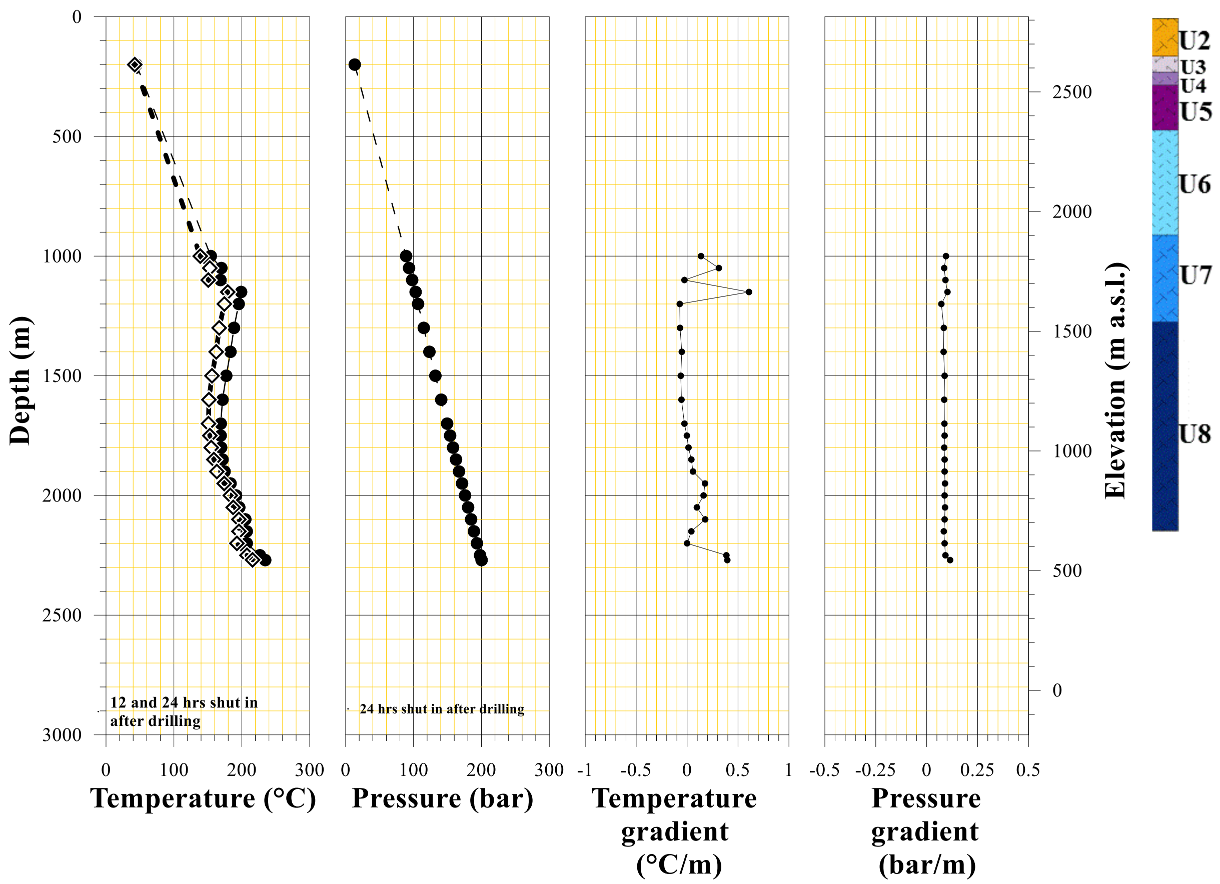

Figure 9: Profiles correlation of temperature, pressure, thermal gradient, pressure gradient and lithology of well H19, located at eastern block of LHGF north zone.

5. RESULTS DISCUSSION

Static characterization of wells of LHGF was applied using thermodynamic measurements carried out at their drilling completion stage. It was taken special care for using measurements logged at similar period times before the field starts its dynamic state due to exploitation.

Using a simple analysis related to temperature and pressure profiles of wells of the LHGF, it can be seen a disordered distribution in these. However, taking into account the curve shape of each graph, it was feasible to select those with similar trend and besides separating those with individual behavior. Using this methodology were grouped wells with similar trend in their temperature profiles.

Through the incorporation of geologic and lithological information besides the thermodynamic in correlations it was feasible to group wells with similar temperature profiles, resulting that this similarity can be related with their locations. According to wells locations it can be identified geological structures presence, so, would be assumed that these structures operate as influence factor becoming different formation blocks, resulting in a compartmented behavior of the system. Under this concept the behavior of each block formation follows a particular trend.

From the LHGF static characterization, its compartmented behavior it can be seen through analysis of different parameters, such as lithological and mineralogical distribution, temperature and pressure profiles, petrophysical properties, among others. From analysis it can be find anisotropy present, including neighboring wells to close. Hypothetically, 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 a similar behavior. However, from the analysis carried out, were obtained different trends assuming that LHGF behaves as compartmented system.

As can be identified in Figures 3(B), 6(B) and 7 (B), particular behavior in the different pressure profile trends of the wells of each block was identified, which allow assuming a heterogeneous reservoir. These behavior, which are different for each analyzed block, allow be correlated with geological structures presence shown in Figure 1.

From the analysis carried out in LHGF unfortunately, in the majority of the wells only high temperature is a common fact, ie, 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 indicator of permeability existence in the thickness being crossing. It is important to emphasize that, low values of circulation during drilling at deeper is common in the generality of LHGF wells. However, it can be seen that all wells included in analyzed blocks, show temperature increase, as depth function. A characteristic behavior found in this analysis is that temperature profiles logged show thermal regression being this more remarked in wells located nearest to geological structures.

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 (such as penetration speed, transient pressure tests) results certainty will increase.

6. CONCLUSIONS

The static characterization methodology was applied by taking control parameters in geothermal reservoirs into account, whose results allow identify unperturbed state of the LHGF Mexican geothermal field. Through the methodology of static characterization used in LHGF, the reservoir initial conditions can be identified, which can be assumed as a reference level, before its evolution starting due to a continuous exploitation stage. Thermodynamic profiles behavior of the LHGF allow to identify its heterogeneity, which is associated with volcanic rocks. From the analysis related to fluid circulation losses during drilling, the major quantity of lost fluid (about 50 m^3/hr) occurred at shallow depths, while at the wells depth only were in the order between 4 to 10 m^3/hr. This behavior would be correlated with low permeability in the reservoir thickness.

From selection of temperature profiles, the shape of the wells were classified with similar behavior founding wells and similar temperature profiles trend, which can be associated with its closeness to geological structures. The static characterization is the technical support to identify reservoir properties at unperturbed state before exploitation start up. Correlation of the profiles of temperature, pressure, their corresponding gradients and lithologic Units support the assumption that LHGF behaves as compartmented. Thermodynamic and petrophysical parameters determined during static characterization are the support for the conceptual model construction and in numerical simulation.

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