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Integrated characterization applied to a geothermal system influenced by geological structures

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ABSTRACT

Even though geothermal systems can be present both in sedimentary and volcanic rocks, the majority are located inside volcanic type. Volcanic geothermal systems are characterized with high temperature containing high-quality energy, but their distribution is subject to geographical limits. Another characteristic is that magmatic set systems can be found in regions with basaltic volcanism. However, in geothermal volcanic systems it is important to note that geothermal resource is part of a geologic system where geologic parameters such as lithology, faults, fractures, fluid chemistry and geochemistry are influence factors in its behavior. The discontinuity in the rock formation due to structures is the reason for variety of different characteristics which, influences in a heterogeneous behavior changing from well to well, its physical, thermodynamic and mechanical conditions. An example of this behavior can be found in a particular zone of the Los Humeros Geothermal Field (LHGF) which is characteristic of a volcanic system highly dominated by its structures distribution. In this study are used both, static and dynamic characterization methodologies with objective for determining the wells performance which, helps to acquire criteria for planning field management. Data used are correlation of the formation lithology, geothermal interest levels, length thicknesses, circulation losses during drilling. Also the measurements temperature-pressure for determining thermodynamic profiles of each well are used. It is a common characteristic that producer wells of this field are of high enthalpy and correspondingly with steam fractions upper 0.75. The mass flow production of field overall wells is no more than 40 t/h, however the study zone involves two of the wells whose mass flow production is over 60 t/h. The behavior found of these different characteristics of this field, leads to assume that this is a compartmented system.

1. INTRODUCTION

Geological structures are known to have a strong impact on the feasibility of both as petroleum as geothermal systems. In both types of systems, the results of structures presence are visualized in the influence on the fluid flow and thermodynamic behavior. However, due to majority of geothermal systems are nested in volcanic rocks physical properties of rock formation are single and different to of sedimentary rocks of petroleum systems. The geological structures influence in existence of low porosities and permeabilities in volcanic formations, so, in rock matrix porosity frequently is assumed null and therefore secondary porosity plays a role in underground flow. Similarly permeability behavior takes place mainly in the flow through geological structures because rock matrix is impermeable. Due to all the parameters involved in volcanic systems, in majority of cases, geological structures and specifically, faults, determine the success or failure of geothermal projects (Loveless et al., 2014).

The impermeability of the rocks can be an advantage of volcanic formations because their capacity for heat conduction, due to solid rock is an excellent vehicle for heat transfer. The result of this conduction capacity of the rock, correlated with existence of the subsurface flow through structures influence in existence of geothermal systems, with enthalpies according to heat and fluid balance. In some cases would be high enthalpy systems or in another cases low enthalpy systems (Younger et al., 2012).

In cases that geological structures behave as conduits, it can be associate as permeability increase (Ferrill et al., 2004), which they may support a geothermal project. However, in some cases geological structures have behavior that makes difficult the underground flow, due to different causes behaving as barriers (Gibson, 1998). It is a common effect that structures in volcanic systems cause that nested reservoirs in this rock type, behave as compartmented system. Under this manner each compartment, even though are close neighbor, behaves with single characteristics, making difficult any possible correlation.

The same fault structure is an important parameter for assessing whether or not fault zones will increase or decrease permeability, which, would behave as conduits or barriers or a combination of both (Bense and Person, 2006). Also it is known that structures array along the geothermal system influences on spatial extents of the reservoirs and their capability. It is important to emphasize that the faults existing in geological environment, of the systems impact the reservoir properties and in each interval assessed. Another variable influencing the performance of geological structures in a system is the single lithology for each structure resulting in permeability variation.

The different distribution, type and direction of structures in geothermal systems together related with their volcanic nature are the reason for identify single behaviors in wells even though are nearby located between them. Another characteristic of these systems type is related to their different magnitude in the drainage radii of the wells, which to difference in sedimentary formations doing that due these radii the wells have individual behaviors. The implication from technical view point is focused for assessing the volume moveable through the structures net in the reservoir for being exploited. This assumption goes far away because could affect directly to reserves calculation in the systems and therefore in projects development (Jolley et al., 2010).

2. BACKGROUND

A geothermal system is generally classified by its geological, hydrogeological and heat transfer characteristics, however geological environment is referred to its domain structures (Sanyal, 2005).

Regarding to main structural elements influencing in depositional settings and fault controlled underground flow Laenen et al. (2004) studied limestones deposited in part of the carboniferous basin of northwest Europe.

Even though at surface the geology of the LHGF would indicate presence of several structures, it was appropriate to verify their continuity at deep, for which was used firstly the geophysical surveys and in drilled wells, their transient pressure tests. Additionally, lithology found in each well was used as a key factor for identifying the continuity of the geological Units with their different thicknesses. Because array and distribution of each lithological Unit allow determine deep and thickness of reservoir layer which could energy store.

Reservoir compartmentalization would cause boundaries due to variety of geological and fluid dynamic factors. In petroleum systems, Jolley et al. (2010) resume that difficulty for underground flow are referred to two possible causes: a) "static seals' in where structures, are completely sealed and capable of withholding (trapping) petroleum columns over geological time and; b) 'dynamic seals' that are low to very low permeability flow baffles that reduce petroleum cross-flow to very slow rates. Due volcanic nature of geothermal systems dynamic seals would be present in underground fluid flow in geothermal reservoirs because found permeabilities are too low, and specifically in LHGF is a common characteristic.

The predictive science and technology applied to reservoir compartmentalization studies are of big importance for company valuation, therefore an unexpected compartmentalization could also seriously impact the profitability of a field (Jolley et al., 2010). In petroleum systems concept of compartmentalization learning process has often driven developments in geoscience, reservoir engineering and related technologies. It has been possible enabling operating companies to identify and predict 'new' untapped volumes in old fields, make general improvements to field management (Jolley et al., 2007) and apply this knowledge to other similar, but less mature fields. However, reservoir compartmentalization can still be underestimated during field appraisal, and can still give surprises that force a re-think of the field development and production plan (Smith, 2008).

Geological structures appearing at field surface are a challenge for identifying the depth at which they have influence in system behavior, due to its nature, show a rapid and unpredictable variation in the rock formation content and architecture (Knai and Lescoffit, 2020). So, structures representation in reservoir models will necessarily be a simplification, and it is important that the uncertainty ranges are considered in the input parameters. Same authors (Knai and Lescoffit, 2020) introduced "Juxtaposition Table Method" technique for efficiently handling all relevant geological and production data in fault property modelling process. This technique, using appropriate parameters can be adaptable to similar studies in geothermal systems.

Due to shown characteristics and behavior of structures inside and around in the LHGF is possible to assume that is a compartmented system. By this reason in this study it was selected a zone of this field which its wells been shown a particular behavior different to those of neighboring zone and additionally different to those of the whole field.

3. THE LOS HUMEROS GEOTHERMAL FIELD

The LHGF is the third place producer field in Mexico with installed capacity of aproximatelly 95 MW (Gutiérrez-Negrín, 2019, Norini et al., 2019). It consists of approximately 25 production and four injection wells and is located in the eastern portion of the Mexican volcanic belt, near the border of the Sierra Madre Oriental province (Ferrari et al., 2012). The producing area is within a complex caldera system, with a mean altitude of about 2800-2900 masl (Ferriz and Mahood, 1984). Figure 1 shows field location together with wells and main geological structures. Since the first stage of fluid extraction which started in 1982 (Arellano et al., 2015), maximum temperatures upper to 350 °C were measured in its geothermal wells located in the northern part of the field. A condition of high enthalpy in the majority of the wells, has characterized the LHGF, excepting in some of them around the zone to well H1.

Along the field development successful drillings have allowed identify locations of production wells; through grouping of these, the field takes an elongated form toward northern section. At present have been drilled about 60 wells with deeps varying between 1800 and 3000 m. The most prolific producing wells are located in the northern part of the field, where hot fluid circulates mainly through the possible active NNW-SSE structures. An important case is that non-productive wells are located in the vicinity of the E-W trending structures in the eastern part of the geothermal field and the region west from the NNW-SSE faults (Norini et al., 2015; 2019)

The flow in the wells of Los Humeros is driven by the interconnected geological structures. This is a normal behavior considering that the geothermal system is composed of volcanic rocks as the host rocks, whose matrix does not have porosity, however only through structures, low permeability and secondary porosity. An important characteristic related with geothermal reservoir is that production intervals in the wells are structurally controlled by intersection of rock formation with main structures. Additionally, the effect of structures intersection with the rock formation creates a damaged zones which, can be extend for several hundred meters giving rise to a widely spread productive well behavior. In some cases, this zone, it can be assumed and correlated with the drainage radius of well and by this reason each one has own.

Through operative life of LHGF wells, has been possible to apply some of the integrated characterization techniques in order to classify them. Information recovered during drilling and heating stages before production discharges have been useful for carry out static characterization. In this work mainly was applied recovered information during heating stage, which involves pressure measurements profiles, in order to identify feeding intervals in the rock formation. Besides, in this work is used, production history and thermodynamic evolution of the wells as demonstration of one of the tools for dynamic characterization.

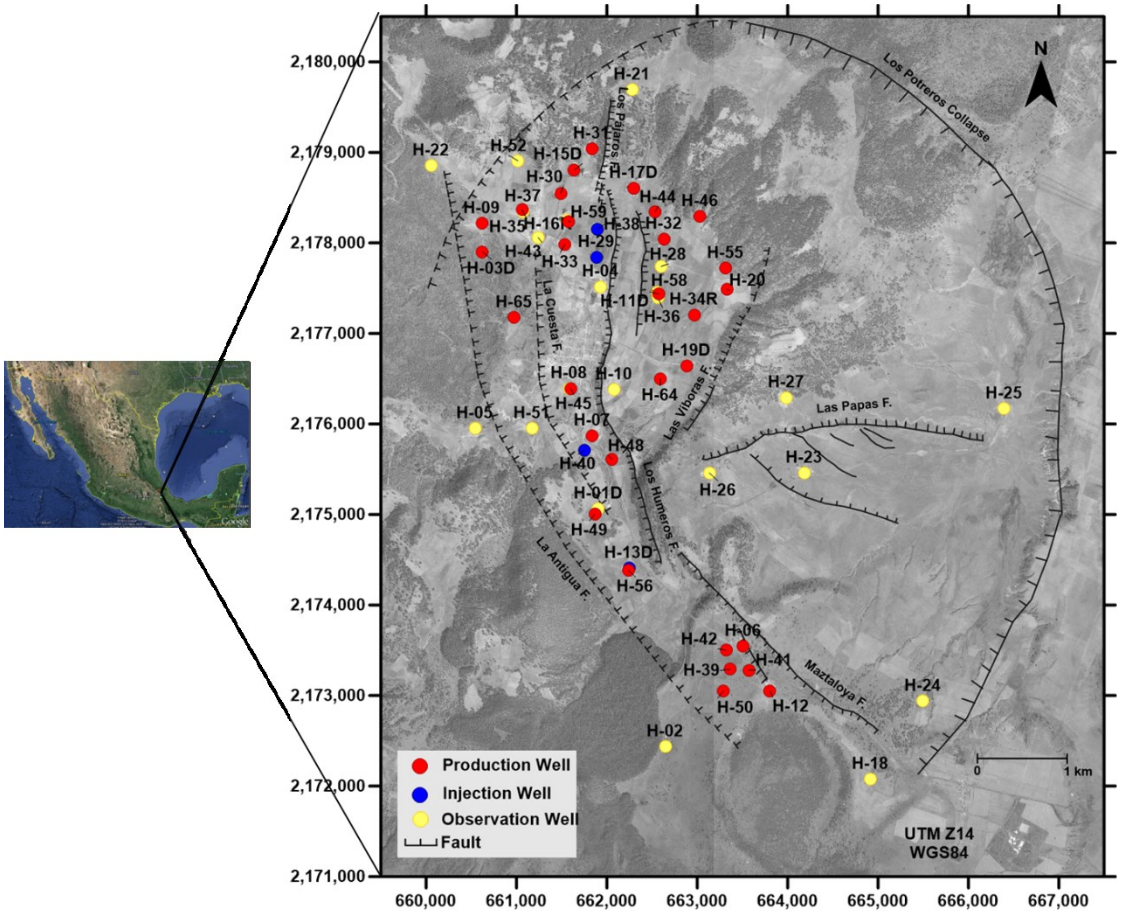

Figure 1: Location of LHGF with its corresponding wells with their own classification and the main structures prevailing.

Analysis of pressure measurements is based on the assumption that after disturbance provoked by drilling and completion activities such as transient pressure tests, the well is closed in order to start its heating stage. During this reposes stage in the well, both pressures as temperatures tend to reach equilibrium with the thermodynamic parameters distribution in the geothermal reservoir. Velocity of this process is function of all the physical and thermodynamic system properties (fluid, rock formation, heat source, recharges entrance, etc., among others) (Grant and Bixley, 2011). Along heating stage, the pressure profiles measured in the well typically move about a fixed point called the pivot point. This is because, during heating up the water density change, the corresponding pressure profile change and in some cases reaches boiling point. Studies carried out by Bjornsson (2004), Hole (2008), Santoso (2017), allowed identify through pivot point location of a single permeable zone.

Taking into account evolution of pressure along the wells profiles due to temperature increase during their heating stage, the methodology applied uses two pressure measurements at different time. Under this way, these pressure profiles during heating up intersect and move around a common point called as "pivot". A characteristic behavior is related that if the well has a single feed zone, the pivot point is located at the depth of that feed zone, whereas if the well has several feed zones the pivot point should be located between these.

Predominantly, the pressure of the pivot point is controlled by the main alimentation of the reservoir that could be the recharge or could be related to the fluid mass distribution along the feed zones. Therefore, the pivot point gives solid information on the pressure of the reservoir at that depth.

Static characterization is useful for determining initial conditions of system through correlations of wells information before startup continuous production. With more wide application, static characterization is one of the bases for evaluating and confirming the original reserve of the system.

Production history and the thermodynamic evolution information of the wells are related to decline trend of each well and moreover through appropriate correlation are useful for identify reservoir decline trend and its remaining reserve.

4. TECHNIQUES APPLICATION

Taking into account the geological structures array of the LHGF, the western section of its central zone was selected for applying characterization techniques mentioned before. Figure 2 shows a visualization of this study area, specifically the analyzed wells are located inside corridor bounded by "La Cuesta" and "Los Humeros" faults. Firstly it is important to highlight that wells located more toward western didn't result producers such as H5 and H51.

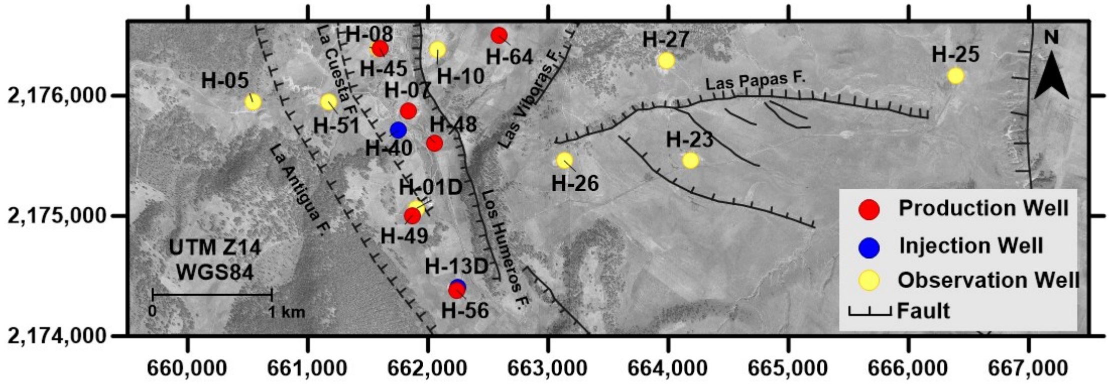

Figure 2: Studied wells located between corridor bounded by "La Cuesta" and "Los Humeros" faults at western section of central zone of LHGF.

In this study, the technique of the pivot point was used as a tool, for static characterization of western sector of central zone of LHGF. For achieving this aim were correlated temperature and pressure measurements during repose time and heating stage in order to identify possible feed intervals in the wells. The wells involved in this study are those appearing in the corridor bounded by “La Antigua” and “Los Humeros” faults, excepting wells H13D and H56 located to south section of this group. Similarly, with comparative objectives, another well, the H64 located in another compartment, bounded by “Los Humeros” and “Las Víboras” faults, is involved.

Through correlation of pressure and temperature measurements along wells profile it was possible to identify the feed interval and pivot point with their corresponding pressure. As an example of this analysis technique in Figures 3 (a) and (b) temperature and pressure profiles of the well H1D are shown, which is one of that resulted producer and declined in its production. While in Figures 4 (a) and (b) temperature and pressure profiles of the well H48 are shown.

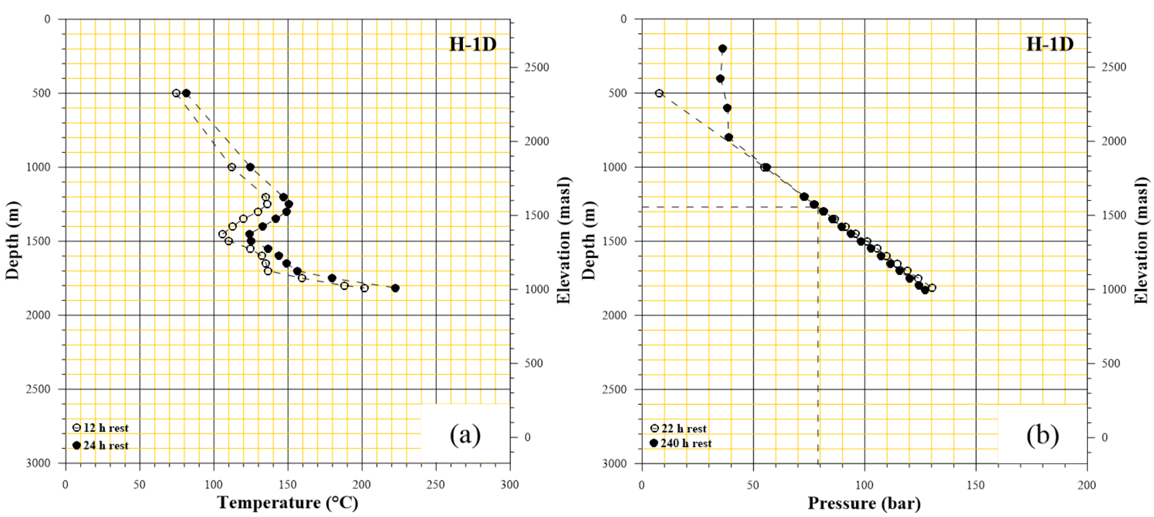

Figure 3: Profiles of temperatures measured during completion stage of the well H1D and pressures during heating stage, for determining its feed interval and pivot point.

After heating stage the well starts up to continuous exploitation and the geothermal system arrives to a perturbed state, so, the dynamic characterization techniques are applied. In this work, production history and thermodynamic evolution of produced mass are used for characterizing wells behavior and by correlation of the whole system.

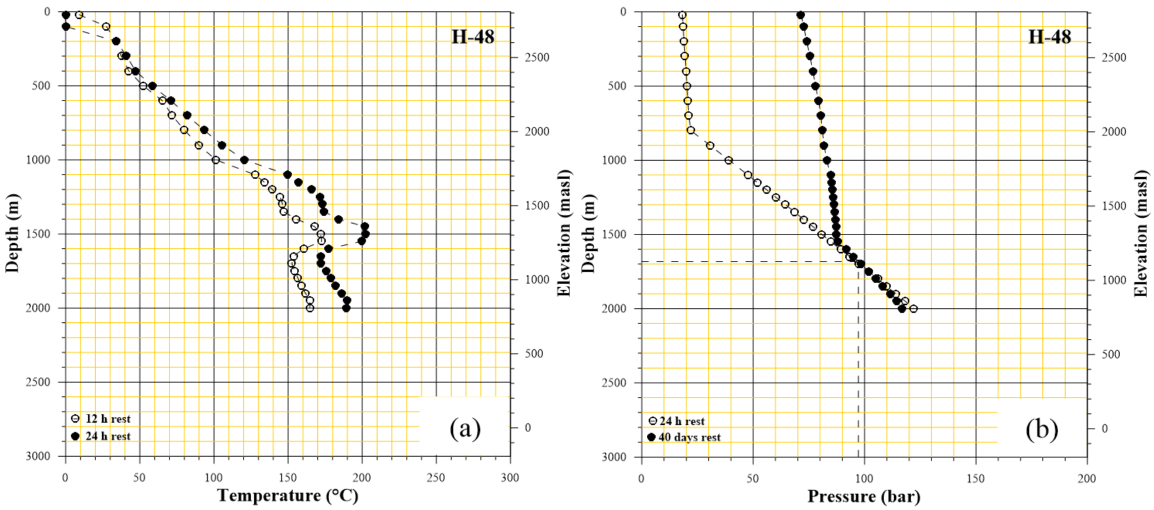

Figure 4: Profiles of temperatures measured during completion stage of the well H48 and pressures during heating stage, for determining its feed interval and pivot point.

For this case were used data of same wells used in static characterization, therefore Figure 5 shows production history behavior of wells H1V (vertical) and H1D (deviated). While in Figure 6 Mollier diagram with production data measured in both wells (H1V and H1D) along their operative life are shown. From this figure it can be identified that enthalpy values of these two wells fluctuate between 1400 and 1500 kJ/kg, while in the wells majority of the LHGF, enthalpy values are upper to 2000 kJ/kg.

The well H1D was drilled with objective for substituting the well H1V which had declined, however also its production decline started after nine years of continuous operation, as can identify in Figure 5. Production of both wells, is with major water that steam quantities and it can be seen in Figure 6 whose steam fraction ranking in values between only liquid to 0.5. The highlight is that the increase of steam fraction in this case comes up with its production decline trend. Through Figures 5 and 6 correlation, it is possible identify the production decline of wells H1 (“V” and “D”), associated with enthalpy increase but pressure decrease. Figure 7 shows thermodynamic behavior of another well of this studied zone, showing prevailing enthalpy in the majority of wells, which is higher compared with that of wells H1s.

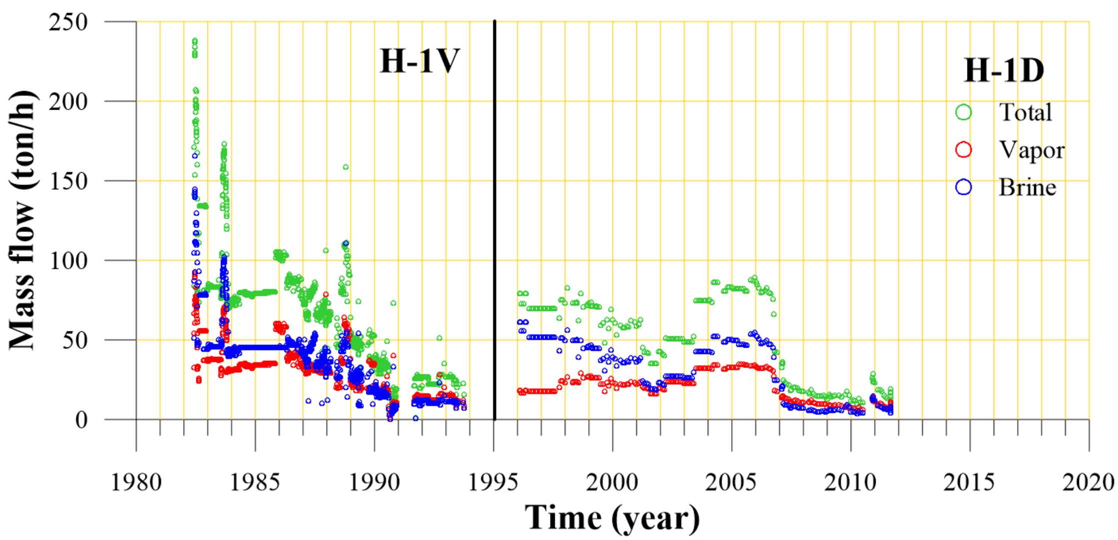

Figure 5: Production history behavior of wells H1V and H1D, located at western section of central zone of LHGF, highlighting their production decline.

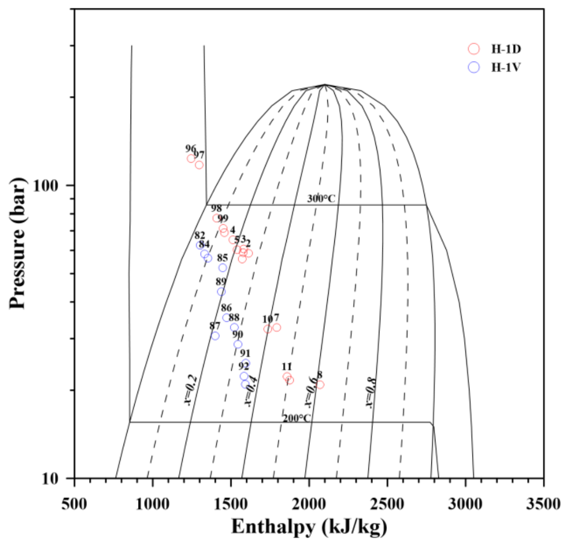

Figure 6: Thermodynamic behavior of wells H1 ("V" and "D") along their operative life.

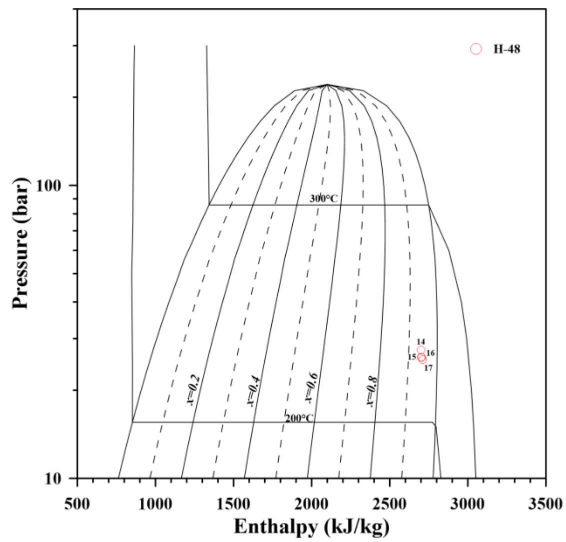

Figure 7: Thermodynamic behavior of well H48 along their operative life.

5. DISCUSSION

As a result of the analysis applied in this work using data for static characterization, locations of pivot point are shown in Figure 8. Taking into account map of Figure 1, it is important to highlight that wells located more toward western didn't result producers such as H5 and H51, which can seems associated with structures influence. Moreover bot two wells are located in another structural corridor bounded by "La Antigua" and "La Cuesta" faults. Regarding this observation, highlights the influence of compartmented behavior of the system.

In order to show an idea about relation of the completions of all the analyzed wells was developed a scheme showing their depths with corresponding thickness open to formation through its slotted liners, shown in Figure 8. As can be seen from Figures 1 and 2, excepting well H64, all considered wells in this section are located between corridor bounded by "La Cuesta" and "Los Humeros" faults. Additionally a slightly more toward southern, appear wells H13 and H56.

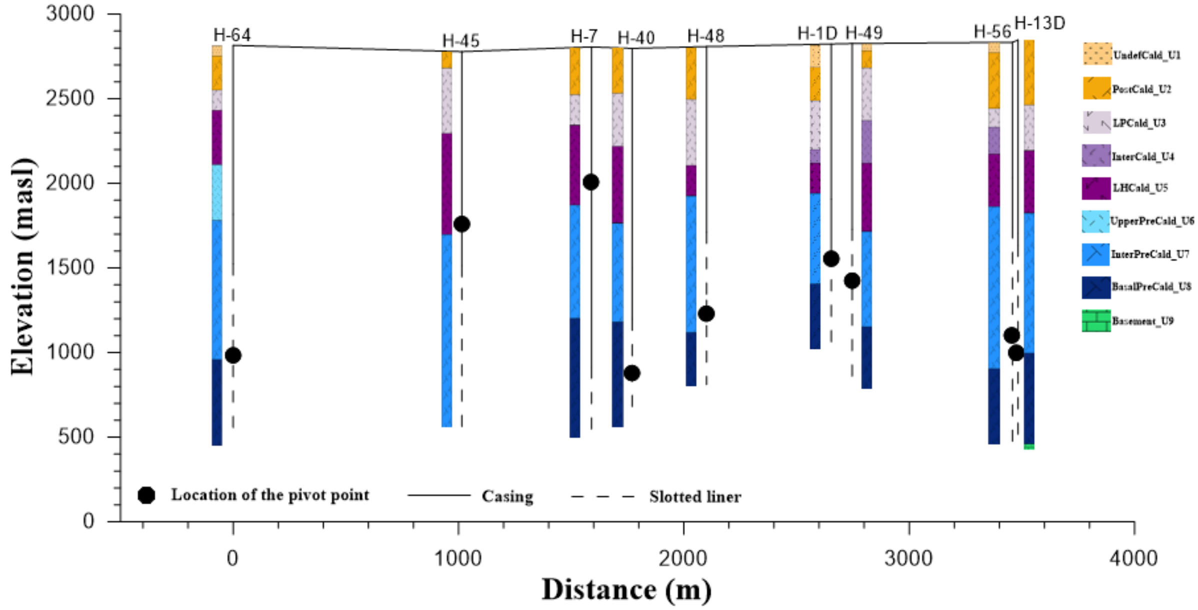

Figure 8: Section involving wells located at the western section of central zone of LHGF, bounded by "La Cuesta" and "Los Humeros" faults excepting well H64 which is located in the corridor bounded by "Los Humeros" and "Las Víboras" faults.

Majority of the wells, considered in Figure 8, excepting H40, resulted producers even though some of them were extracted of operation, because their production decline. However it is highlighted the common characteristic that generally theirs completion levels are at similar level. Also in this same figure are included lithological Units found in the wells distinguishing that even though the well H45 resulted producer, it is lacking of the lithological Unit 8. Besides, the wells located inside this corridor between “La Antigua” and “Los Humeros” faults even though resulted producers, some of them are turn off from operation due to their production decline.

Another observation resulted from this study is that, the pivot points of all the wells majority of section of Figure 8 were located at similar levels. However the pivot points of wells H7 and H45 were located at different upper levels to of the wells of this block. Another observation in static characterization is that excepting H45, even though is deep, all the involved wells found lithological Unit 8.

Using dynamic characterization, related with thermodynamic behavior in wells, it can identify that steam fractions of well H1, show lower values, respect to another wells of LHGF, whose steam fraction are upper 0.8.

Regarding production behavior of wells in this studied zone even more can be identified another classification; first one, with those wells located inside corridor bounded by “La Cuesta” and “Los Humeros” faults (H7, H8, H45 and H48). Another one, with the wells located more toward southern, where the corridor enlarges its width, bounded by "La Antigua" and "Los Humeros" faults (H1V, H1D, H49 and H56). Calculated production decline rates by year, of these wells, using linear and normalized techniques (Sanyal et al., 2000), are shown in Table 1. From this table, it can be seen the difference in decline production shown by wells located in the shorter corridor compared with production decline of wells located in the wider corridor

Table 1: Decline analysis of the production wells located in the central area of the LHGF.

Well	Total production (ton/h) / year		Status	Period	Boundary faults of the Corridor
	Linear	Normalized			
H1V	-10.46	-10.48	Turned off	Jun 1982 – oct 1993	“La Antigua” and “Los Humeros”
H1D	-13.93	-14.75	Turned off	Feb 1996 – sept 2011	
H7	-1.03	-0.13	Producer well	Jun 1991 – jun 2017	“La Cuesta” and “Los Humeros”
H8	0.09	0.27	Turned off	Sept 1991 – jun 2010	
H45	-5.75	-5.76	Producer well	Feb 2011 – jul 2017	
H48	0.56	0.22	Producer well	Apr 2015 – jul 2017	
H49	-23.83	-26.29	Producer well	May 2015 – dec 2016	“La Antigua” and “Los Humeros”
H56	-89.85	-90.86	Producer well	Jun 2016 – sept 2016	

6. CONCLUSIONS

From wells behavior in LHGF it was found that the geological structures influence that each well behaves singly with characteristics different from its neighboring.

Due that LHGF is nested in a volcanic systems it is important to note that geothermal resource is part of a geologic system where parameters such as lithology, faults, fractures, fluid chemistry and geochemistry are influence factors in its behavior.

The discontinuity in the rock formation due to structures is the reason for variety of different characteristics which, influences in a heterogeneous behavior changing from well to well, its physical, thermodynamic and mechanical conditions.

The volcanic nature of LHGF does that heterogeneity domains the system and by this reason, the complete column of lithological units not always appear in wells or exists discontinuity, even though are nearby.

The continuity lack in lithology of volcanic systems is manifested in the petrophysical properties due to its heterogeneity and the effect is even more intense in underground flow and its thermodynamic properties.

In LHGF both as petrophysical properties, thermodynamic distribution, as production behavior have contributing for a scenario of compartmented system. Under this concept were reviewed geological structures which have influence in the whole system, majority of them, can be distinguished at surface.

The studied zone of this work was selected due to it seems a little isolated from the wells group of north and south zones and production wells, startling show particular characteristics between them, even though are in same compartment.

The review results were compartments identification which are bounded by geological faults. Characteristics of compartmented behavior allow determine external bounds of the reservoir and evaluate only resource reserve, which conform the base of static characterization.

Methodology applied allowed identify thermodynamic evolution in the reservoir through wells behavior in which highlights the enthalpy increase but pressure decrease till to arrive admission critic limit to power plant.

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