PROCEEDINGS, 49th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 12-14, 2024
SGP-TR-227

Correlative Analysis of Parameters for Taking Decisions of Geothermal Well Completion

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Keywords: Loses circulation, lithology, pressure, temperature, transient pressure testing, production thickness

ABSTRACT

The drilling of the Wells is a direct alternative for verifying the hypotheses formulated from geochemical, geological and geophysical surveys developed during exploration stage of a field. The target of the well drilling is to achieve reservoir and identify firstly, its main physical characteristics such as formation thickness with the seal cap and basement, its permeability, porosity. Nevertheless, even though thermodynamic characteristics are the main objective be achieved in a geothermal well; it is important emphasize that combination with the physical rock properties, adds for obtaining successful results. Due that drilling represents an important possibility for knowing reservoir characteristics it is required a specific and continuous monitoring of each parameter associated to reservoir response. Among others, these parameters are: Rate of penetration (ROP) during drilling, input and output temperatures of drilling fluid, lithology definition from analysis of cutting samples rock formation, fluid circulation losses, temperature and pressure log series and in some cases chemical sampling of fluid drilling. Combination of permeability (identified from high fluid circulation losses) associated with its lithologic formation and high temperature provides a technical support for deciding the drilling stop and analyze formation conditions. In this stage, are programming log series of temperature-pressure at different repose time and transient well test, whose results allow to take decisions on drilling continuity or initiate well completion. Thermodynamic log series allow determine static rock formation temperature, its heating intervals, profile of indices heating and combined with transient pressure test to design the appropriate well completion and arrangement of slotted liners or without slots. In this paper are shown cases of geothermal wells where was applied this methodology helping to take decisions on the thickness or thicknesses selection be exploited in the well, with its corresponding completion design.

1. INTRODUCTION

The deep drilling wells, was initiated as ordinary practice in petroleum technology for oil and gas extraction, even though had been used wells for water exploitation however these type wells are of shallow depths. With development of geothermal resources, as a procedure for heat extraction associated with reservoir fluid, the drilling of deep wells was chosen. So, many techniques of petroleum were adapted to geothermal engineering, taking into account the differences of the wells depth, fluid characteristics, thermodynamic properties, formation types etc., among others.

Even though superficial exploration techniques could give an idea on the presence of geothermal reservoir, these can only be confirmed through drilling. The drilling is the main possibility for supporting hypothesis formulated by the geoscientific surveys could, due to, it is the direct way for knowing reservoir properties. During the drilling exploration stage, there is a risk that the well does not resulted producer and would be a reason for the project abandonment, by this reason it is a main task consider the analysis that could conduct to identify geothermal characteristics during the well drilling. Correlation of all information obtained during drilling stage helps to achieve successful results in the well and to design its appropriate completion. It is important monitoring each one of the events occurring during the drilling well because these help to construct a concept about its characteristics at depth. Firstly, at drilling starting these events are associated with formation rock properties, between them are mentioned drilling speed, hardness rock, lithology, losses fluid drilling. With drilling advance and depth increase, thermodynamic parameters take a relevant importance, in this sense the monitoring difference between entrance and exit of circulation fluids temperature is an indication of the nearby with geothermal strata.

Geothermal conditions require combination of rock formation permeability with thermodynamic state of fluid in the well. However, ach parameter along drilling advance allows identify the appropriate depth for taking so thermodynamic logs and analyze convenience for carry out transient pressure tests. The results of these two lasts are useful for taking decision on the well completion, selecting the depth and designing its intervals open to formation.

A successful completion of the well involves determination of formation intervals with characteristics be exploited which finally conform the reservoir thickness be used in numerical simulations for reserves evaluation and reservoir characterization. Besides, the appropriate selection of depth for drilling suspend in order to carry out thermodynamic logs and transient pressure test helps to avoid expenses, due to drilling continuation which could be unnecessary. The design of the well mechanical completion is based in reservoir characteristics, and is focused to care in locate efficiently of slotted pipes for best inflow from the reservoir to well.

By all concepts mentioned before, the decisions taken on the drilling continuity at depth are supported by each one of the monitored parameters during drilling, even though the decisions on the well completion are the thermodynamic conditions and permeability. The results of the analysis of the measurements carried out at the completion stage are useful for taking decisions on the use of the well. Even though the main objective is obtaining a producer well, its conditions (such as low thermodynamic parameters and permeability lack) could orientate be used for other objectives.

Under this idea, it is important take into account the done inversion for the well drilling and therefore it seems appropriate and necessary to consider an alternative use with which can recuperate at least some part of its cost. So, the well rescue could be focused for be used as injector of the produced waste brine. Besides, if there is not permeability, some of the alternative uses could be such as; for taking advantage of the low enthalpy heat in applications such as binary cycle, heat exchangers, direct uses, among others. Due to is required that renewable energy technology be much more sustainable, the state of the art on the utilization and improvement strategies use of geothermal energy is reviewed by Sharmin et al., (2023).

The objective of this work is to show a review of the drilling parameters influencing for taking decision on the appropriate depth for the well completion and select its appropriate mechanical design, in order to obtain de major benefit possible.

2. CONCEPTUAL FRAME

Typical rock types in geothermal reservoirs include: Granite Granodiorite, Quartzite, Greywacke, Basalt, Volcanic tuff, which are characterized by its hardness, high density, low permeability, poor or null porosity and highly fractured. These characteristics are influencing factor for identifying the appropriate levels and thicknesses of geothermal interest in the well (Hu et al., 2022). Confirmation of the type rock is done during drilling through the cutting samples recovered in order to construct lithology columns whose correlation between neighboring wells allows obtain system configuration. Lithologic columns constructed from drilling cutting samples allows monitoring the nearby of the target at depth, such as Ranalli and Rybach, (2005) in Central Lattera, Italy, Mc Namara et al. (2019) in Wairakei geothermal field of New Zealand and Zierenberg et al., (2021) in well IDDP-2 in Iceland.

The rock formation hardness is directed associated with its lithology type and in consequence with penetration rate during drilling. In the framework of the ThermoDrill project (included in H2020-EU Program), Baujard et al., (2017), analyzed rate of penetration at depth of some of the wells drilled in different sites in European Union (Soultz-sous-Forets, Rittershoffen, Insheim and Basel).

In the majority of the cases geothermal wells are drilled with long segments of lost circulation, which could create drilling problems including complete loss of drilling fluids and blind drilling. Total lost circulation occurs as a result of a weaker formation or open fractures or voids. Under this circumstance, stratigraphic information typically gleaned from cutting samples is unavailable. Drilling fluid loss can be massive, requiring pumping rates of hundreds of barrels per hour and resulting in underbalanced drilling, influencing in high costs, besides making casing cementing difficult (Rehm et al., 2013; Hickson et al. 2020). Lavrov, (2016) indicated that the circulation loss-related costs were around 10% of total non-productive time. Between the risks of circulation losses are: a) that the cuttings that do not are extracted to surface are introduce inside the well cavities causing damage to formation and, b) that can provoke suddenly lower the fluid level in the well allowing the formation fluids to enter the wellbore causing loss of well control (Kipsang, 2017). In geothermal systems, the lost circulation in drilling wells has been due to natural fractures (Cole et al., 2017) and complex networks of fractures, in addition to the those thermally induced (Rossi et al., 2020). A review of drilling challenges related to lost circulation problems in geothermal drilling was carried out by Saleh et al., (2020). Mitigation of the drilling high costs in order to change it in an opportunity for obtaining a successful well was analyzed by Magzoub et al., (2021). Even though the fluid circulation losses during drilling represent a challenge in its advance in a certain manner are indicative of permeable intervals presence in the rock formation.

Thermodynamic conditions are the main target for finding in geothermal drilling and these are the support for verifying the hypotheses developed from superficial studies and measurements carried out during exploration stage. The target depth is accomplished when is found a perfect combination between thermodynamic saturation state, permeability and hydraulic recharge at the bottom hole.

An analysis review on the relationship between reservoir thermal parameters and geothermal energy output was carried out by Grippi (2018). In his study, six reservoir parameters well depth, temperature, enthalpy, mass flow rate, thermal gradient and crust thickness were plotted against the net electrical output per production well and exergy efficiency of 64 geothermal facilities. From this study, Grippi (2018), identified that reservoir temperature has the greatest proportionality to power output, with yields above 10 MWe exhibited only for high enthalpy reservoirs. However well depth has the greatest inverse proportionality to exergy efficiency, with upper limit values declining below 80% for wells deeper than 3000 m.

During drilling suspension at short repose time, occurs transient state and heat-up is used for determining profiles of the static temperature and pressure which are measured to identify the pressure control point which helps in identification of the major feed zone and the well thermodynamic state. Similarly, this measurement set, allows identify the well main feed zone from which is going to produce; as well its injectivity for determining the transmissivity of the producing formations (Grant and Bixley, 2011; Bixley et al., 2016).

The completion testing program includes several tasks, which that help identify the main feed zones in the well, between them are mentioned next: a) serie of temperature-pressure logs at repose times of 6, 12, 18 24 and 30 hours; b) at least three injection tests at different flow rate each one, with buildup and fall off periods, if possible with long times for achieving pseudo steady state, including the spinner measurement if it is possible; c) it is recommendable a second series of temperature-pressure logs at repose times of 6, 12, 18 24 and 30 hours. This last series of measurements is useful due to thermal disturbance times and repose are known times; however due to cost of drilling equipment without working, sometimes does not feasible.

3. PARAMETERS PRESENT DURING THE WELLS DRILLING

In this section, a review of the drilling parameters which help for taking decision on the appropriate depth for the well completion and select its convenient mechanical design is done.

3.1 Lithology

In an geothermal system are concurrent one source of high temperature, reservoir of hot fluids, lithology with permeable structures and, its cap rock which acts as seal. Lithology is one of the technical tools for rock formation characterization in geothermal reservoirs helping to an improved understanding of rock mechanics in a geothermal environment. (Wering, 2015). It is important to consider that permeability related to fault zones is a first-order control on fluid flow in the system. Lithology found along the drilling well is determined from the cutting samples brought to the surface by circulating drilling mud and its monitoring helps for indicating location of target depth of the geothermal reservoir.

It is important to take into account that geothermal systems are nested in volcanic formations which are heterogeneous and the structures domain the underground flow. The lithological column of the wells is constructed progressively during its drilling advance and this is the first technical tool for confirming the formulated hypotheses by the exploratory geological and geophysical surveys. Its monitoring during drilling gives information on the nearby of geothermal depth can be assumed as target for exploitation. Correlation with neighboring wells is even most useful for configuring its distribution around the field in order planning its development. In spite of the geothermal system is into fractured volcanic environment, with structures and faults, correlation of lithology between wells can deal to identify bounds of the system. So, through correlation of lithology distribution with bounds of the system, thermodynamic properties, formation intervals with some permeability can be constructed conceptual model for numerical modeling and initial reserve evaluation.

By the different mentioned reasons, the lithology monitoring is one of the technical tools used as guide for knowing traversed formations during drilling and the closeness with possible geothermal interest intervals. This is being as an ordinary task in different geothermal fields around the world as can be seen in Figure 1, which shows lithologic columns found in geothermal fields of Central Lattera, Italy (Ranalli and Rybach, 2005), Cerro Prieto, México (Arellano et al., 2011), Wairakei, New Zealand (McNamara et al., 2019), and Reykjanes, Iceland (Zierenberg et al., 2021).

3.2 Temperature

Thermodynamic conditions are the main target for finding in geothermal drilling and these are the support for verifying the hypotheses developed from superficial studies and measurements. Temperature profiles taken along geothermal wells provide very useful information regarding the fluid and thermal properties of the reservoir formation. The well temperatures are highly disturbed by drilling fluid circulation due to cold water injection into the well the temperature profiles could provide results altered of the state real in the well due to transient effects. In order to obtain an approximation of the well temperature at steady state conditions, it was introduced, from petroleum technology, the Horner method (Horner, 1951), for determining static temperature of the rock formation. The static temperature profiles, can be used for modeling the natural state of the system in order to estimate initial reserves of heat stored. Techniques for determining static temperature profiles use temperature measurements at different period of repose times during drilling. Due to stand by times for achieving repose in the well, during drilling are high cost, it is a customary to program series of temperature-pressure logs taking advantage of the cement jobs of the different pipes. In this way series of temperature-pressure measurements are carried out at 6, 12, 18, 24 and in some cases till 30 hours of repose time.

Taking advantage of pipe cementing according to the well design, some periods of repose time (6, 12, 18, 24 hours) are used for obtain temperature-pressure measurements. The depth at which occurs each drilling stop is the point with minor thermal disturbance caused by fluids circulation. So, this point represents an opportunity for applying numerical methods for determining static temperature at steady state after transient effects have been overcome. Besides, through correlation of these measurements with neighboring wells it is feasible obtain temperatures distribution in the system. A previous sign that the drilling is nearby of the interest thickness is through record of entrance and output fluids temperature. Through indicative combination temperature increase (Δt) and circulation losses can to take decision on the drilling break off and to program temperature-pressure measurements and possibility for developing transient pressure tests.

Temperature profiles of Los Humeros, México geothermal field, taken at different repose period times in some wells are shown by Aragòn et al., (2023). From these measurements were determined static temperatures and were compared, in some cases, with measurements carried out at long times (during the heating stage, before production starting. Figure 2 shows a compilation of temperature measurements in one of the Los Humeros wells, taken with short repose times (between 6 and 24 hours), after appeared signs of temperature increase and circulation losses during drilling. From this figure it can be identified the thermal conductive effects along repose time after cooling caused by drilling fluid disturbance. The repose period of these measurements is at short times (between 6 and 24 hrs) i.e. these still corresponding to transient state and due this condition it can be see that exists heating in the well. After heating interval can be identified another of cooling which elongates to total depth of the well.

3.3 Pressure

Pressure is one of the thermodynamic parameters used for well characterization, together with temperature log. For this reason, both logs are run along the drilling wells to assess reservoir conditions for taking decisions on the appropriate depth for stop drilling and carry out tests and measurements for the well completion. In water-dominated reservoirs, above the steam zone the pressure will increase with increasing depth. Inside the steam zone, the fluid pressure will stay almost constant, below the steam zone, the liquid occupies the opened channels, which will make pressure increase again with increasing depth.

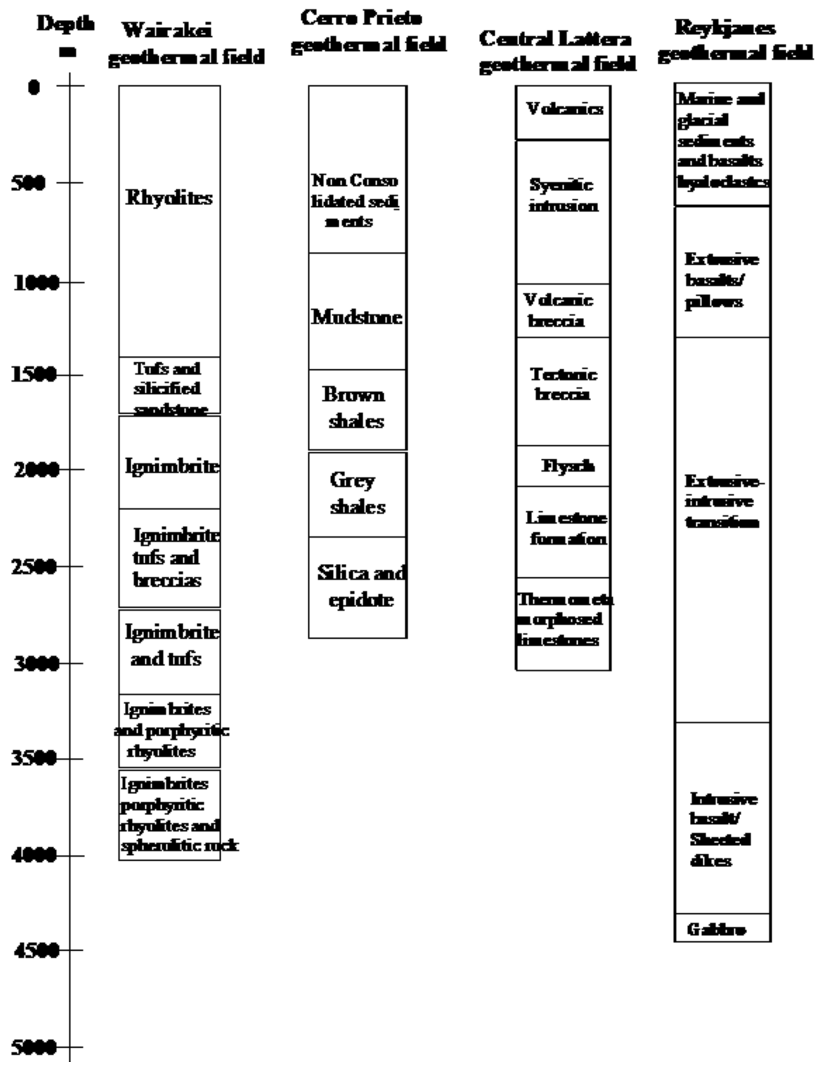

Figure 1: Lithology columns constructed from cutting samples in geothermal fields Wairakei, New Zealand (McNamara et al., 2019), Cerro Prieto, México (Arellano et al., 2011), Central Lattera, Italy (Ranalli and Rybach, 2005), and Reykjanes, Iceland (Zierenberg et al., (2021).

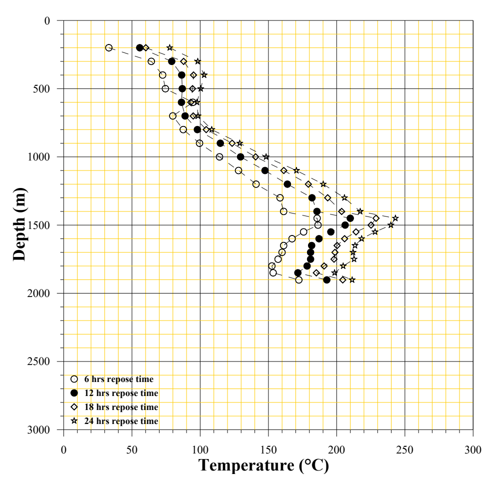

Figure 2: Temperature profiles measured at short repose period times in well H30, of Los Humeros México, geothermal field

The continuous phase along the opened channels is hot water and the hydrostatic pressure increases with depth (Ranalli and Rybach, 2005). In wells with steam cap the pressure profile becomes lower in the upper part that the hydrostatic pressure profile. The water-dominated reservoirs with a steam cap have a high storage coefficient, for this reason the pressure drop is lower.

Pressure profiles are used for determining the communication intervals with shallow aquifers and its relation with the reservoir feed. Identification of static level in each well and its correlation with its adjacent helps for developing aquifer configuration in relation to its pressure distribution. Maximum reservoir pressures, at 4000 m depth vary around 400 bars, which correspond more or less the hydrostatic charge. However, in geothermal systems due to depth of static level, fluid temperature, its density, influence for obtaining slight less values. Similar observations done by Robins, (2021) are focused to some geothermal fields where the groundwater and geothermal fluid, mesh in the subsurface, as a natural process, resulting pressure values less than a hydrostatic column.

A main characteristic of geothermal systems, due to its vulcanism, is that related to in a same field the static level could vary in its wells even in those neighboring, such as shown by Aragón et al. (2023). Pressure profiles of Figure 3 correspond to four different wells of Los Humeros, México, geothermal field and these, show different depths at which static level was determined. By correlation of temperature, pressure, circulation losses profiles with lithology found it is possible define to appropriate depth for the drilling suspend and analyze conditions for carry out transient pressure tests and possibility for the well completion.

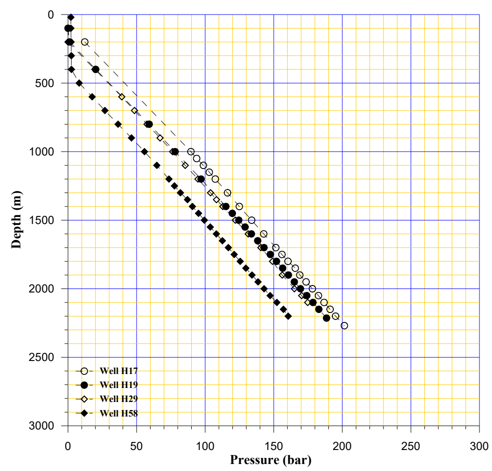

Figure 3: Pressure profiles of four of the wells of Los Humeros geothermal field, developed with measurements taken at their completion stage.

3.4 Transient pressure tests

Technology of transient pressure test was introduced in petroleum system. The objective is generating a transient disturbance in the reservoir through the well, following stop of this effect, observe the reservoir response. Along development of technology, pressure, as disturbance appropriate has been chosen, because reservoir shows sensibility to production or injection through pressure changes. As mentioned before main factor used for producing pressure transient is the flow rate, therefore in producer wells changes in production are applied; opening, closing, increasing or diminishing well production. While, for cases of no producer wells such as are in drilling completion stage; it is used water injection for create pressure disturbance. Taking advantage of injection there is a first period (build-up) is measured pressure increase and in posterior period after stop injection, (fall-off) it is measured decrease pressure to its initial state (Bobadilla, 2012).

A pressure-versus-time plot yields a curve whose shape is dictated by reservoir characteristics; information embedded in these curves constitutes the primary goal of transient testing interpretation. Among various applications of transient pressure tests analysis are; reservoir parameter characterization, assessing heterogeneity, estimating boundaries, thickness, and geometry, as well as hydraulic communication between wells. Transient Pressure Test analysis has been successfully employed in numerous case studies worldwide, serving diverse purposes in the characterization of geothermal reservoirs. A two-rate flow test, conducted in Cerro Prieto geothermal field by Rivera and Ramey (1977), concluded that it was possible to calculate basic reservoir parameters. Bakar and Zarrouk (2018), carried out a study applied in the Soda Lake geothermal field in the Carson Dessert, Nevada, showing a similar approach using the TOUGH2 geothermal reservoir simulator, for fractured well behavior during injectivity testing.

Pressure transient analysis in well MOL-GT-03 located at northern Belgium was applied by Adiputro et. al., (2020); this study case presents a numerical framework utilizing the TOUGH2 simulator to analyze wells displaying oscillations that cannot be easily interpreted using existing analytical methods. Pressure behavior in volcanic systems such as existing in geothermal resources, is different to that manifested in petroleum systems; the main reason is the rock formation heterogeneity. Therefore, pressure transient tests have behaviors which could be considered particulars, because do not follow the patterns established for petroleum systems. An example of the particular time-pressure behavior curve in a geothermal system, is shown by Sanchez et al. (2015). This behavior has been found in different geothermal wells drilled in volcanic systems. An example of this graphic type time-pressure for an injection test which would behaves with pressure constant increment during build up period is shown in Figure 4; however, it can be identified a different behavior due to volcanic system.

Transient pressure test data initially are plotted in different coordinate systems: a) Cartesian graph, for general diagnosis of the test, b) Semilog graph (log time versus pressure) for parameters calculation through MDH and Horner methods, c) Log-log graphs, for analysis application using methodologies of type curves (Agarwal, Ramey, Al-Hussainy); Derivative pressure (Bourdet and Gringarten 1980; Tiabs, 1993).

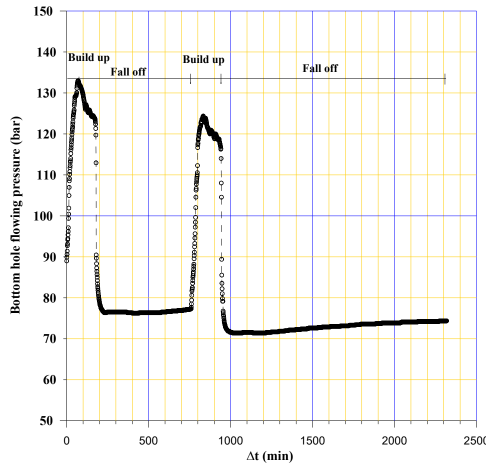

Figure 4: Behavior of bottom flowing pressure in build-up and fall-off periods in transient pressure tests of well H44 (Sanchez et al., 2015), using injection with two flow rates.

For analysis of these transient pressure tests, only is possible to use recovered data during the fall-of pressure periods; due to pressure instability shown in bottom hole flowing pressure during build-up periods.

4. DISCUSSION

In geothermal and oil technologies, similar parameters for taking decisions for the well completion are used, such as, those mentioned in this work. However, it is appropriate to emphasize those electrical surveys, used for precisions of target depth in oil wells cannot be used in geothermal wells due to high temperatures which affect behavior of electrical components.

An alternative use for the electrical logs in geothermal drilling are monitoring fluid circulation losses profiles; temperature differences between input and output of the drilling fluids; thermal and pressure gradients along the well profile and fluid density changes. As mentioned previously all the monitored parameters during drilling give useful information for the appropriate depth for suspend it and start measurements in order to research if it is come up the target interval. Thermodynamic logs and pressure transient pressure tests are the base that supports taking decision on the appropriate depth for the well completion, and design of slotted liners along its profile.

It is appropriate to emphasize that although feed zones are an indication of permeable zones in a well, not all permeable zones act as feed zones which can be identified during thermodynamic measurements. A feed zone requires interconnected permeability and a pressure difference with respect to the fluid column in the wellbore at that depth (Mbithi, 2016). Intervals of fluid circulation losses during drilling, variations in gradients of temperature and pressure are some of the techniques for identifying feed zones in the wells, corroborated finally with the results of transient pressure tests. It is appropriate to develop an integral analysis of the monitoring parameters during drilling in order to take decision at the moment for drilling suspend and carry out transient pressure tests. An example of a useful graph would help in this decision take is shown in Figure 5.

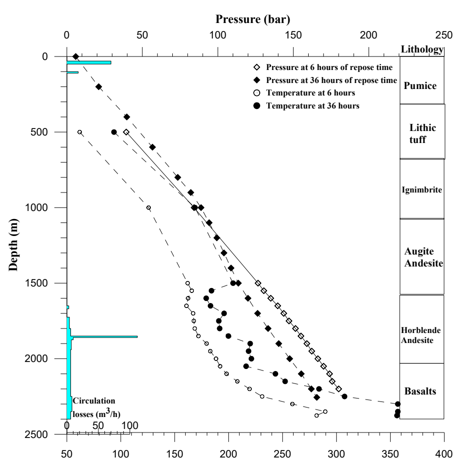

Figure 5: Correlation of main parameters recorded during drilling of a geothermal field, useful for taking decisions on its appropriate completion depth.

All the parameters correlated with neighboring wells help to configure petrophysical distribution of reservoir which can be used for modelling, original reserves estimation, knowing initial state and its future development.

It is highly important monitoring of formation lithology, fluid circulation losses, hardness rock, rate of penetration, differential temperature between entrance and fluids exit, helps in the well completion. However, results of the series of thermodynamic logs (temperature-pressure), correlated with permeability, storage, drainage radius, obtained with the transient pressure tests, are the base for the final decision on the well.

5. CONCLUSIONS

A review of the different variables occurring during drilling geothermal wells can be monitoring in order to opportunely suspend operations for carrying out thermodynamic logs and in its case transient pressure tests.

Formation lithology is related with rock hardness and rate of penetration during drilling, which increase under presence of fractures, favoring its communication with geothermal reservoir

Lost circulation during drilling near to target depth, helps to identify intervals with permeability signals, which correlated with thermodynamic conditions, can be associated with thickness of geothermal interest.

Thermodynamic (temperature-pressure) measurements are useful for indicating the presence or closeness of the target depth and its interval of geothermal interest in order to take decisions for drilling suspend and develop transient pressure tests.

Transient pressure tests represent the base technical support, for drilling suspending and well completion, or continue in order to find a depth with better permeability.

According to review done in this work, an integral analysis involving correlation of lithology, intervals permeable thickness, thermodynamic profiles and results of transient pressure tests is applied for completion and mechanical design of the well.

It is important to consider that, could be occur that thermodynamic measurements are below to the saturation conditions and in this case, it is recommendable suspend drilling and searching for an interval permeable in order to use the well as injector and in this way, rescue a little of its cost invested.

Another situation would be that thermodynamic measurements satisfy the saturation conditions, however, the well formation is impermeable and does not guaranty geothermal production, therefore will be necessary implement alternative methods, different to the conventional, for heat extraction.

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