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Investigating the Effect of Lithological Characteristics and Structural Attributes on the Drilling Rate: Casestudy of Olkaria Geothermal Field, Kenya

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Abstract:
The development of high temperature geothermal systems in Kenya is partly due to the occurrence of shallow magma bodies under volcanoes in the axis of the rift. Drilling of geothermal wells presents a critical development activity of a geothermal project. However, drilling activityfaces numerous challenges which negatively affect drilling rates. The drilling costs are increased since drilling operations are run on tight schedules and any delays come at a high cost. Some of the most common drilling problems can be attributed to lithology and stratigraphy of the formations. This research assessed the effect of lithological characteristics and structural attributes on the drilling rate at Olkaria geothermal field. The study investigated the joint effect of lithostratigraphy, geological structures and hydrothermal alterations on the drilling rate usingwells OW 724B and OW 45V as case study. These wells experienced drilling challenges caused by severe formation problems leading to high non-productive-time and cost overruns. Geological data ofthe wells included structures, and detailed stratigraphy of the sampled wells. From the study, the joint effect of lithostratigraphy, rock secondary structures and hydrothermal alterations on the drilling rate was found to be significant. However, changes in hydrothermal alterations caused the most significant variations in the daily drilled depths when compared to changes in lithostratigraphy and rock secondary structures. The findings revealed that 11% of the variations in the drilled depth could be explained by lithostratigraphy, rock secondary structures, and hydrothermal alterations.

Key Word*:Olkaria geothermal field, Lithostratigraphy, rock secondary structures, hydrothermal alterations, drilling rate.*

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I. Introduction

The installed electricity capacity in Kenya is majorly by Geothermal and hydro sources with a contribution of 865 MWe and 820 MWe, respectively (Omenda et al, 2020). Thermals, solar and wind energy contributes a total of 807 MWe, 92.5 MWe, and 336 MWe, respectively.In Kenya, the high-temperature geothermal occurrences are, to a larger extent, associated with Quaternary volcanoes found within themain rift valley's axis (Omenda et al., 2000). The heat sources for a majority of the systems have been linked to the magma bodies found shallowly under the volcanoes. According to Mangi (2016), fourteen large Quaternary volcanoes exist in Kenya. These volcanoes, together with other prospective sites, can provide an estimated generation of up to 10,000 MWeif fully exploited.

Recent reports indicate that over 300 production wells have been sunk in Olkaria area, yielding an average of 8 MW per well. The largest producing well at Olkaria discharges about 25 MWe. The six operating stations are Olkaria I, OlkariaII, Olkaria III, Olkaria IV, Olkaria V and Oserian Power plant. The sixth station at Olkaria I unit 6 is under construction. The Olkaria I station produces 45 MWe from 15 wells. The 105 MWeOlkaria II plant is operated using 22 wells. Olkaria III plant owned and operated by Orpower4, Inc, has an installed capacity of 170 MWe with 150 MWe dispatched to the grid. OlkariaIV and V power plants have installed capacities of 150 MWe and 172.3 MWe, respectively.

The drilling of geothermal wells has presented significant challenges which may lead to high costs and delays. For example, geothermal well drilling constitutes up to 30% of the cost of the entire geothermal project. In drilling geothermal wells, several challenges are encountered. The major challenges include lost circulation due to highly permeable formations, high reservoir temperature, and well collapse, among others. These challenges result in drilling timelines not being met as well as resulting in increased drilling costs.

Also, the delays in the drilling of wells can directly result in cases of lost generation opportunity. A significant amount of revenue is lost between the time awell is completed and when it is connected to a power plant. Moreover, it is important to note that the cost of a well is directly proportional to the time it takes to drill a well. Figure 1 shows that the two wells, OW-724B and OW-45V,tookmoretime than the planned time. The delays indicated in the figure were linked to non-productive times (NPT) when there was no actual drilling taking place. According to Nyota and Murigu (2016), increased costs due to longer drilling times result in expenditure beyond the budget allocation necessitating mitigation actions.

The long non-productive times are as results of the gaps in the drilling knowledge about the various challenges likely to occur at depth zones with certain lithological characteristics and structural attributes. Hence, efforts can be made to solve the problem by first investigating the association between lithological characteristics and structural attributes, and drilling depths in a bid to understand the lithological factors that are likely to bring most challenges to the drillers.

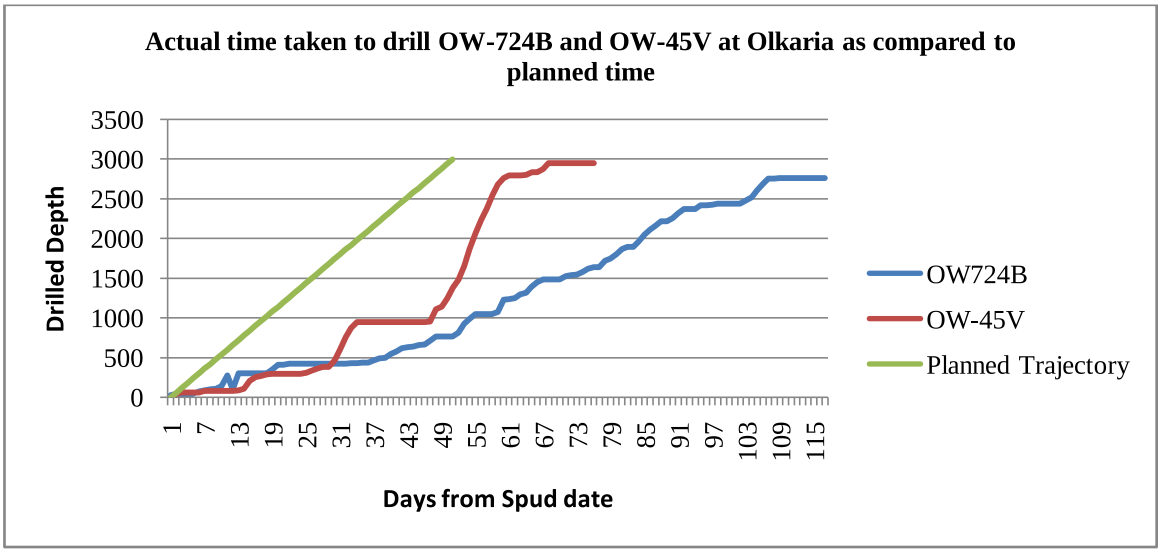

Figure 1: Actual time taken to drill wells at Olkaria as compared to planned time (Nyota and Murigu, 2016)

This paper investigated the effect of lithological characteristics and structural attributes on the drilling rate. The effects of the three lithological variables namely lithostratigraphy, rock secondary structures and hydrothermal alterations on the drilling rate were assessed jointly.

II. Previous Work

2.1 Geothermal Surface Exploration

Exploration of geothermal resources in Kenya began in 1952 through a consortium of several companies such as Power Securities Corporations Ltd, EAPL Company Ltd, Babock and Wilcox Ltd, and Associated Electrical Industries Export Ltd (Simiyu, 2010). After a study that indicated the potential of geothermal resources within the central part of Kenya's Rift valley, particularly Olkaria, two wells were sited and drilled to a total depth of 950m and 1200m in the year 1956 (Mwangi, 2010). However, the two wells were not able to discharge during the initial testing but well X-2 discharged in 1971. Hence, as described by Mwangi (2010), geothermal research and development were abandoned until the early 1970s. In 1971, a joint mission by the Kenya Government and the United Nations Development Program, to explore the geothermal resources in Kenya, was initiated to carry out exploration works at Olkaria, Eburru, and Lake Bogoria geothermal prospects. During this time, the significant activities included geological mapping, gravity studies, hydrogeological assessments, and infra-red imagery assessments (Bertani, 2016).

In 1973, after a discussion by a technical review committee, a recommendation to drill four deep wells of the approximated depth of 2,200 m was made, and the drilling commenced with financial help from UNDP (Simiyu, 2010). The progress was then gradual, where six exploratory wells were drilled by the year 1976. The successful drilling of the six wells ensured availability of data which led to a feasibility study by SWESCA, VRKIR Consulting Group Ltd, and Stockholm who recommended the power stations' development (Kiplagat et al, 2011).

More wells were drilled in 1977 providing enough steam for the generation of electricity, and by 1981 commissioning of the first 15 MWe generating Olkaria unit 1 power plant was done. Improvement in the drilling processes was made gradually, and by the end of 1984, a total of 33 wells had been drilled in the Olkaria East Field with a steam capacity capable of generating 45 MWe. Hence, by 1985, three 15 MWe generating units had been commissioned. Later in the 1990s, the Olkaria field was divided into seven sectors to ease the management and exploration processes (Omenda, 2007).

2.2 Drilling Challenges

According to Karanja and Wagumba (2015), the energy manifested on the earth's surface through altered grounds is extracted using wells drilled to tap steam and water at high temperatures of between 250 and 350 degrees Celsius and pressures ranging between 600 and 1200 PSI at depths of between 1 and 3 km. The steam is tapped then directedto a turbine and used to rotate turbines which generate the electrical energy.

Okwiri (2014) investigated the successes and challenges of drilling in Menengai geothermal field. The researcher observed that the most common challenge was the insufficient water supply for drilling. During the time of the research, four rigs were drilling within the Menengai caldera and all depended on the same water supply. Just like the case of Menengai, Olkaria area is highly fractured, and the drilling crew faces frequent long-lost circulation periods necessitating constant supply of drilling water.

Also, Okwiri (2014) highlighted several formation challenges to the drilling crew at Menengai. According to the researcher, the geology of the area presented the biggest challenges to drilling and was responsible for the slow drilling rate. The hard formation, especially on the upper sections caused large vibrations resulting in surface equipment damage. In other cases, there was loose formation that kept on collapsing during drilling. On the other hand, lost circulation issues were pronounced in Menengai and Okwiri (2014) proposed that they were due to the fractured nature of the formation. Moreover, changing lithologies at different depths created a set of variables that affected the durability of bits.

2.3 General Mitigation Practices

Some of the general mitigation practices against the above drilling challenges include plugging loss zones and high viscous mud to regain loss of circulation in the problematic zones, hammer drilling especially for the hard-abrasive top section to increase the rate of penetration, using brine from discharging wells to supplement drilling water. Drill string inspection after 200 rotations reduce instances of drill string failure (Mwaura and Kada 2017). Several other mitigation measures have evolved over the years. Proactive methods involve all the remedies applied prior to entering lost circulation zones with the aim of preventing the occurrence of losses. Preventive measures for lost circulation included the use of conventional lost circulation materials (LCMs), which include pre-treatments, squeezes, and pills. On the other hand, simpler methods such as reducing the pump pressure and drilling mud weight, increasing the drilling fluid viscosity, and using nozzles bits have been applied to inhibit or restore lost circulation mud.

Further, to curb the challenge of high pressures that affects the drilling processes, especially during cementing, the BOP should be closed for lesser hours insteadof the normal 8 hours to allow for backfill operation with the aim of creating a high hydrostatic pressure of the cement column that would balance the formation pressures (Karanja and Wagumba, 2015). Also, drillers are encouraged to pump high-density cement to increase the required hydrostatic pressures (Kandie, 2018).

As suggested by Okwiri (2014), the challenges associated with the hard formation, especially on the top sections can be overcome through the use of tri-cone bit that depends on rotary action to drill or percussion hammer. Okwiri (2014) observed that the wrong choice of the bit was due to insufficient knowledge about the formation of the area being drilled.

2.4 Research Gap

Efforts have been made by previous researchers to describe the lithology of various geothermal areas. In particular, previous researchers have used the fault trend prominently displayed at the Mau escarpment to describe the secondary rock structures at Olkaria geothermal area. Further, Omenda et al (2000) utilized data from cutting and cores from more than eighty deep wells in the geothermal area to provide the lithostratigraphy of the Olkaria area. The subdivisions were mainly achieved on the bases of tectono-stratigraphy and age. The cuttings were also used to reveal the levels of hydrothermal alterations at different depth zones. Despite this very important information, none of the researchers in the past provided statistical evidence on the link between drilling rate and lithostratigraphy, rock secondary structures, as well as hydrothermal alterations,in an attempt to find out solutions to the drilling challenges. None of the previous literature sufficiently addressed the geothermal well drilling challenges that were directly related to geology. In particular, the previous research failed to adequately describe the exact impact and the direction of the impact of the three major lithological characteristics and structural attributes including lithostratigraphy, geological structures, and hydrothermal alterations on the drilling rate. None of the previous studies revealed the nature of the association between lithostratigraphy, geological structures and hydrothermal alterations, and drilling rate.

III. Methodology

This study assessed the joint effect of lithostratigraphy, rock structures and hydrothermal alterations on the drilling rate. The study sought to analyse drill time risks due to formation related problems on two wells that suffered this problem, i.e., OW-724B and OW-45V. The study focused on lithostratigraphy, rock secondary structures, and hydrothermal alterations. The response factor was drilling rate as described by the depth of the well-drilled per day. A linear regression model was fitted to the data with lithostratigraphy, rock structure, and hydrothermal alterations as explanatory variables and drilling rates as the response variable. The data was fitted to a regression model represented by Equation 3.1.

Equation 1: Regression model

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \varepsilon$$

Where; y was the drilling rate, x_1 the lithostratigraphy, x_2 the rock structure, and x_3 the hydrothermal alterations. The β_i were the model parameters while the ε was the error term in the model.

IV. Results and discussion

The regression model was fitted into the data to assess both the joint and individual effects of lithostratigraphy, rock secondary structures, and hydrothermal alterations. The model summary results produced values equal to 0.323 and 0.105 for the R-value and R-squared value, respectively (Table 1). The Value of R represented the coefficient of multiple determinations, and it implied that jointly, the independent variables and the dependent variable in the model were correlated with a correlation score of 0.323. On the other hand, the value of R-squared represented the coefficient of multiple determinations, and it implied that 10.5% of the variations in the drilled depth were explained by lithostratigraphy, rock secondary structures, and hydrothermal alterations.

Table 1: Regression Model Summary

Model	**R value**	**R Square value**	**Adjusted R Square value**	**Standard E of the Estimate**
1	0.323	0.105	0.084	47.99695
Predictors: (Constant), Hydrothermal alterations, Rock secondary structures, Lithostratigraphy				

The joint effect of lithostratigraphy, rock secondary structures, and hydrothermal alterations on drilling depth was assessed using ANOVA(Table 2). The analysis produced a computed test statistic equal to F=5.022, with a significance value of 0.003. The significance value was less than 0.05, implying that the test rejected the null hypothesis of non-significance. A conclusion was, hence, made that the joint effect of lithostratigraphy, rock secondary structures, and hydrothermal alterations on drilling ratewas significant. In other words, the model fit was good and that the researcher was justified to make conclusions based on the regression results.

Table 2: Regression ANOVA Results

Model		**Sum of Squares**	**Degrees of freedom**	**Mean Square**	**F-value**	**Significance value**
1	Regression	34708	3	11569	5.022	0.003
	Residual	297178	129	2304		
	Total	331886	132			

a. Dependent Variable: Drilled depth

b. Predictors: (Constant), Hydrothermal alterations, Rock secondary structures, lithostratigraphy

The individual effects of the three independent variables, namely, lithostratigraphy, rock secondary structures, and hydrothermal alterations on the drilling depth, were assessed using the regression model's parameters assessment whose findings are presented in Table 3. The analysis produced values equal to 58.86, 2.226, -2.542, and -13.98 for the model constant and coefficients of lithostratigraphy, rock secondary structures, and hydrothermal alterations, respectively. The values implied that the fitted model was represented by the equation.

$$y = 58.86 + 2.226x_1 - 2.542x_2 - 13.98x_3$$

Where; y was the drilled depth and x_1, x_2, and x_3 the lithostratigraphy, rock secondary structures and hydrothermal alterations, respectively.

Table 3: Regression's Model Coefficients Result

Model		Unstandardized		Standardized	t-values	Significance value
		B's	**Standard Error**	**Beta's**		
	(Constant)	58.86	16.07		3.662	0.000
	Lithostratigraphy	2.226	3.405	0.055	0.654	0.514
	Rock secondary structures	-2.542	4.112	-0.052	-0.618	0.538
	Hydrothermal alterations	-13.98	3.651	-0.323	-3.829	0.000
Dependent Variable: Drilled depth						

The model suggested that, on average, the drillers would drill 58.9m if the effects of lithostratigraphy, rock secondary structures, and hydrothermal alterations were eliminated. Also, the model suggested that the drilled depth was expected to change by 2.2m for a level change in the lithostratigraphy, holding the effects of rock secondary structures and hydrothermal alterations, constant. Conversely, the model suggested that the drilled depth was expected to decrease by 2.5m for a level change in the secondary rock structures. Also, the drilled depth was expected to decrease by 14.0m for a level change in the hydrothermal alterations.

The significance analysis of the individual effects was done using T-test technique. According to the results, the t-statistics together with the associated probability values for the lithostratigraphy, rock secondary structures, and hydrothermal alterations were equal to 0.654 (p=0.514), -0.618 (p= 0.538), and -3.829 (p=0.00), respectively. The null hypotheses for the effects of lithostratigraphy and rock secondary structures on drilling rate were not rejected. Conversely, the null hypothesis for the effect of hydrothermal alterations on drilling rate was rejected. It was, hence, revealed that the effects of lithostratigraphy and rock secondary structures were not statistically significant while the effect hydrothermal alteration was significant. Hydrothermal alterations are believed to influence the drilling rate by changing the mineralogy of the rocks. This results into softness which should in turn increase the rate of drilling. However, the study showed that the drillingrate decreased with increase in hydrothermal alterations. The slowness in the drilling rate could be as a result of increased drilling challenges such as sticking pipes, problem very common inclay rich zones.

V. Conclusion

The results of theresearch revealed that the rock secondary structures, hydrothermal alterations and lithostratigraphy, were linked to the average drilled depth. The study concluded that lithostratigraphy, rock secondary structures, and hydrothermal alterations explained 11% of the variations in the drilled depth. Further, the study suggested that, on average, the drillers would drill 58.9m if the effects of lithostratigraphy, rock secondary structures, and hydrothermal alterations were eliminated. Also, the study suggested that the drilled depth was expected to change by 2.2m for a level change in the lithostratigraphy, holding the effects of rock secondary structures and hydrothermal alterations, constant. Conversely, the drilled depth was expected to decrease by 2.5m for a level change in the secondary rock structures. Also, the drilled depth was expected to decrease by 14.0 for a level change in the hydrothermal alterations.

It is inevitable that problems will always occur while drilling a geothermal well, even in a carefully planned situation. The study observed that daily drilling depth was significantly reduced when drillers came across zones with high levels of secondary rock structures, high levels of hydrothermal alterations, and undesirable rock types such as pyroclastics, basalt, and rhyolite.Future researchers are recommended to broaden the research scope and investigate all the factors believed to influence the drilling rates in geothermal wells. The joint assessment will reveal the overall effects as well as individual contributions of the various factors on the drilling rate.

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