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GEOTHERMAL DRILLING TIME ANALYSIS: A CASE STUDY OF MENENGAI AND HENGILL

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ABSTRACT

Drilling operations are run on tight schedules and drilling time delays come at a high cost. A large part of drilling workdays is spent on making the wellbore, and activities that support drilling, contribute to productive time (PT), while a significant part of the time is spent on drilling problems, and activities aimed at finding solutions and solving these problems. This contributes to non-productive time (NPT). Problems occurring during drilling can be avoided sometimes but, on other occasions, they are beyond the drilling crew's control; the causes are numerous and their effects are undesirable. This paper evaluates the extent of NPT associated with 15 wells drilled in Menengai, as well as identifying their causes and effects, and finally suggests recommendations aimed at increasing PT while reducing NPT to make the drilling process more effective. Data from 19 wells in Iceland were used for comparison. Workdays were analysed for 12 activities including: actual drilling, casing, cementing casings, cementing losses, equipment repair, wait on water, logging, changing the bit and bottom hole assembly (BHA), fishing, stuck pipe, reaming and 'other' activities. 'Other' activities were mostly waiting on materials, instructions and personnel. Blow out preventers (BOP) and wellhead installation and any other equipment installed after spading was included in this category. The analysed data was obtained from completion reports and drilling logs.

Because of the challenging geological conditions, drilling wells in Menengai took longer time than planned. In addition, the field was new and the crew did not know what to expect. The crew members were also new to each other and had to become accustomed to working together. Lost circulation was the major formation problem experienced, resulting in further problems of stuck pipe and drillstring failure. Drilling problems due to the formation increased with depth, with major challenges experienced at depths of about 2200 m, with a stuck pipe topping the list of drilling problems. It was concluded that productive time in Menengai could be increased through a change in technology, especially bit technology, while activities such as cementing could be accelerated with more knowledge of the subsurface conditions through logging and a thorough job of managing the loss zone. It is not possible to totally eliminate NPT, but minimizing it and increasing PT will result in a shorter project implementation time and reduce drilling costs.

1. INTRODUCTION

The objective of drilling a geothermal well is to drill a fit-for-use well, in a safe manner, using the available technology while minimising the overall cost. To control well costs, it is important to improve drilling efficiency and cut down on drilling time. Time analysis of drilling a well is important as it will eventually influence the economic analysis of a drilling project.

Drilling operations are not always completed on schedule. There are many factors and events that come into play, such as drilling problems and some technical and non-technical non-productive time (NPT), pushing the drilling operation behind schedule, hence, increasing the cost of the wells. It is almost certain that problems will occur while drilling a well, even in very carefully planned wells. For example, in areas in which similar drilling practices are used, hole problems may be reported where no such problems existed previously, because the formations are non-homogeneous. Therefore, two wells near each other may have totally different geological conditions (PetroWiki, 2013a).

The most common drilling problem in geothermal wells leading to NPT has always been formation related, leading to stuck pipes and bottom hole assembly failure. In some cases, efforts to retrieve the string are unsuccessful and this leads to the expensive process of side-tracking or, in the worst case, abandoning the well when further work is no longer considered economically viable. Such wells bring the drilling company into time overruns and eventually cost overruns. Other common causes of NPT in drilling geothermal wells include, but are not limited to, lost circulation, formation damage and rig equipment failure. Personnel experience and available technology may also influence drilling time.

This paper presents an analysis of the drilling time of 15 wells drilled in Menengai geothermal field and compares them to 19 wells drilled in Hengill field in Iceland. Time spent on different activities was analysed and how they, in turn, affected the drilling performance with an emphasis on NPT as the major cause of drilling time extension. The aim of this paper is to identify the NPT affecting wells drilled in Menengai field, using wells drilled in Hengill area for comparison, determine their causes and effects and attempt to come up with solutions to reduce them and positively influence drilling performance. The activities analysed included actual drilling, running casing, cementing casing and circulation losses, logging, reaming, fishing, stuck drill pipe, repairs, wait on water and 'other' activities.

1.1 Menengai

Menengai is a major Quaternary caldera volcano forming one of fourteen geothermal sites in Kenya. It is located within the axis of the central segment of the Kenya Rift just north of Nakuru town and a few kilometres south of the equator. The Menengai geothermal field is characterized by complex tectonic activity associated with two rift floor tectono-volcanic axes (TVA), Molo and Solai, that are important in controlling the geothermal system (Njue, 2011).

Geothermal drilling in Menengai field started in February 2011. The aim was to determine geothermal resource availability, hydrothermal capacity and the chemical characteristics of the resource. The project was initiated following a detailed exploration conducted in 2004 that pointed to the existence of an exploitable geothermal resource within the caldera. Currently, drilling of production wells is ongoing following the completion of exploration and appraisal wells. By July 3, 2013, fifteen wells had been completed. The location of these wells within the caldera is shown in Figure 1.

Drilling in Menengai is carried out using four rigs (Simba 1, Simba 2, Kifaru 1 and Kifaru 2) owned by Geothermal Development Company (GDC) in Kenya. Simba 1 and Kifaru 2 are top drive rigs, while Simba 2 and Kifaru 1 are rotary driven. All the rigs have the capacity to reach a depth of 7000 m with a maximum hook load of 4500 kN. Menengai geothermal wells have targeted depths of 2500 m, drilled in four sections, as shown in Figure 2. The casings are usually screwed together. The 26" hole is drilled using a tri-cone roller mill tooth bit down to 80m, while the other hole sections are drilled with a tri-

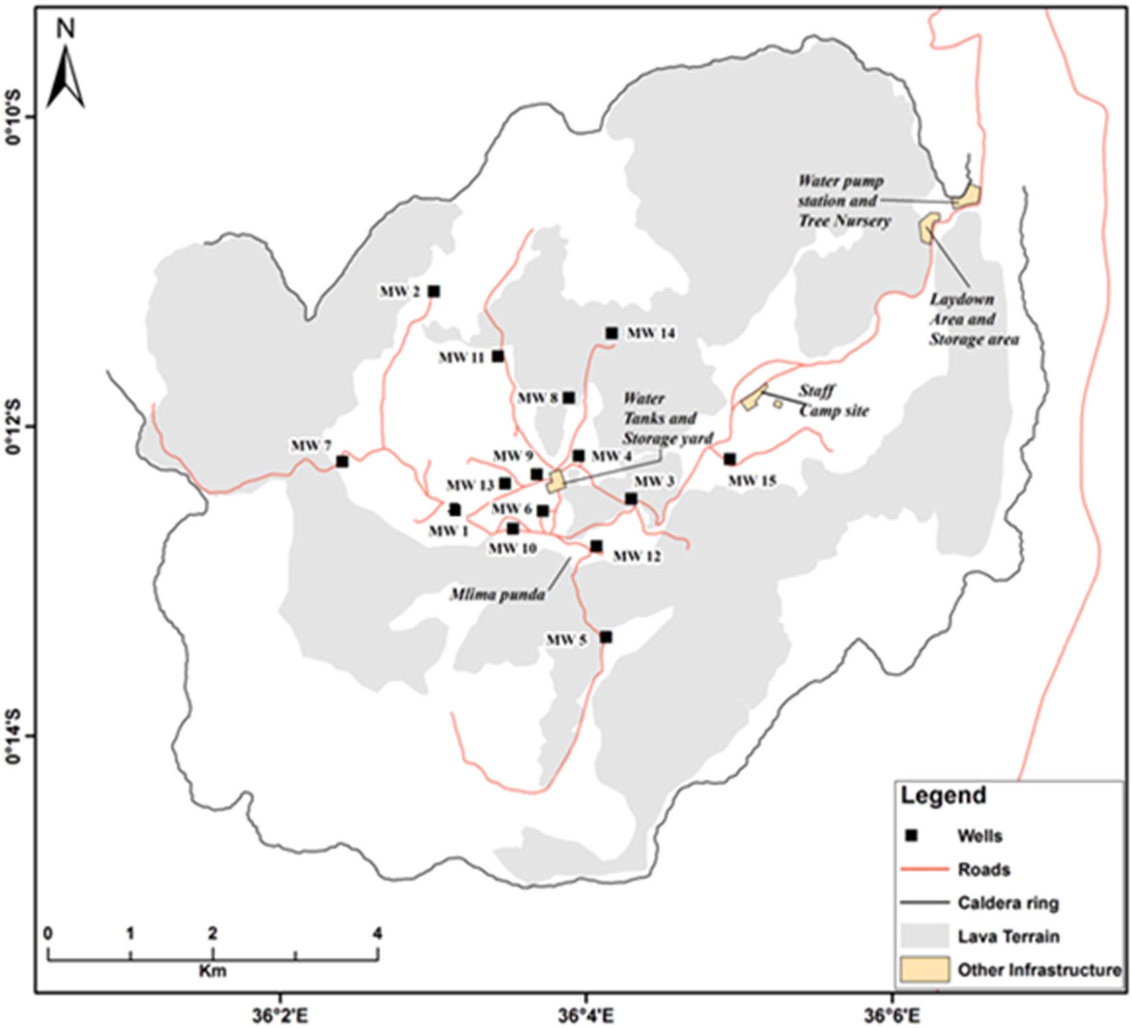

FIGURE 1: Location of wells in Menengai

cone roller tungsten carbide insert bit. Cementing is done using the single stage method where cement is pumped through the casing with backfills through the annulus, with 8 hours setting time in between cementing jobs. The drilling fluid used in the upper parts of the well is simple water-based bentonite mud. When fractured zones are encountered above the production casing shoe depth, attempts are made to seal these losses using Loss of Circulation Materials (LCM) and, in extreme cases, cement plugs are used. The final hole section is drilled with water and, in areas of lost circulation, aerated water and foam are used. The majority of well logging is carried out during well completion but a few are carried out during drilling. The well logs are usually temperature, pressure, injection tests and a full set of lithological logs when the wells are completed.

1.2 Hengill

The Hengill high-temperature field rates as one of the largest in Iceland. It is located 30 km east of Reykjavik on the eastern border of the Reykjanes Peninsula, SW-Iceland. The Hengill volcanic system is composed of crater rows and a large fissure swarm. It has a 100 km long NE-SW axis, 3-16 km wide. The Hengill central volcano covers an area of about 40 km^2 (Björnsson et al., 1986).

Hengill wells were drilled in four successive sections. Two small rigs with a hook-load capacity of 50 tonnes (t) were used for the initial drilling to 90 m depth. An intermediate size rig (100 t) was used for the shallow sections (1 and 2) of a few wells. Four larger rigs (179-300 t) were used for the main drilling. A total of seven drill rigs owned by the Iceland Drilling Ltd were used in the drilling effort. All the rigs are hydraulic with a top-drive and the large ones have automatic pipe handling. The initial drilling (21" hole) in Hengill is performed with air hammer and foam or tricone bits with tungsten carbide inserts, using mud and water as circulation fluids. Rotary drilling techniques with tricone bits were applied in Section 1 from 90-300 m depth, but in section 2 from 300-800 m depth a mud motor was used to rotate the bit and a Measurement While Drilling (MWD) tool was inserted in the drillstring to monitor the direction (azimuth) and inclination of the well. In section 3 from the 800 m production casing to the total depth, no mud was used; drilling was carried out with water only as long as there were no severe circulation losses. Most wells were then switched over to aerated water by compressed air for pressure balance until the total depth was reached (Sveinbjörnsson and Thórhallsson, 2013). The casing programme for Hengill wells is as shown in Figure 3. Logging was done in all four sections of the Hengill wells when casing depths had been attained. Logs carried out were usually temperature and pressure; injection tests were generally carried out when a final depth had been reached to estimate the permeability of the well and to decide whether it should be protected with a perforated liner or whether it should be drilled deeper. Caliper logs were carried out before cementing casing and loss zones and cement bond logging (CBL) was carried out after cementing. A full set of lithological logs were carried out when a well was completed.

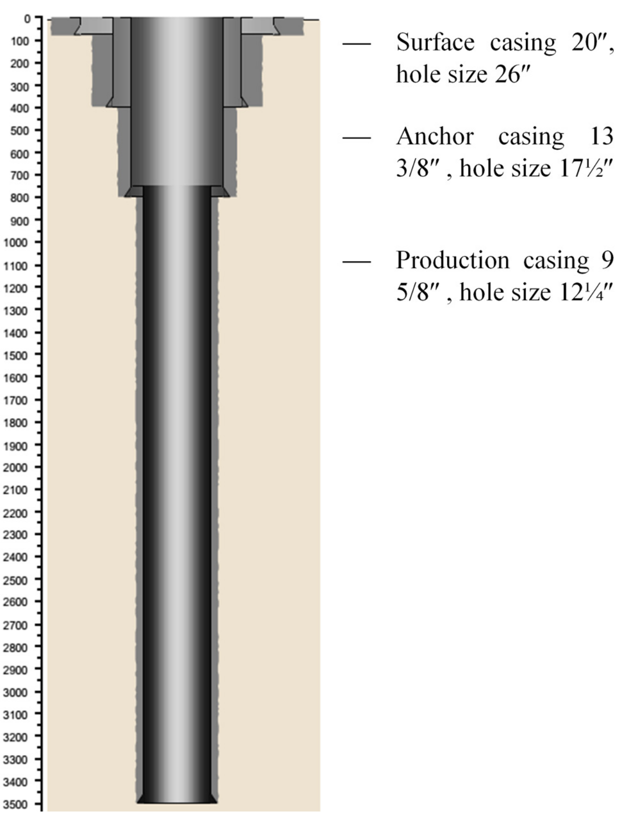

FIGURE 2: Casing programme for Menengai wells (Figure generated in RIMDrill)

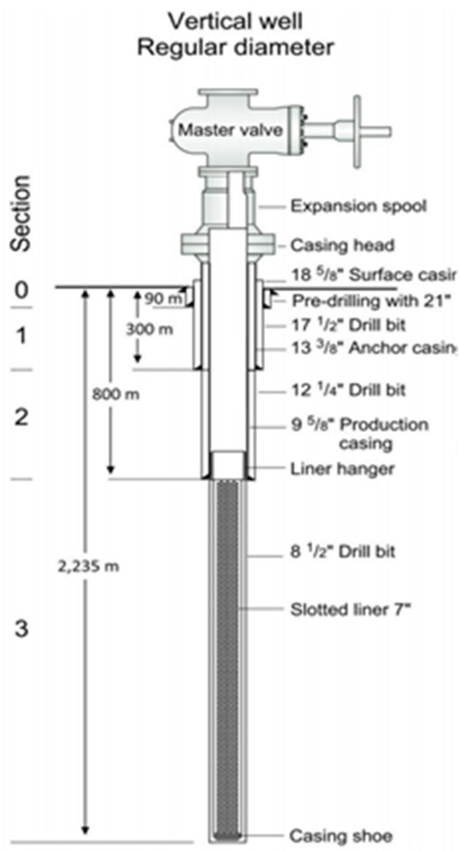

FIGURE 3: Casing programme for Hengill wells (Figure from ISOR)

2. DRILLING TIME ANALYSIS

2.1 Factors influencing drilling time

The time taken to drill and complete a well directly influences the cost of any geothermal project. Hence, completing a well in time is cost effective and essential. Noerager (1987) stated that the measured depth is the most important factor in predicting the time it will take to drill a well. But this is not always the case as drill rates are often constrained by factors that the driller does not control (Kaiser, 2007). These factors include geologic conditions at the drill site where Rate of Penetration (ROP) is controlled by the hardness or softness of the formation, available weight on the bit, location of the target reservoir, physical characteristics and prevailing reservoir conditions. Exogenous events such as stuck pipe, adverse weather, and mechanical failure cannot be predicted and can have a significant impact on the time and cost to drill a well (Kaiser, 2007). Other factors such as wellbore quality, experience and preferences of the driller cannot be quantified. The technology and resources used also contribute to drilling rates. All these factors influence drilling performance metrics.

2.1.1 Geological conditions

The most obvious aspect of the downhole environment that influences drilling difficulty is the physical characteristics of the rock (lithology). Drilling through hard and very hard, abrasive formations results in the most difficult problems in the drilling industry, despite the developments and improvements of drilling tools, equipment, machines and techniques. Soft formations are easily eroded by the drilling fluid or mechanical abrasion caused by the drilling fluid, resulting in large cavities in the well bore. Cementing this type of formation is problematic and may result in an increase in the cementing time. Loose formations that collapse easily add to hole cleaning time and could end up causing a stuck pipe, while a fractured formation will result in lost circulation problems.

Information on the geology is obtained from drill chips/cuttings and lithology logs. Lack of knowledge of the change in hardness of the formation may cause several problems during a drilling operation. These unfortunate incidents may occur on the borehole wall, down in the hole or could lead to equipment wear and eventually equipment failure. Too little knowledge about the formation being drilled may lead to the wrong choice of bit. Incorrect bit type causes low ROP and eventually equipment failure (Solberg, 2012). Having the right information on the geology of the area is paramount in making sound decisions in planning for the well.

2.1.2 Prevailing reservoir conditions

Downhole pressure, temperatures and reservoir fluids affect the way a well is drilled. They provide information for locating the productive zones and, hence, influence where casings are set and how cementing is done. Formation pressure influences how much drilling fluid is pumped into the wellbore. Choosing the right pump rate is of great importance as higher formation pressure that overrules wellbore pressure will lead to kicks and eventually blowouts if not controlled. Higher wellbore pressures may cause formation damage and lost circulation problems, resulting in greater problems such as stuck pipes.

2.1.3 Available technology

Recent advancements in technology have benefitted the drilling industry and the choice lies with the operator to suit his preference. Top drive, power swivels, air/foam balanced drilling, PDC bits, horizontal drilling, casing while drilling, reverse circulation cementing, logging while drilling, environmentally safe fluid formulations, micro drills, and coiled tubing are all good examples of these improvements (Dumas et al., 2012). The use of current technology has revolutionised how drilling is carried out and increased drilling progress efficiency and safety. In addition, implementation of new technologies has led to a reduction in drilling time and cost. Even so, technology comes with its own challenges. For example, the sensitive nature of technologically advanced equipment such as a top drive predisposes them to more breakdowns, especially when drilling in areas with lots of vibration. This means more downtime for repairs for rigs with top drives than those without.

2.1.4 Equipment and consumables availability

Drilling operations are run on tight schedules and costs are based on the number of days needed to complete the operations. Therefore, drilling companies have invested in expensive equipment. It is important to ensure that this equipment is always available for efficient drilling. When equipment breaks down, it is essential to restore it quickly through repair and replacement of parts. Spare parts for drill rigs are a complicated and important task to be handled. To avoid having to stop the drilling operations, it is very important to have a functioning system which can provide spare parts if and when a component breaks down or needs maintenance (Samland, 2011). It should be noted that the integrity of drilling equipment and its maintenance are major factors in minimizing drilling problems. Proper rig hydraulics (pump power) for efficient bottom and annular hole cleaning, proper hoisting power for efficient tripping out, proper derrick design loads and drilling line tension load to allow safe overpull in case of a sticking problem, and well-control systems (ram-, annular- and, internal preventers) that allow kick control under any kick situation are all necessary for reducing drilling problems. Proper monitoring and recording systems that monitor trend changes in all drilling parameters and can retrieve drilling data at a later date, proper tubular hardware specifically suited to accommodate all anticipated drilling conditions, and effective mud-handling and maintenance equipment that will ensure that the mud properties are designed for their intended functions are also necessary (PetroWiki, 2013b).

Drilling materials and consumables such as cement, fuel, drilling detergent, drilling mud and even water are also important; without these, drilling cannot proceed. Drilling operations will be greatly compromised without proper planning for these materials.

2.1.5 Personnel experience

Given equal conditions during drilling operations, personnel are the key to the success or failure of those operations (PetroWiki, 2013a). Drilling is an industry of learning by doing and it takes years to build the experience necessary for the industry. Experience will make a difference on how efficient a drilling job is carried out, in that operations will be safer and drilling performance improved. Other than experience, it is important to continue training personnel on new technologies and new engineering practices as the drilling industry is changing fast, with increased automation and better procedures intended to improve performance.

2.1.6 Well specification

Well specifications affect how much time is spent on a particular well. There may not be much time difference in drilling directional and vertical wells (Sveinbjörnsson, 2013), but directional wells do come with their own unique challenges, different from those encountered in vertical wells. More surveys must be carried out. It is not possible to apply desired weights or rotary speeds as it is in vertical wells. Other factors on well specification may include the number of casing strings and where they are set. Correct determination of where casing strings are set to shield against problematic zones, such as lost circulation zones, will ensure a reduction in drilling problems. Bit and casing size selection can mean the difference between a well that must be abandoned before completion and a well that is an economic and engineering success. Improper size selection can result in holes so small that the well must be abandoned because of drilling problems (PetroWiki, 2013a).

2.2 Drilling time

Drilling time is the time required to drill the wellbore to maximum depth. It includes productive time (PT) spent on activities that actually contribute towards the construction of the wellbore, and were planned for, and non-productive time (NPT) spent on activities that had to be done, but were not planned for. This information is presented in Table 1, showing a summary of PT and NPT activities, adapted from previous work done by Adams et al. (2009) to fit this study. Drilling time for a particular well or project can be identified through reports generated from drilling and logging wells in an area. This data is able to detect trends and irregularities in drilling time and delineate problematic areas. Proper analysis of drilling data will provide insight on expected characteristics and problems to be encountered in the well, which is important in planning for any well.

TABLE 1: Productive Time, PT, and Non-Productive Time, NPT, activities

Activity	PT	NPT
Drilling	Actual drilling Tripping in drill	Stuck pipe BHA change Reaming Fishing Circulating to clean well
Casing	Running in casing	Stuck casing\hung up casings Lay down damaged casing joints
Logging	Running in logging tool Actual logging	Stuck tool string
Cementing	Cementing casing	Cementing loss\plug jobs Cement backfills\top ups
Equipment	Equipment service	Equipment breakdown
Others	Nippling up BOP and Blowie line	Wiper tripe Tripping in for other reasons other than drilling Wait on materials, spares, fuel and personnel, water and instructions

2.2.1 Non-productive time (NPT) defined

Drilling time studies have been undertaken by companies for some time. All have different names for NPT. Amoco refers to this time as Unscheduled Events; BP calls it 'Non-Productive Time'; Mobil and Superior both call it 'Accountable Lost Time'; Dome refers to it as 'Problem Time'; while Exxon and Tenneco call it 'Trouble Time' (Kadaster et al., 1992).

NPT is any occurrence which causes a time delay in the progression of planned operations. It includes the workdays required to resolve that problem, and the time to bring the operation back to the point or depth at which the event occurred. NPT is, thus, anything that you did not intend to do but are required to do anyway. Therefore, anything that occurs outside of the well's original plan should be counted as NPT (Kadaster et al, 1992). Hsieh (2010) defines NPT as time periods during which the drilling operation is ceased or the penetration rate is very low; it is not a performance metric of what has gone wrong but a way to identify things that can be improved.

As companies consider the definition of NPT differently, activities considered to be non-productive are varied. It should be considered though that any activity that is carried out during drilling time without progress being made on the wellbore should fall into the NPT category.

2.2.2 The Causes of NPT

Causes of NPT in drilling are varied; they can be due to unforeseeable events that the drilling crew cannot control, or be due to inadequate planning for a job.

2.2.3 Effects of NPT

Time overrun affects the progress of drilling, leading to fewer wells being drilled by the end of the stipulated drilling project period. Time overrun means the drilling crew could not carry out their work within the scheduled period. It is important that the drilling time be reviewed at the completion of the well; knowledge built on the causes of the delays can be applied to the next wells to be drilled to improve efficiency.

Cost overrun: arises when the cost of the well surpasses the budget allocation. This could be due to overhead costs required to solve the problems that caused NPT and kept the crew on the rig for extra days. Drilling problems such as sticking and fishing may require the involvement of a fishing specialist which will increase the drilling cost. Cost overrun is related to time overrun; once a project cannot be completed on time, it will most certainly incur extra cost.

Change of well plan| side-tracking: When skill and force fail in retrieving a drillstring lost in a well, sometimes the only solution is to abandon the stuck portion and drill a sidetrack around it, changing the drilling program completely and potentially adding millions of dollars to the well cost (Aldred et al., 1999). Other reasons for sidetracking could be to get past a problematic zone such as a circulation loss zone that cannot be healed, or be an incompetent formation that keeps collapsing or a fishing challenge. This may be justified by the high investment already in that particular well, in terms of time and money, or the belief that the well will be a good producer. This is a consequence of NPT, as the change in plan always comes after time has been spent on trying to solve the problem.

The drilling plan may also be changed when drilling problems do not allow drilling to proceed. This may be due to harsh wellbore conditions, such as extreme temperatures, and pressures causing drillstring failure, leading to a reduction in the target depth to depths that the drillstring can perform.

Total abandonment: A well is abandoned when it is deemed no longer economically viable, in terms of time and cost, to continue putting resources into it, even when the well is at an advanced stage. Other reasons for abandoning a well are the same as those for changing a well plan or side tracking. Problematic wells that are advanced in depth may still be used for production, even if drilling is terminated before the target depth is reached.

3. DATA ANALYSIS

Of the total time it takes to drill a geothermal well, only 30-40% is actually spent in making a hole by rotating the drill bit on the bottom. The rest of the time is spent on: rig-up and down, installing cement casings, installing valves, logging, operations to solve drilling problems related to loss zones, instable formation or for "fishing" when the drill string becomes stuck or breaks. A good way to assess what the problem may be is to look at a curve plotting depth vs. days that the job has taken for each well. Any "flat spots", where there is no advance in depth for several days, show up clearly and will indicate that there may be a problem (Thórhallson, 2006).

Figure 4 shows drilled depths vs. workdays for the Menengai wells. Wells MW10 and MW14 were abandoned at 740 and 750 m, respectively, following a stuck pipe. In both cases, attempts to free the string resulted in drillstring failure. The fishing exercise was unsuccessful. Well MW13 had a long flat time due to equipment breakdown. More than half of the wells had a long flat time at the end because of sticking.

Well construction activities and drilling problems affecting overall drilling time were considered for 15 wells drilled in Menengai and 19 wells drilled in Hengill to compare the total time for the wells. These wells are presented in Table 2. In the analysis of activities sections, more wells in Hengill were used to strengthen the data set.

TABLE 2: Summary of wells studied; note that section 0 is excluded in workdays

Icelandic wells				Kenyan wells			
Well no.	Total drilled depth (m)	Section 1 - 3		Well no.	Total drilled depth (m))	Section 1-3	
		Drilled depth (m)	Workdays			Drilled depth (m)	Workdays
HE-03	1,887.0	1,797.6	39	MW-01	2,207.0	2,126.3	70
HE-04	2,008.0	1,936.4	45	MW-02	3,200.0	3,120.0	112
HE-05	2,000.0	1,909.5	44	MW-03	2,112.5	2,031.5	85
HE-06	2,013.0	1,940.0	37	MW-04	2,117.0	2,035.1	72
HE-07	2,270.0	2,162.0	47	MW-05	2,095.7	2,034.7	89
HE-08	2,808.0	2,668.0	38	MW-06	2,203.0	2,122.0	73
HE-13	2,397.0	2,324.0	42	MW-07	2,135.9	2,076.9	109
HE-20	2,002.0	1,901.0	72	MW-08	2,355.6	2,290.5	113
HE-21	2,165.0	2,070.0	32	MW-09	2,089.0	2,027.5	92
HE-26	2,688.0	2,596.0	51	MW-10	740.8	679.4	94
HE-36	2,808.0	2,703.0	61	MW-11	1,842.0	1,771.5	122
HE-51	2,620.0	2,522.2	33	MW-12	1,842.0	1,783.0	82
HE-53	2,507.0	2,437.5	57	MW-13	2,012.1	1,950.8	141
HE-54	2,436.0	2,342.0	34	MW-14	750.1	687.8	117
HE-55	2,782.0	2,685.0	34	MW-15	1,679.6	1,603.6	68
HE-57	3,118.0	3,023.0	41				
NJ-23	1,751.0	1,659.0	45				
NJ-24	1,929.0	1,849.7	35				
NJ-25	2,098.0	1,993.0	31				
Average	**2,330.9**	**2,237.8**	**43.1**		**1,958.8**	**1,889.4**	**95.9**

The activities analysed included actual drilling, casing, cementing casing, cementing loss, repairs, sticking, fishing, change of BHA, wait on water and logging. Evaluation was made on the time taken for each activity, assuming NPT to be the main reason for the extended drilling time. Trip time was considered as part of the activity that was being tripped for, i.e., tripping time for BHA change was considered a part of the BHA change time, while tripping time for logging was considered as logging time. 'Other' activities referred to include time spent waiting on materials, fuel and instructions, installation of BOP and wellhead and any other activity time that was not captured in the analysis, most of them being NPT activities. To compare the drilling time for different activities, the respective numbers of workdays were normalized to the same reference well both for Menengai and Hengill wells.

Section 0 was excluded from the data in comparison for the total time because there was a difference in width of the surface hole, 26" in Menengai and 21" in Hengill, some of the data for Hengill wells was not available, and a small 50 t rig was used to drill them. Average depth drilled per day in sections 1, 2 and 3 for Hengill wells was 52 m/day and 22 m/day for wells drilled in Menengai. The average meters per day for Menengai wells were calculated without Wells MW10 and MW14, as the last section for these wells was never drilled. The sections used from Hengill wells were from both vertical and directional regular diameter wells because a former time analysis of directional and vertical wells resulted in no significant difference (Sveinbjörnsson, 2010). Table 3 shows the reference well used in normalisation of the data used in the analysis. The rest of the analysis was carried out, included more wells from Hengill including injection wells and wells whose designs were changed from large to regular diameter because of problems. These additional wells included six in section 0, six in section 1, four in section 2 and three in section 3.

TABLE 3: Reference well

	Depth
section 0	80
section 1	400
section 2	850
section 3	2000

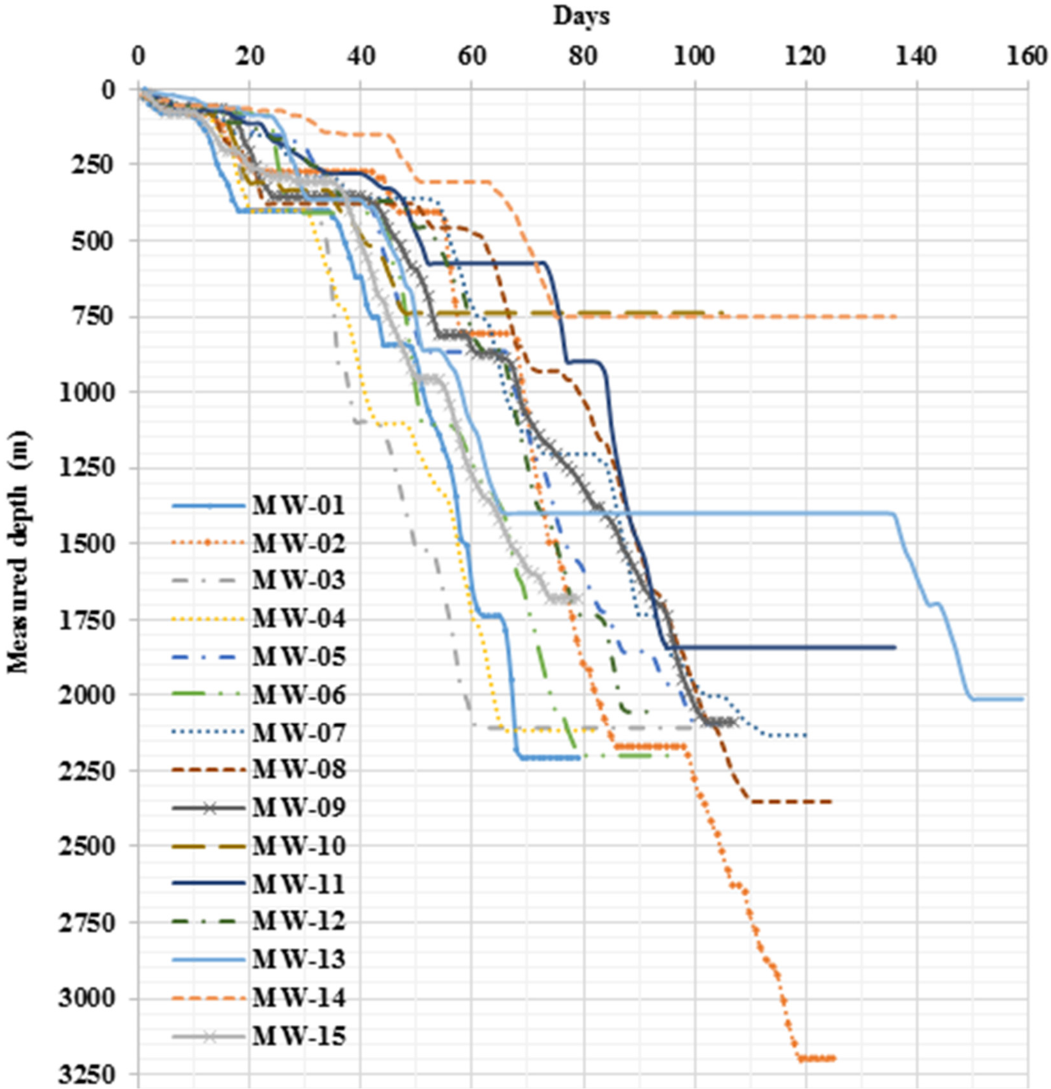

FIGURE 4: Depth vs. days graphs for Menengai wells MW01 to MW15

Equation 1 below was used for normalization of the drilling time data for different activities (Sveinbjörnsson, 2010).

$$T_i = \frac{Drilled\ reference\ depth}{Actual\ drilled\ depth} \times t_i \quad (1)$$

where T_i= The normalized number of workdays for section *i*; and
t_i= The actual number of days spent on section *i*.

Tables 4 and 5 show normalised data for each section and the overall average working days for Menengai and Hengill, respectively.

TABLE 4: Normalized days for activities in Menengai

Section	Total	Active drilling	Placing casing	Cementing casing	Cementing loss	Stuck	Reaming	Fishing	Wait on water	Changing bit	Repair	Logging	Other
0	16.7	6.5	0.5	2.6	0.9	0.2	0.5	0.1	0.6	0.1	0.6		4.1
1	31.0	10.4	1.0	3.5	2.5	0.7	1.5	0.8	3.1	0.5	0.9	0.4	5.8
2	16.1	8.1	0.6	2.4	0.5	0.1	0.3	0.9	0.2	0.7	0.4	0.2	1.7
3	45.3	20.1	1.3		0.0	5.1	1.2	2.3	0.7	2.0	5.6	1.2	6.0
Total	109.0	45.1	3.3	8.4	3.9	6.0	3.4	4.0	4.7	3.3	7.6	1.8	17.6

TABLE 5: Normalized days for activities in Hengill

Section	Total	Active drilling	Placing casing	Cementing casing	Cementing loss	Stuck	Reaming	Fishing	Wait on water	Changing bit	Repair	Logging	Other
0	5.10	2.53	0.65	0.81	0.59	0.05	0.25	0.05		0.08	0.02	0.09	
1	10.62	5.03	1.35	1.66	1.00	0.51		0.03				0.91	0.12
2	7.41	3.55	0.71	0.86	0.62	0.26	0.05		0.17	0.01	0.10	1.05	0.03
3	15.58	8.69	0.96		0.67	0.54	0.62	0.14	0.12	0.46	0.26	3.02	0.09
Total	38.7	19.8	3.7	3.3	2.9	1.4	0.9	0.2	0.3	0.6	0.4	5.1	0.2

Figures 5 and 6 show graphs of the workdays spent per well for actual drilled depths in each field, together with the average time. The data here excludes section 0 for reasons explained above. For the 3 sections used in the graph, the longest time spent on a well in Menengai was 141 days and the average time per well in Menengai was 94.5 days. The Hengill wells took an average of 43 days and the well with the most workdays took 72 days. These graphs were produced from raw data before normalisation.

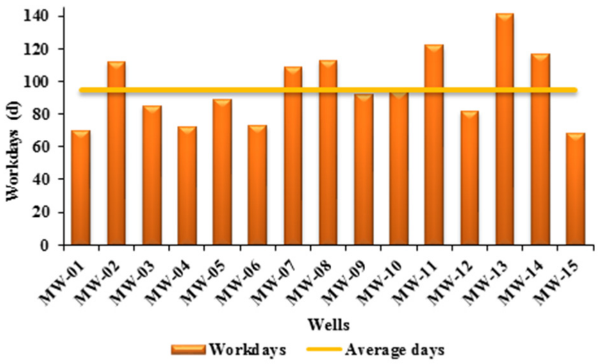

FIGURE 5: Menengai wells: actual workdays for actual drilled depths excluding section 0

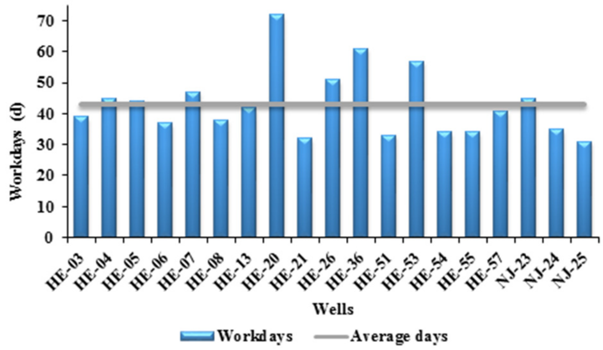

FIGURE 6: Hengill wells: actual workdays for actual drilled depths excluding section 0

Figures 7 and 8 are pie charts representing the percentage distribution of activities in Menengai and Hengill. 44% of the time in Menengai was spent on actual drilling, accounting for 45.1 days out of 109 days, while the category "other activities" took the second highest time with 14%, accounting for 17.6 days. 52% of the total time in Hengill was spent on actual drilling, accounting for 19.8 days, with logging taking up 16% of the total time, accounting for 5.1 days. The category 'Other' was lowest for Hengill with 1% accounting for 0.2 days, while logging was lowest for Menengai with 2% accounting for 1.8 days. Figure 9 is a bar graph comparing the two fields; the values were weighted by the average of activity time per section.

Figures 10 and 11 are pie chart representations of the NPT distribution in each field. The 'other 'activities' was the largest contributor of NPT in Menengai, with 37%, while cementing loss zones was the largest contributor of NPT in Hengill wells with 49%. The activities considered here as NTP were cementing loss, sticking, fishing, wait on water, changing bit, equipment repair and 'other' activities. These activities contributed to NPT as their occurrence hindered wellbore progress. The rest of the activities were considered as PT as they contributed directly to well creation. Figures 12 and 13 are pie chart representations of the ratio of PT to NPT in the two fields. Menengai wells experienced a larger

NPT. 40% of the total drilling days were spent on NPT which equals 43.7 days. Hengill wells experienced lesser NPT with only 14% of the total workdays, amounting to 5.4 days.

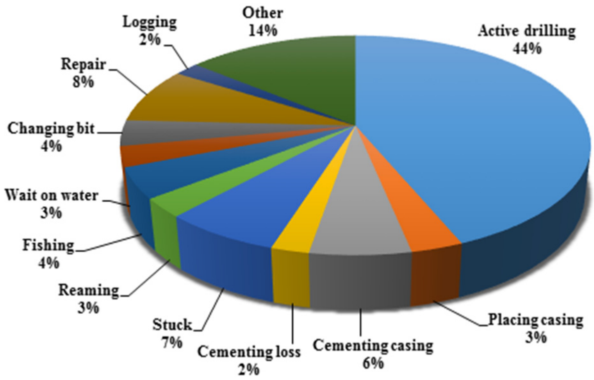

FIGURE 7: Percentage distribution of activities in Menengai

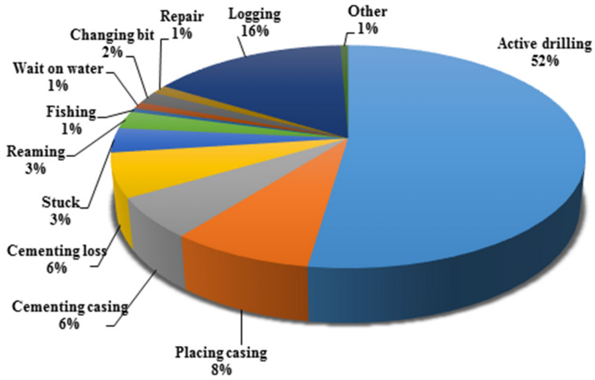

FIGURE 8: Percentage distribution of activities in Hengill

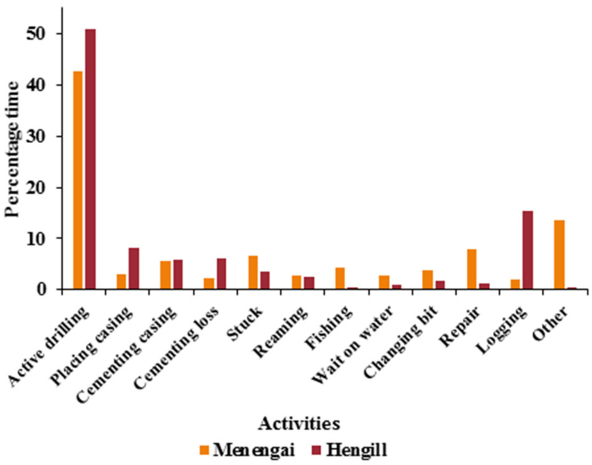

FIGURE 9: Weighted average of percentage per activity for Menengai and Hengill

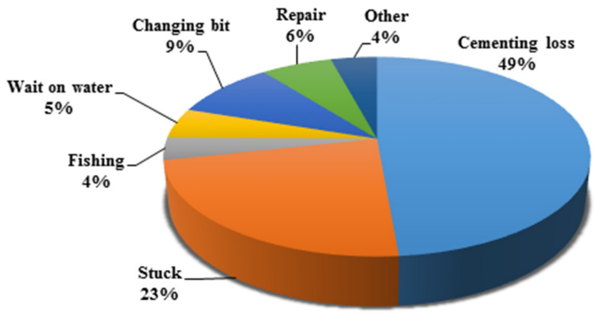

FIGURE 10: Percentage representation of NPT distribution in Hengill

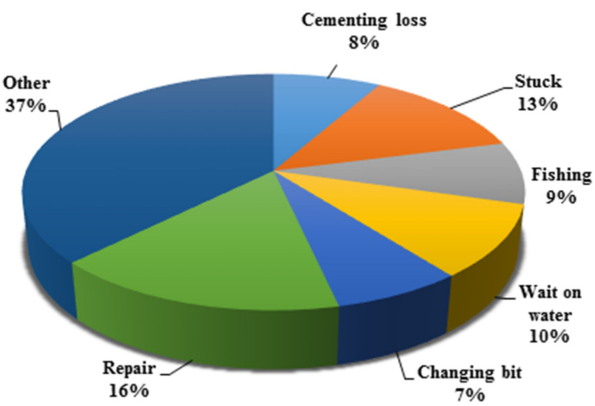

FIGURE 11: Percentage representation of NPT distribution in Menengai

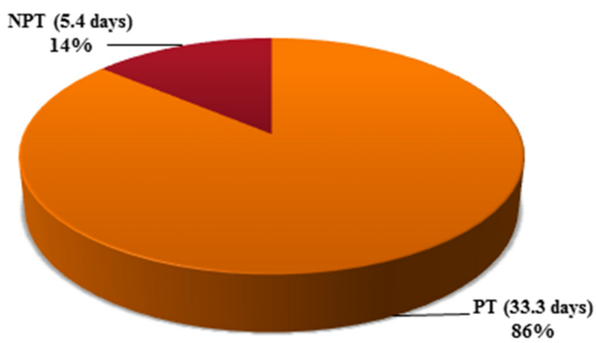

FIGURE 12: Productive time compared to non-productive time in Hengill

4. DISCUSSION

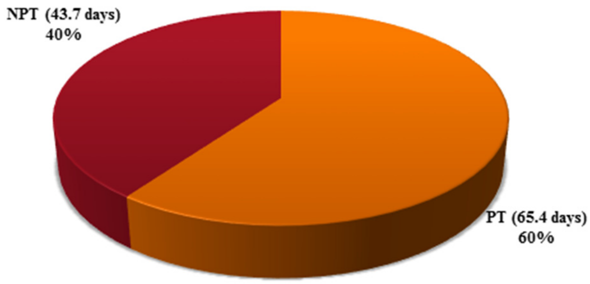

FIGURE 13: Productive time compared to non-productive time in Menengai

Using the normalised data on the reference well, wells drilled in Hengill took an average of 38.7 days to complete the well to 2000 m, while wells drilled in Menengai took an average of 109 days. Therefore, it took almost three times longer to complete similar wells in Menengai as in Hengill. From the raw data analysis, it was found that the average depth per day was 52 m/day in Hengill while it was 22.9 m/day in Menengai. The actual rate of penetration with the bit on bottom was 102 m/day in Hengill and 46 m/day in Menengai. There was more NPT in Menengai wells, amounting to 40% the total work time while Hengill wells incurred a NPT of 14.7% of the total work time.

4.1 Actual drilling

45.1 days were spent on actual drilling in Menengai and 19 days in Hengill which was 42.7 and 51.0% of the workdays, respectively. It is possible that the length of time spent in drilling Menengai wells could be due to hard formations as the rate of penetration was relatively low. Section 0 in Menengai took 6.5 days, while In Hengill it took 2.5 days. This can be explained by the fact that in Menengai this section was drilled using a tricone bit that depends on rotary action to drill. The problem results from the shallow nature of the hole in this section; the rigs had no room for collars, hence the weight on the bit was far too low and large vibrations were experienced. In Hengill, this section is generally drilled with an air hammer, making the drilling faster; furthermore, the diameter of the hole in Menengai is usually large while a regular diameter is used in Hengill. The actual cause of a longer drilling time for the rest of the sections is not clear, other than the hard formation. It could also be considered that Menengai is a new field and the crew was also new to each other and had yet to become accustomed to working together.

It can be said that the drilling rate depends largely on the hardness or softness of the formation being drilled on. This goes to show that bit selection is an important factor and so is the weight on bit and the RPM applied in determining drilling time.

4.2 Casing

Casing time for both fields was relatively low, with 3.3 days in Menengai and 3.7 days in Hengill. The size of the casings and depths did not influence the casing time much, considering section 0 in Menengai had a large diameter. On considering the percentages, Menengai wells spent 3% of the total time in placing casing, while 8% of the total time was spent in placing casings in the Hengill wells. This could be attributed to the fact that the 18⅝" casing was welded and the other casings were screwed together.

4.3 Cementing casing

Cementing in Menengai took longer, with an average of 8.4 days, while in Hengill an average of 3.3 days was spent on cementing. This indicates that most of the cementing jobs for the Hengill wells were done in the first step, thereby reducing backfills. The use of caliper logs ensured shorter cementing time for Hengill wells. Caliper measurements give approximate wellbore diameters that were used to accurately calculate the amount of cement to be used. A rule of thumb in planning cementing jobs in

Hengill: twice the theoretical volume of slurry is calculated based on the bit size used. It should also be noted that cementing methods also play a role in the cementing time. In Hengill, the cementing is done using the inner string method which allows cement slurry to be pumped until returns are obtained on the surface and has a reduced cement displacement time. However, a single stage method is used in Menengai. Single stage cementing has shortfalls such as an increased risk of cement settling within the casing, resulting in large amounts of cement being drilled out, adding to the drilling workdays. Figure 14 is a pie chart representing the total casing cement job carried out in Menengai. Backfills took four times longer than primary cementing, as there was no information on the cement volume needed.

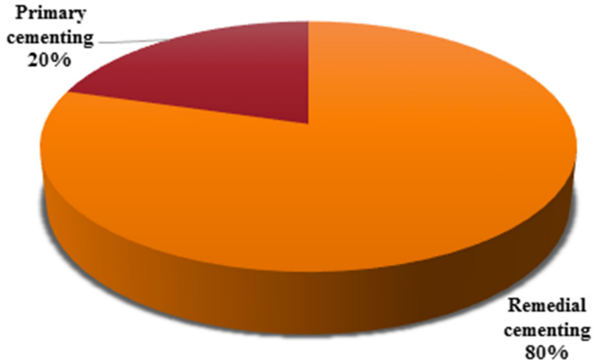

FIGURE 14: Ratio of primary cementing to remedial cementing time in Menengai

4.4 Cementing loss

Cementing loss time in Menengai was 3.9 days, while in Hengill it was 2.9 days. This translates to 2% of the total workdays in Menengai and 6% of the total workdays in Hengill. Considering that a caliper log is usually run before a plug job is done in Hengill, while in Menengai plugging is done without actual knowledge of the wellbore area being plugged, then plugging in Menengai may not be sufficient. A loss circulation problem is pronounced in Menengai; this is due to the fractured nature of the Menengai formation. Drilling practices may also lead to induced fractures aggravating loss circulation problems. If not managed, loss circulation can cause other problems in the well bore.

4.5 Logging

Hengill wells were logged more often than the Menengai wells. 16%, equivalent to 5.1 days of the total workdays in Hengill, was spent on logging. 2%, equivalent to 1.8 day, was spent on logging in Menengai. Several logs were carried out throughout the course of drilling the wells in Hengill while, in Menengai, most of the well logs were carried out during well completion. These logs usually included temperature, pressure, caliper, cement bond log (CBL) and other well completion logs. The caliper and CBL logs were not carried out in Menengai. The frequency of logging was also low in Menengai compared to Hengill.

Well logs are the only link to bottom hole conditions and, therefore, their importance cannot be over-emphasised. The more information available about the reservoir conditions, the easier it is to make accurate decisions on drilling and to develop solutions to drilling problems, such as areas to case off to avoid cold zones, and in making decisions on how to treat loss zones. Caliper logs and CBL logs are important for cementing job integrity.

4.6 Bottom hole assembly (BHA) change

Hengill spent 0.6 days in BHA change while Menengai spent 3.3 days. Most of the BHA change time was spent in tripping out to change worn-out bits. Reducing the number of BHA trips will eventually reduce this part of the NPT. The drill bit is the single equipment component that most impacts the rate at which a well progresses to total depth. Improved bit life determines how often a bit must be changed and often eliminates the incremental bit trip, and resultant delays and lost time. Changing lithologies at various depths, such as those in Menengai, also create a set of variables that affect bit durability. Other factors influencing ROP and durability include drilling fluid condition, weight on the bit (WOB), and rotary speed (RPM) of the bit. Drilling challenges are overcome with improved drill bit technology (Cochener, 2010).

4.7 Fishing

Fishing time was longer in Menengai wells, with an average of 4 days; in Hengill wells, the average was 0.2 days. Most of the fishing time experienced in Menengai was a result of drillstring failure from a stuck pipe. In the effort to free the stuck pipe, the drillstring was subjected to high torque and large over-pull, causing it to strain and eventually fail. Excessive tension from over pull and fatigue from repeated stress can also lead to drillstring failure.

To reduce the number of drillstring failures, it is important to ensure drill pipes and other tubes are inspected for faults and defects as required.

4.8 Stuck pipe

On average, Menengai wells were stuck for 6 days, while Hengill wells were stuck for 1.4 days. Both drillstrings and casing strings experienced sticking. There was more sticking in section 3 than in all the other sections. In Menengai, most of the sticking followed a period of problematic circulation and a moment of stopped circulation such as after pipe connection. There were also cases where the sticking occurred when drilling resumed after a period of waiting on water. Due to lost circulation, most of the cuttings were not removed from the hole and were left suspended; as a result, these cuttings fell to the bottom and onto the string. Loss of circulation results in poor hole cleaning and, if enough efforts are not made to regain it, sticking is inevitable.

Poor hole cleaning may not be the only cause for a stuck pipe. Some of the wells that experienced sticking in Menengai, especially in section 3, had good circulation returns with cuttings being received on the surface when sticking occurred. According to Mibei (2012), chilled fresh glass was encountered at 2,174 m in well MW05 (now named MW06), indicating a possible intrusion of magma. Glass is susceptible to alteration and at such depths in a high temperature geothermal system such as Menengai, it would have altered completely unless it was a very recent intrusion that was chilled by the drilling fluid. Drilling challenges were experienced at these depths, i.e. sticking of the drillstring. Anomalously high temperatures were recorded at the bottom of these wells. This is probably due to a high heat flow influx from the magmatic intrusion into the country rocks. Figure 15 shows the drilling parameters for Menengai Well MW06 at the time of sticking at 2202m. The sticking was sudden and there were no signatures of sticking observed prior to sticking. Other wells experienced similar sticking around the same depth.

Sticking is an expensive NPT occurrence in drilling, especially when the drillstring fails during efforts to free it, resulting in the loss of the bottom hole assembly. In such a case, much of the well will be blocked by the lost pipe. It requires either drilling a long sidetrack or performing time-consuming fishing operations to clear the hole.

4.9 Other activities

Other activities referred to here include: top drive, wellhead and BOP installation, and wait on fuel, material and instructions. Any activity that had to be carried out and was not planned for was included in this category. These activities took 17.6 days in Menengai and 0.2 days in Hengill. This was the second largest time of the total Menengai workdays and the largest NPT. Top drive installation was included here since, in Menengai, it is not used until after section 0. This is because the top section is

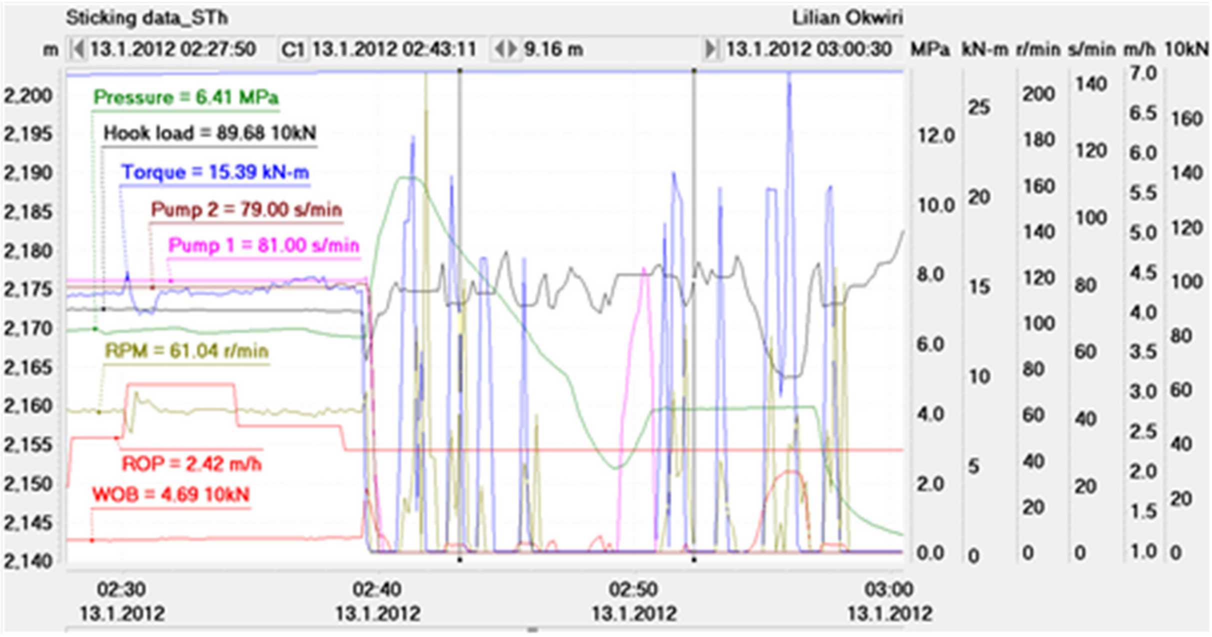

FIGURE 15: Drilling parameters at the time of sticking in Well MW06

usually characterised by a hard formation. Low ROP causes high string vibration, leading to frequent top drive breakdown. In Hengill, the top drive is rigged up on the big rig after section 0 is done. BOP installation took a relatively longer time to install in Menengai and materials took longer to be delivered to the site. Significant time was spent waiting for instructions which could signify planning was not sufficient in the first place. A consideration should be made on planning for trouble time when planning for the well. This will ensure that when drilling problems occur, the crew will know how to proceed even if further instructions are given later.

4.10 Repairs

Repairs were the third largest time consumer in Menengai wells, accounting for 7.6 days, while in Hengill, 0.4 days were spent on repairs. The larger part of equipment repairs was due to waiting for spare parts, as the procurement process is long and some of the spares had to be sourced from abroad. The big question is, is it economically viable to have in storage expensive spare parts\equipment that may not fail for years or risk not having it and incur the cost of waiting for days, even weeks, when it fails. According to Samland (2011), the costs of having a drill rig wait for several days and the consequences of a serious accident while drilling are of such magnitude that expensive equipment, advanced monitoring, redundant systems and other safety measures may often be worthwhile. To complicate the planning of spare parts further, many parts have an unpredictable demand, some parts will become unavailable, new manufacturers and brands are introduced and delivery times may vary from the stated values.

4.11 Reaming

On average, 3.4 days were spent on reaming in Menengai while 0.9 days were spent in Hengill. Reaming is usually done to straighten a crooked hole or to enlarge a tapered or tight well bore. If it is left uncorrected, it will cause problems during running in the casings. The crooked hole is a result of a change in formation that is beyond the control of the driller but, with the right choice of BHA, it can be minimised; a tapered wellbore is usually a result of under gauge bit.

4.12 Wait on water

Wait on water days were 4.7 in Menengai, while 0.3 in Hengill. In Menengai, this was necessitated by the severe loss of circulation encountered throughout the drilling process. Loss of circulation meant that water in the mud tanks and the pond were depleted fast and the replenishing rate was not as fast. Four rigs drill in the Menengai caldera and all four depend on the same supply. Water in Menengai is supplied from drilled wells, and sometimes brine from discharging wells. The formation in Menengai is highly fractured and drilling crews experience frequent long lost circulation periods. This means that there should be a constant supply of drilling fluids at the drilling sites. The use of fluids such as drilling mud and lost circulation materials is not advised in production zones because of their sealing properties which could end up compromising productivity. Therefore, water is used in drilling blind in this section.

The importance of water on a geothermal drilling site cannot be over emphasised. It is the basic drilling fluid in geothermal drilling; it can be used on its own and can be used to mix mud and can even be used when drilling with aerated foam. It is used in cementing and also in quenching a well during kicks and blowouts.

5. OPPORTUNITIES TO REDUCE NPT

It is not possible to completely eliminate NPT but it can be minimised to an extent that it does not impact drilling time so much. Process improvement and change of drilling practices are fundamental in ensuring that inefficiencies in the drilling process have been taken care of.

5.1 Acceleration of other drilling activities

Actual drilling is mostly dependent on the formation being drilled and to some extent the experience of the driller and the drilling technology used. Having the best of the three does not always guarantee a faster ROP. To reduce drilling time, other drilling activities can be accelerated to fast track drilling time. Figure 16 is a scatter plot showing NPT against workdays for Menengai wells. Statistically, there is a low correlation between the time it took to complete a well and the time spent on NPT; therefore, as much as NPT adds to drilling time, there are other causes for time overruns. As previously observed, cementing is one of those activities to be fast tracked, by reducing the time spent on backfills and carrying out the bulk cementing in the primary cementing. Planning for early delivery of materials, spares and equipment, ensures the drilling progress will be uninterrupted. Changing bit technology to achieve one bit per section for the upper shallower depths and fewer bit changes for the deeper production section will reduce bit trip time. The use of an air hammer to accelerate drilling the top hole will reduce drilling time for this section.

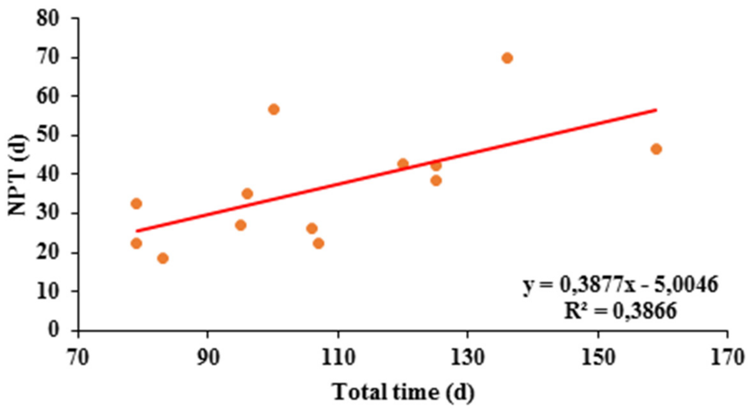

FIGURE 16: Non-productive time vs. total time in Menengai

5.2 Learning curve analysis

It is important to study the performance of successful wells to identify success factors, and to attempt to duplicate the success. A learning curve involves learning from the experience of the first few wells and incorporating those lessons into planning the next well to reduce drilling time and increase performance in subsequent wells. Drilling is a repetitive job, therefore, the more wells drilled the more learning takes place. Knowledge is acquired and a set of skills required for the job are improved with every new well drilled; this leads to a reduction in the drilling time for new wells. Figures 17 to 20 attempt to analyse whether learning took place as more wells were drilled in these fields.

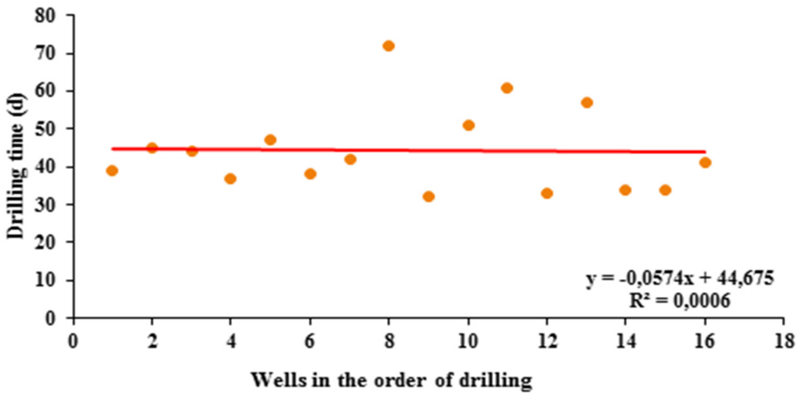

FIGURE 17: Drilling time vs. order of drilling for Hengill wells

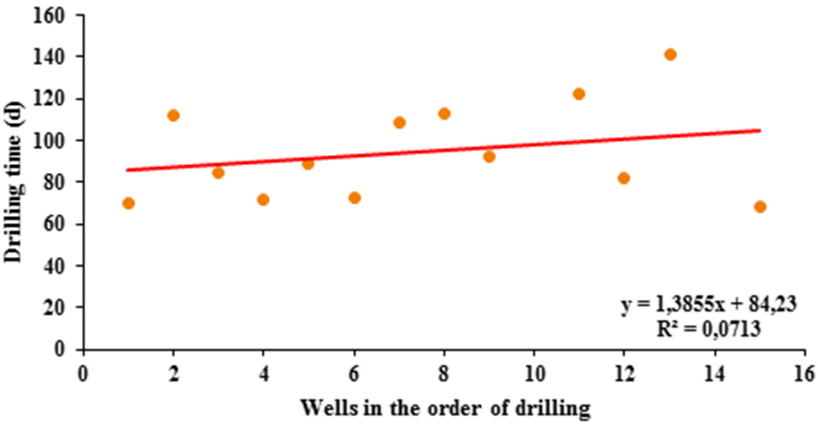

FIGURE 18: Drilling time vs. order of drilling for Menengai wells

Figures 17 and 18 are scatter plots showing drilling time against the order of drilled wells. The correlation of workdays to wells drilled was 0.00 in Hengill and 0.07 in Menengai. Statistically, neither field showed any correlation between drilling time and the order of drilling. These figures show that the drilling time is constant for all the wells drilled in these fields, with a slight increase in time on wells drilled in Menengai.

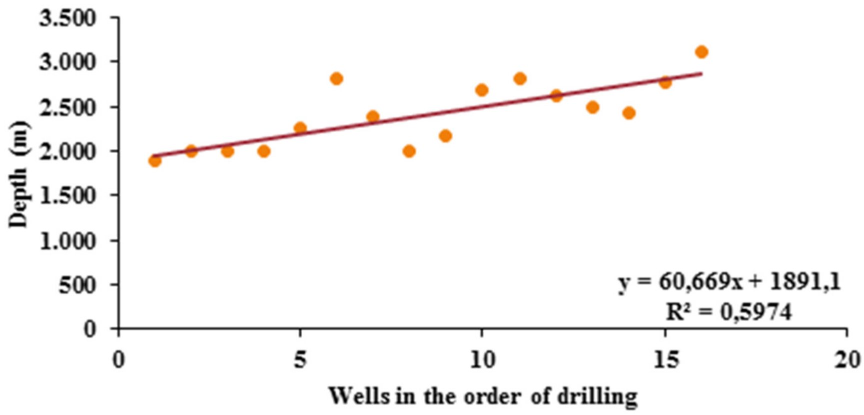

FIGURE 19: Depth vs. order of drilling for Hengill wells

Figures 19 and 20 are scatter plots showing drilled depth against wells in the order of drilling in the two fields. In Hengill, a positive correlation of 0.5974 was found between depth and wells in order of drilling. A correlation of -0.421 was found for Menengai wells. Statistically, the depths for wells drilled in Hengill increased as more wells were drilled. This can, therefore, explain Figure 17. In as much as the drilling time remained constant, the depths increased. Unfortunately, for the wells drilled in Menengai, the depths reduced as more wells were drilled in the same field.

The graphs show that if all wells drilled in Hengill were of the same depth, then the overall amount of workdays would reduce for the latest wells. There is an indication that learning took place in this field as more wells were drilled. There was an increase in experience while drilling more wells and increased knowledge of the field. This was not so for Menengai. Drilling time was constant with an increased number of wells drilled. There is need for learning in Menengai field through a transfer of knowledge and experience from one well to another. This would ensure that best practices were carried forward and drilling mistakes in one well were not repeated in another.

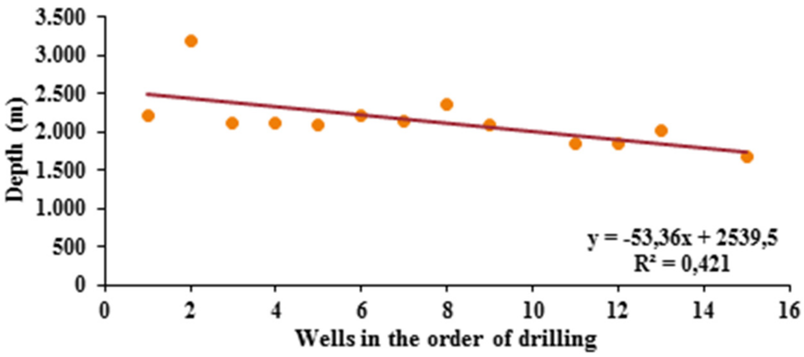

FIGURE 20: Depth vs. order of drilling for Menengai wells

Reduction in well time is realised as learning takes place, rapidly improving efficiency and performance on subsequent wells as lessons are learnt and technology is applied more effectively. Ensuring that personnel work with their experienced counterparts while incorporating training and retraining on the job instills the learning process. Training comes at a cost but the trade-off is realised when drilling efficiency is increased. Drilling data gathered during drilling should be analysed to build knowledge on what works and what does not. The information obtained will also play a key role in planning subsequent wells and the transfer of lessons learnt will improve drilling performance.

5.3 Planning

An efficient drilling process depends on continual planning for normal drilling activities and for unforeseeable occurrences in drilling. Having a plan to handle common drilling problems will see drilling problems solved faster and some even prevented. Studies of previous drilling performance will give insight as to where planning was not sufficient. Therefore, proper planning for a new well should involve collecting and analysing data from previous wells, identifying root causes of problems encountered in those wells and developing solutions. This means that sound records should be kept as this will be a guideline not only of what went wrong but for what could be done better. The planning process should be flexible, incorporating new ideas and technologies as the drilling process demands.

Proper planning ensures that even the most complex of wells can be drilled efficiently and safely. Drilling times would be reduced, irrespective of well specifications with proper planning. Figures 21 and 22 are scatter plots of time against depth for Hengill and Menengai, respectively. Time versus depth had a correlation of 0.56 in Hengill and 0.056 in Menengai. Statistically, there was no correlation between time and depth in both fields. This goes to show that even the deepest wells can be drilled in the

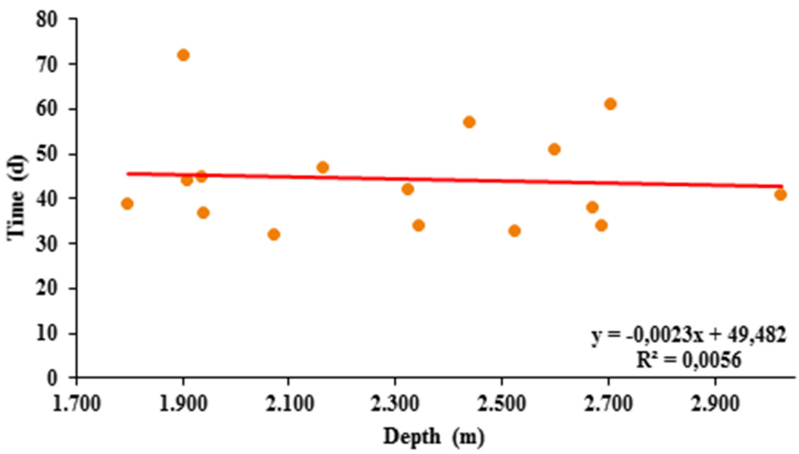

FIGURE 21: Time vs. depth for Hengill wells

shortest time possible if well planned for. It should be noted that the data sets used herein were small; it would be interesting to learn the outcome if more data was added.

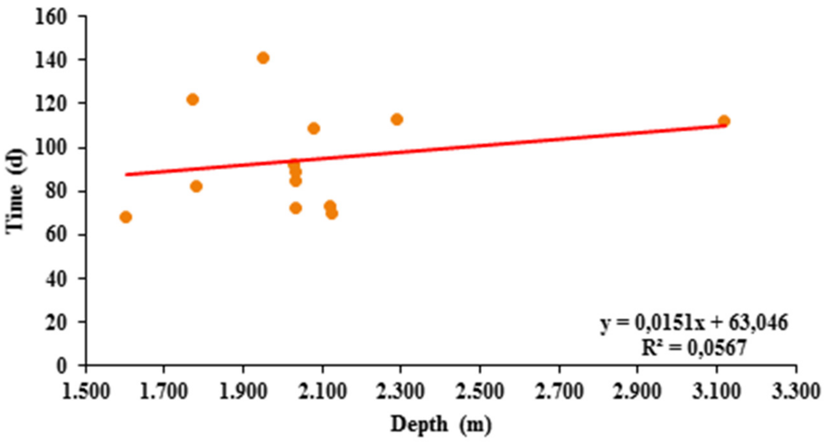

FIGURE 22: Time vs. depth for Menengai wells

Successful drilling hinges on developing a sound plan, continually updating it in light of new information, and keeping involved personnel informed on a timely basis. The plan must include procedures to follow under normal circumstances and methods for dealing with the most likely and most severe problems that may be encountered. With proper training, a well-defined drilling process, sufficient data and tools for interpretation, successfully drilling a well should be a routine process (Aldred et al., 1999).

5.4 Innovations

Innovation involves the deliberate application of new or different solutions that meet new requirements and lead to better results. Today's drilling technology has greatly improved and most of the industry's problems are routinely being solved. Applying different technology already existing in the market in problematic areas could be the solution to NPT. Time spent on activities such as tripping for bit and BHA change and also reaming due to a tapered formation could be greatly reduced through investing in better quality bits. Cementing time could be greatly reduced through logging before any cement job. A little more time might be spent on logging but the trade-off is much less time spent on cementing which would be of great help in reducing the NPT.

6. CONCLUSIONS

The geology in Menengai presents the biggest challenge to drilling, slowing down drilling activities and creating drilling problems. It contributed a larger part of NPT experienced in this field and leads to extended drilling days.

Menengai wells experienced more challenges and deviated from the original time schedule, incurring significant time overruns. Formation geology of the site played a major role in the problems experienced, considering the amount of time spent on stuck pipes, reaming, cementing losses and the time it took to drill the reference well, compared to Hengill. Initial problems experienced such as a stuck pipe led to other problems that also contributed to NPT, such as drillstring failure and equipment (i.e. top drive) breakdown, owing to overpull and high torques applied during stuck pipe and fishing operations. Drilling problems related to wellbore pressure such as lost circulation, and stuck pipe increased significantly with depth.

Time spent on activities such as tripping for bit and BHA change and also reaming due to a tapered formation could be greatly reduced through investing in better quality bits. Air hammers should be considered for drilling section 0 as this would greatly reduce the drilling time and equipment breakdown caused by vibrations.

Cementing time could be greatly reduced through logging before any cement job. Caliper logs would aid in determining how much cement to pump while cement bond logs would ensure that the cement job was done right. A little more time might be spent on logging but the trade-off is a better cementing job and much less time spent on cementing. Considering a change in the cementing method to the inner string method could also make a difference. Despite the use of cement plugs to cure losses in sections 1 and 2, lost circulation related problems were still experienced. A thorough job should be done to ensure that the loss zones are sealed and do not disturb the drilling process.

'Other' activities accounted for 17.6% of the total drilling time at Menengai. These were mostly waiting on materials, consumables and instructions. There is a need to change how the materials and consumables are planned for. Adequate planning from the beginning of the drilling process would ensure that unscheduled events or problem time would not be a surprise and, therefore, drilling progress would not be halted while waiting for instructions.

Drilling has been problematic as the 2200 m depth is approached. Eight wells got stuck at these depths and some resulted in loss of BHA. The wells are, however, productive and it may, therefore, not be desirable to attempt drilling deeper.

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