Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Dealing with Circulation Losses in Geothermal; Case Study Menengai Geothermal Field, Kenya

Marietta Mutonga

Geothermal Development Company, 17700-20100, Nakuru, Kenya.

mariettamu@gmail.com/mmutonga@gmail.com

Key words: Geothermal, Circulation losses, drilling fluids, geology

ABSTRACT

Geothermal wells world over have at one point experienced circulation losses which more often result in longer drilling time as the drilling team tries to cure the losses. Menengai geothermal field is no exception. It is located in the Kenyan rift valley and it is characterized by highly fractured permeable formations with high heat flows attributed to its volcano-logical evolution. Circulation losses have been encountered in most of the sections of the wells drilled in Menengai. Sometimes prevailing from top to the bottom of the wells. They are particularly more serious when we are drilling directional wells because it is critical to control the flow of fluids into and out of the bore especially before setting the casings. Various interventions have been applied to try and cure circulation losses and regain full geological control of the wells. A post-job analysis is shared and presented by discussing results from three different directional wells located in fairly different parts of the field.

1.0 INTRODUCTION

Menengai Geothermal field is located Nakuru County in Kenya, it is 10 km from Nakuru town in the central part of the Kenyan Rift (Figure 1). It is strategically located in a trachytic central caldera volcano in the Kenya rift valley underlain a high level magma chamber (Leat, 1984) with abundant high-temperature geothermal activity. It is one the seven quaternary caldera volcanoes in the inner trough of the Kenyan rift valley which are associated with high temperature gradients as a result of shallow magmatic intrusions (Mbia et al., 2015). The quaternary calderas overlap in space and time. The rocks are overwhelmingly peralkaline, ranging from silica over saturated and under saturated trachyte to rhyolite compositions (Macdonald and Scaillet 2006). Trachyte is the most dominant formation in Menengai geothermal field, it varies from fresh to a highly altered formations where high temperatures are encountered. The second most dominant is syenite which is mostly found at the deeper parts of the well and it is normally hard and abrasive. After concerted geothermal exploration efforts by various players, drilling in Menengai geothermal field commenced in 2011 with a number of exploration wells being drilled and temperatures exceeding 390^{o}C being realized. The discharge of the first three exploration with a 66% success led to drilling of six appraisal wells MW-06, MW-07, MW-05, MW-04, MW-08 which provided more information of the extent and characteristic of the geothermal reservoir. Increased production drilling led to improvements in the geothermal model hence understanding of the geothermal system has been enhanced, more so with directional drilling which kicked off with the drilling of MW-01A in 2014, which was a success. The drilled wells so far have proved steam for the 105 MWe geothermal power plants. A post-job analysis of three wells MW-17A, 12A and 08A is presented. MW-17A and MW12A experienced severe loss of circulation in at least 50% of the wellbore, while in MW-08A despite similar challenges the team managed to maintain circulation in most of the wellbore.

2.0 GEOLOGICAL SUMMARY

The Menengai caldera is a conspicuous geographical feature on the floor of the central rift valley (Figure 1) first studied in detail by McCall (1957a, b, 1964, 1967). Regional surface geology (Figure 2) of Menengai is largely composed of late Quaternary volcanics (with the dominant formation being trachyte). The Evolution of Menengai began with the building of a low angle trachytic shield about 200,000 years (200 Ka) ago. The shield had a volume of about 30 km^3 which was followed by a Krakatau style collapse that resulted in the formation of a 12 km x 8.5 km caldera about 84 km^2 in size, this was accompanied by the eruption of ash-flows tuff representing about 50 km^3 of magma. Around 29 Ka and 8 Ka, numerous eruptions (more than 70) took place after the caldera was formed with about 25 km^3 of lava being erupted on the caldera floor as lava flows (Leat, 1984). The caldera floor is characterized by young ropy lavas. Most lavas and pumice falls were erupted from vents located near center of the caldera. Regionally the caldera is straddled by two main regional structures the NNW Molo TVA (tectono volcanic Axis (TVA) and the NNE Solai Tectono volcanic (Axis TVA) which is much younger and associated with the Solai Graben where Lake Solai is located. These structures are believed to host the Menengai geothermal system. They also control recharge of the Menengai geothermal system which is further enhanced by the ring caldera fracture and numerous structures that cross-cut the Caldera floor from E-W, SW-SE, SE-SW.

The formation that is most encountered while drilling in Menengai is trachyte, it mostly intercalates with tuff and pyroclastics and at times can be found intercalating with syenite. The formation varies from very fresh at the shallow sections of the wells to moderately to highly altered at the bottom of the wells. Most often it transcends the well from top to bottom. The formation is usually fine grained and quite fractured. The second most abundant formation is syenite which is mostly encountered at the bottom of the wells it is hard and coarse grained, however it is altered at very high temperatures. Other formations include pyroclastics and tuff. They are the result of ash flows during the evolution of the Menengai caldera, Figure 3.

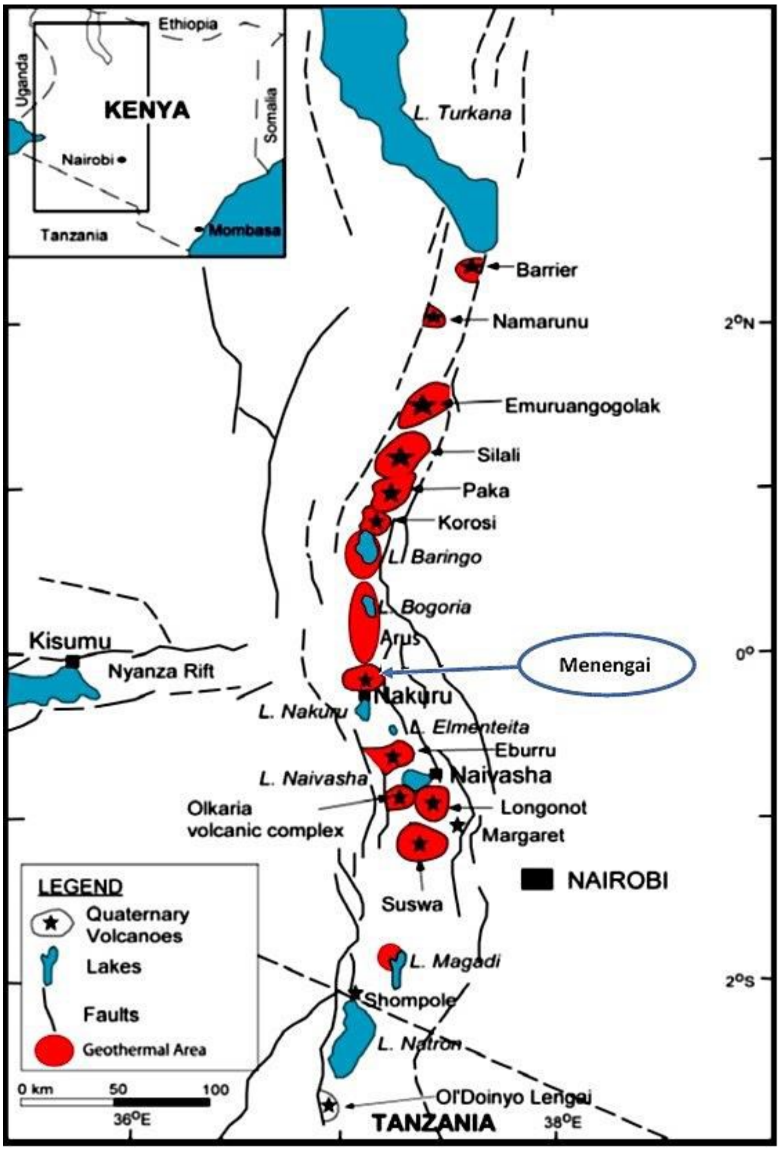

Figure 1 Map showing Location of Menengai within the Kenya rift.

3.0 DRILLING

Drilling is an essential part of geothermal development because it enables us to tap the high thermal energy that is stored in the deeper parts of the earth. While drilling geothermal wells it is important to maintain circulation, to do this the drilling team normally uses drilling fluids, albeit with challenges. The drive behind drilling fluids is that during drilling, the drilling fluids allow cooling of the drilling environment and equipment, maintain well stability and provide pressure and lastly clean the wellbore from cuttings. Drilling in Menengai geothermal field kicked off in 2011 with the first three exploration wells being drilled and temperatures exceeding 390^{o}C being realized. More wells have since been drilled with each new well adding more data leading to a better understanding of the field. Understanding of the geothermal system has been enhanced with directional drilling, which kicked off with the drilling of MW-01A in 2014. Drilling in Menengai has not been straightforward, as we have had to overcome a myriad of challenges. A post-job analysis is shared and presented by discussing results from three different directional wells located in fairly different parts of the field (Figure 3) the stratigraphic sections of this wells indicate most of the well bores suffered loss of circulation, including the wells MW-12A and MW-17A. In well MW-08A the team managed to surmount the challenges and loss of circulation was at a minimum.

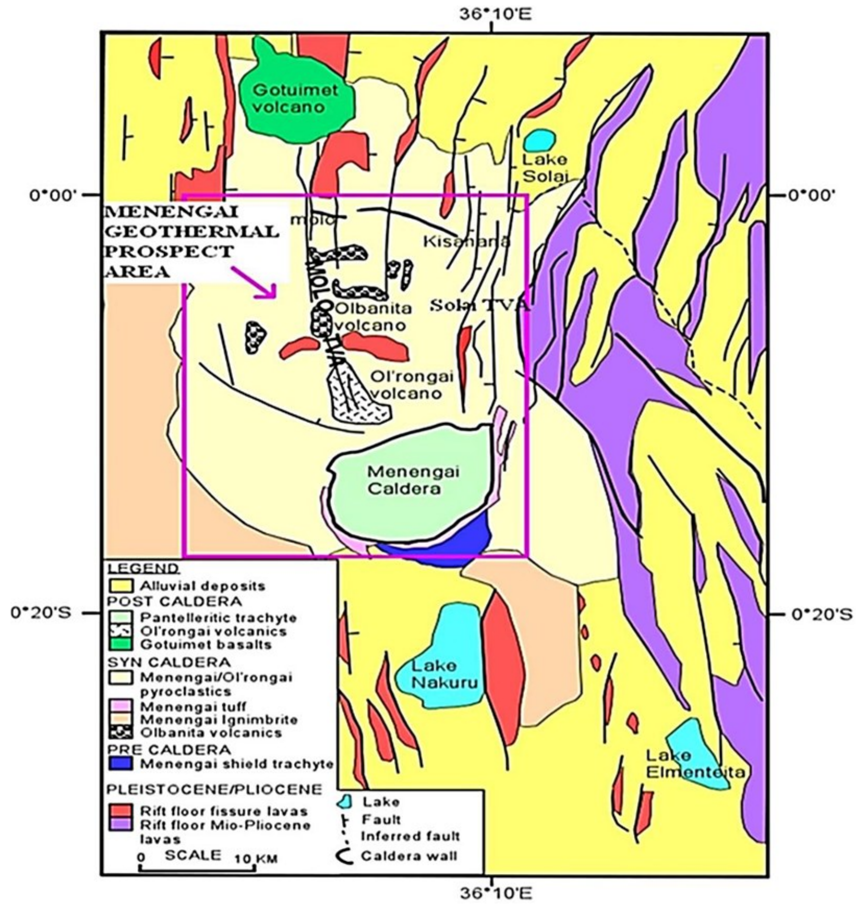

Figure 2 The Geology of Menengai

3.1 MW- 17A

MW-17A (Figure 3) is the third directional well to be drilled in Menengai with the aim of providing more steam for the 105 MWe power plants and to further explore the western part of the caldera with the intent to intercept the E-W arc structure. It is an S-type directional production well, with casing shoe depths being as follows 20" 68.28 m, 13⅜" 354 m, 95/8 1119.6 m and 7'' landing depth being 2364.41 m. The well suffered the most severe losses over almost the entire well bore as shown in Figure 3. Total losses of circulation were encountered from 160-380 m, 680-1100 m, 1900-2000 m, 2100-2400 m mostly where the trachyte formation was most fractured and soft.

3.1.1 26''hole section

Drilling commenced with returns on the surface but with low penetration rates. Bentonite was introduced at 42 m to maintain hydrostatic pressure of the well and to cure losses in circulation. Drilling continued up to 76.88 m where the string got stuck. To free the string aerated water and foam was pumped and the string was fled. The hole was reamed to avoid problems while running in. Casings were run in and the shoe set at 68.28 m after a third backfill.

3.1.2 17½" hole section

This was the most challenging section to be drilled. After setting the casing, cement was drilled out and the BHA was changed and drilling resumed with water and mud sweeps. While drilling, loss of circulation was noted at 169.12 m and in an effort to heal the losses the well was plugged. Cement was drilled out and still no returns were received on the surface. It was therefore decided to drill the well blind. Drilling continued without returns up to 243.5 m prompting more plug jobs. There were still no returns, so to heal losses sawdust was poured through the annulus, and the hole was plugged further with 4.8 m^3 of cement with slurry density of 1.8g/cm^3. Further circulation yielded no returns therefore it was decide to add 36 bags of bentonite and 10 bags of walnuts in the well bore to heal the circulation, the well was then plugged and cement tagged at 199 m. Further circulation yielded no returns. Sawdust was then added and another plug job done. Further circulation still yielded no returns, so it was therefore decided to drill the well blind to casing depth. A total of 8 plug jobs were carried out in this section. Casing was set at 354 m. The well was mostly drilled blind in this sections after several attempts failed to heal the well even using walnuts and sawdust.

3.1.3 12¼'' hole section

After the casing was set at 354 m, cement was drilled out with water and good returns were received on the surface. Drilling on the bottom continued to a depth of 402 m where directional drilling started. Drilling on bottom using water and mud continued from 450-505.64 m with intermittent returns after which returns completely disappeared from a depth of 469 m where the bit was changed. The well was then drilled with water and mud sweeps to a depth of 601 m with partial returns being received at the surface. The well was further drilled to a casing depth of 1242 m, however attempts to run in the 9⅝″ casing failed due to formation collapse forcing the crew to pull out of the hole 34 joints. The well had to be drilled on a slightly different trajectory. The wellbore was plugged and a squeeze job was done to stabilize the formation which was later drilled with water, mud and aerated foam to a casing depth of 1125 m. 13 plugs jobs and 4 backfills were carried out this section.

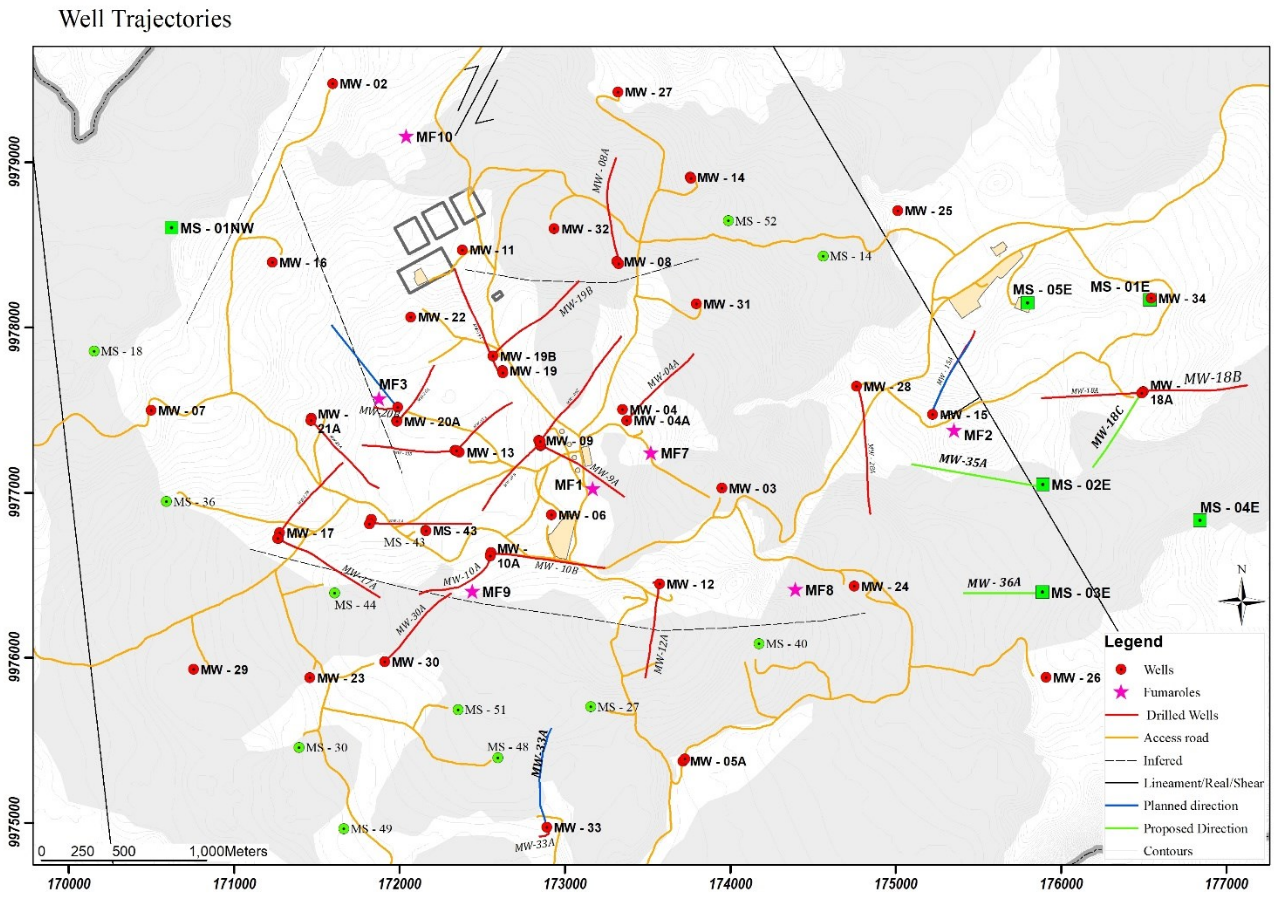

Figure 3 Menengai Geothermal field Map showing structures and well locations

3.1.4 8 ½'' hole section

Top of cement was tagged at 1095 m. Drilling cement using sliding BHA and water continued with good returns being received on the surface. Drilling on formation using aerated water and foam with full returns continued to a depth of 2045 m, thereafter total of loss of circulation was experienced to a depth of 2372 m where the well was terminated.

3.2 MW-12A

The well was a J-Type directional well and was deviated to the south with an azimuth of 180° and was inclined at 16.17° at TD. The well was drilled to further explore the field south of the E-W structure. It was drilled to a total depth of 2305 m. The surface, anchor and production casings were set at 77.72 m, 375.5 m and 1211.17 m respectively. It is also one of the wells that proved to be most challenging, experiencing severe loss of circulation (Figure.4). The formation drilled throughout most of the wellbore in this well was mostly trachyte with only tuff being encountered at the bottom of the well as tuff intercalations (Figure 4).

3.2.1 Drilling of the 26" section

Bentonite was introduced at a shallow depth of 17.1 m to maintain hydrostatic pressure and curb any losses in circulation. Drilling continued with intermittent returns on hard formation up to 30 m depth. Drilling resumed later but progressed at an extremely low ROP whereby it took 36 hours days to drill 10 m. The formation stabilized and drilling progressed with no major incident, but at a relatively low ROP to casing depth of 84.76m RT. Casings were run in successfully and the shoe set at 67.72 m RT. After 15 backfills, it was recommended that a hammer bit should be used for the top hole section to curb extreme low ROP in future wells.

3.2.2 Drilling of the 17½" section

Top of cement was tagged at 73.70 m CT. Drilling out cement with water and slick BHA followed with full returns received on surface. After drilling out cement, the BHA was changed and drilling continued with water and mud sweeps on hard formation with no returns. Four more plug jobs were carried out, but none managed to heal the loss zone forcing blind drilling. Blind drilling on hard formation continued up to a depth of 379 m, after which a wiper trip was carried out before RIH the 13⅝" casing. The casing shoe was set at a depth of 375.59 m CT after 12 backfills.

3.2.3 Drilling of the 12¼" Section

Top of cement was tagged at 339.77 m, and drilling out cement with water continued with good returns. Drilling on bottom continued to a depth of 401 m where the well was kicked off. Drilling on bottom using aerated water and mud continued to a depth of 642 m with intermittent returns where the drill string was pulled out of hole to change BHA after successfully building the required angle. Drilling continued unperturbed to a depth of 769 m whereby the string was pulled out to modify the BHA and to prevent the inclination from dropping. Drilling continued thereafter to a depth of 862 m with intermittent returns before pulling the string out of hole again to change the BHA. Being a soft formation, the azimuth had exceeded the target by about ten degrees hence the need to correct it with a mud motor. Sliding was done up to a depth of 902 m before pulling out the steering assembly and running in-hole with a holding assembly and drilling with aerated water and foam without returns to a depth of 1145 m. At 1196 m a squeeze job was carried out to stabilize the formation and later drilled with intermittent returns to a casing depth of 1207 m. The 9⅝" casings were run in-hole and the shoe set at 1201.19 m after six backfills.

3.2.4 Drilling of the 8½" Section

Upon drilling out cement to the shoe, a shoe track test was performed, but the test failed resulting in carrying out cement plug to cement the shoe. After finishing drilling out cement, the BHA was changed to holding assembly. Drilling on formation using aerated water and foam with full returns continued to a depth of 1430 m when the string was pulled out of the hole to change the BHA. At this point, the azimuth had deviated owing to the soft formation hence the need to correct it. Sliding continued to a depth of 1534 m when the string was pulled out to change into holding assembly. Drilling continued to a total depth of 2305.2 m with minor incidents. A short wiper trip was thereafter carried out and running in of 7" liners.

3.3 MW-08A

MW 08A is an S-type well with Azimuth N000°E with GPS coordinates E 173325.665, N 9978385.927 at an elevation of 2015 m.a.s.l (Figure 3). It was kicked off at 453.72 m with a target depth 2300 m TVD the casings were set as follows; 20" casing shoe depth - 67.68 m, 13⅜" casing shoe depth-368.68 m, 9⅝″ casing shoe depth-1175 m, 7" liners landing depth-2409 m, top of liners-1142.25 m. It is one the wells that had surmounting challenges but the team was able to deal with the loss of circulation successfully (Figure 4).

3.3.1 Drilling of the 26'' hole section

26" diameter hole was drilled from 0 to 11 m with minimum challenges. Decision was made to pull out of hole to change to air hammer bit. The hole was then drilled from 11 to 19 m. Hole collapse was experienced a number of times while drilling from 19 to 85 m. A wiper trip was then done followed by pulling out of hole. 26" tri-cone bit was run in to 68 m.

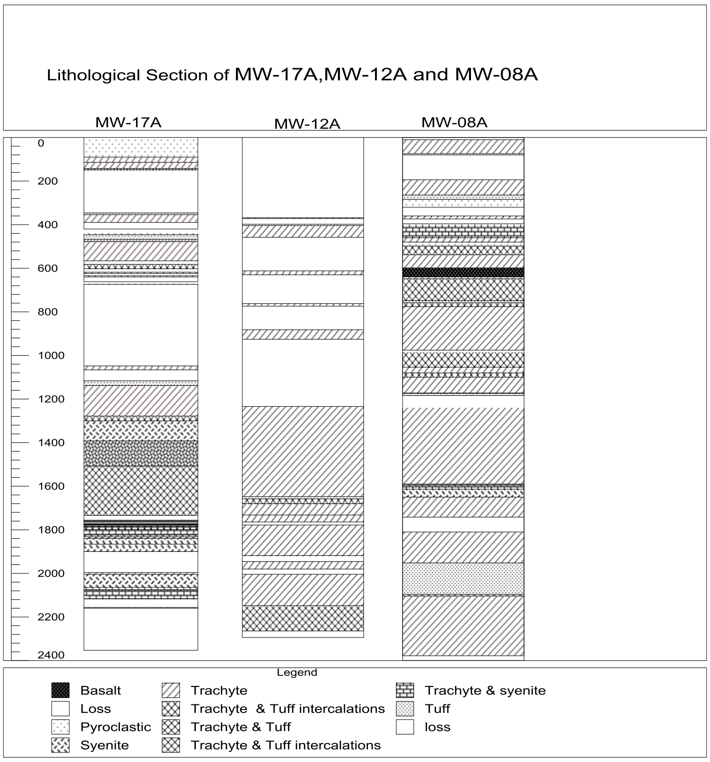

Figure 4 Stratigraphic sections

The hole was circulated so as to clean it, and then pulled back to 58 m. This was followed by running in back to bottom. After this, the drill string was pulled out of hole to surface so as to run in hole 20" surface casing. While running in the surface casing, tight spots were encountered but were worked through. The 20" surface casings were successfully landed at a depth of 60 m. In the primary cementing of 20" casing, 27.8 m³ of cement with a density of 1.72 g/cm³ was used. During this surface casing, a total of 5 backfills were pumped before cement retuned to surface.

3.3.2 Drilling of 17½" hole section

After drilling out cement, the 17½" diameter hole was drilled ahead from 85 to 94 m. This was followed by drilling ahead from 94 to 99 m. The hole was then circulated for 15 min. This was followed by drilling ahead from 99 to 127 m. The 17½" hole was drilled ahead from 127 to 319 m. At a depth of 319 m, there was total circulation losses and hole collapse. Tight hole was experienced and finally lost rotation. The pipe was worked and pulled at 140,000 lbs. The string got free. The crew then did circulation back to bottom and pulled tight pipe again to get free. This was followed by pulling out of hole to do a cement plug. 5.5m^3 of cement with a volume of 1.82g/cm^3 was pumped. This was followed by wait on cement for 11 hr and wait on jars for 48 hr. This was followed by making up BHA and running it in hole. Cement was tagged at 265 m. Drilled ahead blindly from 265 to 320 m. Drilled ahead from 320 to 323 m and back reamed from 323 to 255 m. Ran in hole and pumped 4 m^3 of cement at 1.8 g/cm^3 then wait on cement for 9 hr. After this, BHA was made up and RIH to 270 m. Drilled ahead 17½" hole blindly from 270 to 290 m. 1 single drill pipe was pulled back and switched to air from 280 to 318 m then waited for foam to come to surface. This was followed by drilling ahead from 318 to 360 m. The hole was then circulated to clean it. Drill string was pulled out of hole to RIH 13⅜" anchor casing. The 13⅜" casing shoe was set at 354.09 m. 13⅜" casing primary cementing was done using cement with a volume of 37 m^3 and a density of 1.72 g/cm^3. Waited on cement for 16 hr. This was followed by rig down. A total of 3 backfills was done while cementing 13⅜" casing.

3.3.3 Drilling of the 12¼'' hole section

For this well this was the most troublesome section to drill. Top of cement was tagged at 342.5 m and drilling out cement with returns being received on the surface up to 375 m where the returns were lost. Drilling out of the cement continued using water but no returns to 385m and the slick BHA was POOH to change to the 12¼ inch mud motor BHA. While RIH, a tight spot was encountered at 353m and the well had to be reamed from this point to the bottom. Drilled ahead by sliding with a mud motor with water on a medium hard formation with returns being received on the surface from kick off point at 385 m to 389 m. Drilling resumed with aerated water and foam on a medium hard formation with returns being received on the surface. Drilling continued by sliding with the formation getting softer at the depth of 526 m on to 685 m where the angle had built to 33.16^0 prompting a change of BHA to dropping BHA.

The 12¼ inch dropping assembly was RIH encountering tight spot at 564 m and had to ream to the bottom. The formation was soft and a directional survey was conducted at 749 m with survey results giving an azimuth of 352.23^o and inclination had rapidly dropped to 19.06^o prompting a change of BHA to holding BHA. Drilling continued with the holding BHA on a soft formation with returns being received on the surface and a deviation survey was conducted at 875 m during which the string got stuck and circulation was lost. Attempts to free the string by working the string up and down and overpull up to 400klbs were proved futile. The drill string remained stuck for several days after which a meeting was held to deliberate on the way forward. It was decided that, the string to be backed off at the deepest possible point. After several failed attempts to free the string a meeting was again held where a decision was made to abandon the tools and carry out a cement plug job. Cement was tagged at 443 m. The cement was drilled out to 520 m and a sliding BHA was RIH and side tracked the hole on a hard formation with aerated water and foam and spotting with mud to 732 m. Partial returns were received on the surface.

The BHA was changed to holding BHA and drilled ahead on a medium soft formation with returns being received on the surface to 807 m where the string got stuck. Attempts to free the string by working up and down while pumping aerated water and foam and succeeded after several attempts. A cement plug was carried out and tagged at 443 m. The cement was drilled out to 514 m after which a mud motor was engaged, sliding on to 617 m. The BHA was changed to a holding BHA, drilled on a medium soft formation with aerated water and foam, with returns being received on the surface up to 839 m where the drill string was stuck. Attempts to free the string by working it up and down with an overpull up to 300klbs proved futile.

A cement plug was conducted and tagged at 421 m after the third backfill. Drilling commenced with Hi-vis complemented with walnut and caustic soda conducting several cement plugs due to lost circulation. The kick off point was at 453 m. Drilling progressed with no major hitch and the formation changing from medium soft to soft up to 777 m where the string briefly got stuck. The string was eventually freed and drilling progressed to 996 m where the string was again stuck. A wiper trip was conducted at 1184m and RIH 9⅝" casings setting the casing shoe at 1175.12 m.

3.3.4 Drilling of 8½'' hole section

Operations for the 8½" hole section commenced after backing off of 9⅝" landing joint. The 8 inch collars were laid down and the 8½ inch slick BHA was RIH to drill out cement. The cement was drilled to 1196 m and a shoe track integrity test was done successfully with a pressure of 500psi and 1000psi. Drilling out cement using slick BHA and water continued with good returns received on surface. After finishing drilling out cement, the BHA was changed to dropping assembly and drilled using aerated and foam on a medium hard formation while receiving partial returns to 1600 m. The survey data showed the inclination to be 16.85^o.

Based on the planned trajectory, we pulled out of hole to change the BHA to holding. The hole was reamed and we continued drilling the 8½ inch hole with aerated water and foam while receiving full returns to 1753 m. A directional survey was to be performed but tools were being used in another well and by the time the survey was done the drill string was stuck. Attempts to free the stuck drill string by working the string up and down and applying over pull of up to 300 klbs were unsuccessful for 72 hours when the string was finally freed. Drilling then continued on a medium soft formation with returns being received on the surface after incorporation of a drilling jar. The well was drilled with aerated water and foam to be terminated at 2419 m CT .The directional survey at 2370 m indicated an azimuth of 25.14^o and an inclination of 15.36^o.

4.0 DISCUSSION

For the MW-17A 26''hole section, bentonite was introduced at 42 m to maintain hydrostatic pressure of the well and to cure losses in circulation. Drilling continued up to 76.88 m where the string got stuck. To free the string aerated water and foam was pumped and the string was fled. The hole was reamed to avoid problems while running in. The 17½'' hole section was the most challenging section to be drilled. All manner of interventions were carried to heal losses (Figure 4) which include adding bags of bentonite, walnuts, sawdust and 8 plug jobs. After all the interventions failed the section was mostly drilled blind to the casing depth. It is noted that use of sawdust was not effective especially if a cement plug is applied on top, as circulation was not regained. Frequent plug jobs were effective on small columns less than 2m. Drilling blind from 200-357 m did not affect the well stability hence can be done with caution. Drilling blind saves on time and cost, while small plug jobs immediately after encountering total loss of circulation help in healing losses. The 12¼'' hole section was drilled mostly with water and mud sweeps yielding intermittent returns in some instances experiencing total loss of circulation to a casing depth of 1242 m. However during RIH of the 95/8" casing the formation collapsed, the section was successfully redrilled on slightly different trajectory with aerated water and mud.

While drilling the MW-12A 26" section, bentonite was introduced at a shallow depth of 17.1 m to maintain hydrostatic pressure and curb any losses in circulation. Drilling continued with intermittent returns on hard formation up to 30 m depth. Drilling continued with no major incidents however casings were run in successfully and the shoe set at 67.72m RT after 15 backfills. Drilling the 17½" section after drilling out cement, the BHA was changed and drilling continued with water and mud sweeps on hard formation with no returns. Four more plug jobs were carried out but none managed to heal the loss zone forcing the team to resort to blind drilling. Top of cement was tagged at 339.77 m drilling out cement with water continued with good returns. Drilling on bottom continued to a depth of 401 m where the well was kicked off. Drilling on bottom using aerated water and mud continued to a depth of 642m with intermittent returns where the drill string was pulled out of hole to change BHA after successfully building the required angle. Drilling continued unperturbed to a depth of 769 m whereby the string was pulled out to modify the BHA to prevent the inclination from dropping. Drilling continued thereafter to a depth of 862 m with intermittent returns. Sliding was done up to a depth of 902 m before pulling out the steering assembly and running in-hole with a holding assembly and drilling to a casing depth of 1207 m. The 9⅝" casings were run in-hole and the shoe set at 1201.19 m after six backfills. The 8½" Section Drilling on formation using aerated water and foam with full returns

While drilling MW-08A, the team was able to minimize the total loss of circulation for most of the well bore despite the well collapsing and getting stuck several times. For the 26" diameter hole section the team conducted wiper trips and circulated to clean the well and regain circulation. For the 17½'' section the well was drilled blind in some sections, back reamed, circulated to regain circulation. The 12¼" hole section was mostly drilled with aerated water and foam. Despite this the well still experienced lost circulation and the well got stuck after unsticking spotting with mud and drilling progressed with partial returns but the string got stuck again, so cement plugs were conducted. At some point Hi-vis complemented by walnuts and caustic soda and some cement plugs were introduced to heal the losses. The number of trip-ins and trip-outs 8½" hole section were minimized for proper hole cleaning and circulation to prevent stuck drill string problems during directional surveys. The 8½" hole section was mostly drilled with aerated water and foam without major challenges receiving partial to full returns,

5.0 CONCLUSION

A post job analysis of drilling three directional wells MW-17A, 12A and 08A in Menengai has shown that directional drilling of geothermal well is quite challenging especially where the formation is as fractured as the geological formations of Menengai geothermal field. Loss of circulation is the biggest challenge, because if not dealt with can result in stuck pipes, and sometimes loss of the wells through abandonment. Circulation losses have been encountered in most of the sections of the wells drilled in Menengai.

Various interventions included; introducing bentonite in the early stages of drilling, adding walnuts and sawdust in a bid to cure severe losses have been tried some working for some wells and failing in others. Also squeeze jobs were carried out to stabilize the formation especially after formation collapse or after long sessions of blind drilling. There is no rule of thumb while drilling these wells, each challenge should be dealt with on a case by case basis. However from the lessons learnt so far the following checklist can used.

- Use of mud is critical in less competent formations reducing significantly the chances of formation collapse and stuck drill strings, and also heals lost circulation,
- Proper hole cleaning is advisable at all stages to clear the well bore,
- Small plug jobs immediately after encountering total loss of circulation help in healing losses.
- Aerated water and foam is the best drilling medium for the 12¼ to 8½ hole sections however,
- If total loss persist, drilling with mud sweeps is advisable.
- Drilling blind saves on time and cost.

6.0 REFERENCES

Geotermica Italiana Srl., 1987: Geothermal reconnaissance survey in the Menengai- Bogoria area of the Kenya Rift Valley. UN (DTCD)/GOK.

Leat, P.T., 1984: Geological evolution of the trachytic volcano Menengai, Kenya Rift Valley. J Geol Soc London, 141: 1057-1069.

Mbia, P.K., 2014: Sub-surface geology, petrology and hydrothermal alteration of Menengai geothermal field, Kenya. University of Iceland, MSc thesis, UNU-GTP, Iceland, report 1, 96 pp.

Macdonald, R., and Scaillet, B., 2006: The central Kenya peralkaline province: insights into the evolution of peralkaline salic magmas. Lithos, 91, 59-73.

McCall, G.J.H., 1957a: The Menengai caldera, Kenya Colony. 20th Int. Geol. Congress, section 1, 1:55-69.

McCall, G.J.H., 1957b: Geology and Groundwater conditions in the Nakuru Area. Tech. Rep., 3. Hydraulic Branch, M.O.W., Nairobi.

McCall, G.J.H., 1967: Geology of the Nakuru-Thomson’s Fall-Lake Hannington Area. Geo. Surv. Kenya, Rep., 78.