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Case Study of Geothermal Directional Drilling: The Menengai Geothermal Field

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ABSTRACT

The Menengai geothermal field is hosted by the Menengai Caldera, the 2nd largest in the world, and is located 20km from Nakuru Town in the Kenyan Rift Valley. The geology of the Menengai Caldera is dominated by trachytic lavas that exhibit textural variation, pyroclastics, ignimbrites and basalts. The youngest lava eruptions are located at the center of the caldera. In 2010 it became the second largest geothermal field in Kenya to be developed for energy generation in Kenya, and by 2013, 22 vertical wells had been drilled in Menengai. To fast track generation of steam for the 105 MWe power plant and to optimize production of the wells, in 2014 drilling of directional wells was considered in Menengai with MW-01A being the first directional well to be drilled in Menengai. Others followed suit; in this paper, the MS-09 series of wells is the centre of discussion because it is unique in the sense that four wells have been drilled from the same well pad. The wells include MW-09, which is a vertical well, and MW-09A, MW-09B and MW-09C, which are directional wells. In a bid to drill productive wells, each directional well was designed to cut across as many structures as possible, with MW-09A having an azimuth of S120oE, MW-09B having an Azimuth of S215oW and MW-09C having an azimuth of N40oE. The structures targeted were mainly the NNW-SSE, E-W and NNE-SSW structures associated with the Molo and Solai TVA's. The lithology that has been penetrated in this well includes, trachyte, pyroclastics, tuff and syenite. The build-hold (J) directional well profile is the most common in geothermal application, however in Menengai the build-hold-drop (s) profile is popular. This is due to the fact that wellpads lie close to each other. An anti-interference policy of 300m minimum distance between wellbores is applied to ensure no interference between

neighboring wells. Due to massive lost circulation encountered while drilling geothermal wells in Menengai, aerated foam drilling has been applied successfully improving hole cleaning in deviated wells.

1. Introduction

The Menengai Caldera is Located in the Great Rift Valley in Kenya hosted by one of the largest calderas in the world, 2nd largest in the world. Leat (1984) describes the caldera as a major topographical feature of Great Rift Valley and the best preserved Krakatau-style caldera in the world. It is a quaternary caldera volcano associated with a high temperature gradient which is as a result of shallow intrusions (Mbia et al., 2015). The caldera boasts of a ring-like 12 km by 9 km depression that is host to the Menengai high temperature geothermal field. It is about 20 km from Nakuru town in Kenya. In 2010 it became the second largest field in Kenya to be developed for energy generation following Olkaria, which has proven to be successful and is currently undergoing expansion. Since 2011 many wells have been drilled in Menengai for the production of geothermal steam to depths greater than 2000 m. The first three exploration wells were drilled in Menengai to prove the existence of a resource; thereafter three appraisal wells were drilled. By December 2013, 22 vertical wells had been drilled in Menengai (Okwiri and Cherotich, 2013), to-date more than 35 wells have been drilled. To fast-track generation of steam for the 105 MWe power plant and to optimize production of the wells, in 2014 drilling of directional wells was considered in Menengai with MW-01A being the 1st successful directional well to be drilled in Menengai. Several others followed. The focus of this paper will be those drilled from the MW-09 well pad. From the MS-09 well pad four wells have been drilled – wells MW-09, MW-09C, MW-09A and MW09B.

2. Geology

The geology of the Menengai Caldera is dominated by trachytic lavas that exhibit textural variation, pyroclastics, ignimbrites and basalts (Mibei et al., 2016). The youngest lava eruptions are located at the center of the caldera. The evolution of Menengai started about 200Ka with the formation of a trachytic shield volcano; remnants of this are still evident at the view point. At around 29Ka large volumes of tuffaceous ash material were erupted resulting in the formation of a huge caldera much larger than the present one. A second large eruption occurred around 8Ka resulting in the formation of compositionally zoned peralkaline trachytic magma that is associated with the formation of the present day caldera (Leat, 1984). More than 70 post-caldera eruptions occurred resulting in lava flows covering the caldera floor as cinder cones and plinian-type tephra sheets. The young post-caldera lavas have been dated around to be 1400 years BP.

The structures that straddle the Menengai caldera mostly trend N-S, NNE-SSW and NNW-SSE (Figure 1). The major regional structures that control the Menengai geothermal system are the Molo tectonovolcanic Axis (TVA) and the Solai Graben. The Molo TVA has a NNW-SSE general trend. The Solai graben is a result of the formation of a normal fault trending NNE-SSW, which is much younger than the caldera as it cuts the caldera rim in the NE. The structures control the Menengai geothermal system. The geothermal manifestations such as fumaroles and eruption centers in the centre, northwest and northern part of the caldera are also aligned to these structures. Fissures cross most of the caldera floor inferring recent faulting activity.

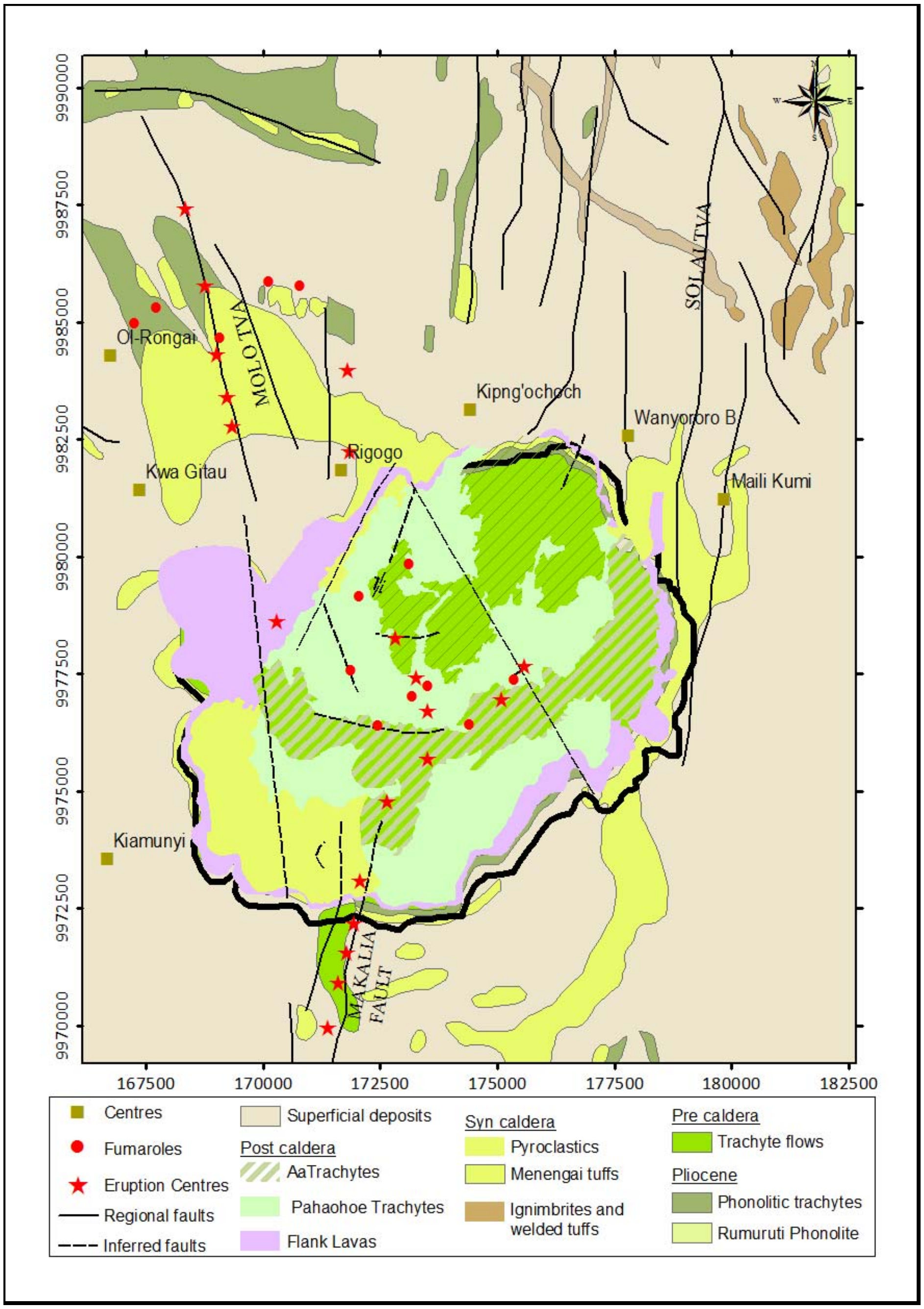


Figure 1: The geology, structural setting and geothermal manifestations map of Menengai.

3. Directional well drilling

The practice of directional drilling started in the 1920's when basic well bore surveying methods were introduced. The methods devised opened the eyes of the drillers to the fact that vertical wells were actually not vertical but deviated meandering in unwanted directions. To deal with this problem the drillers devised ways of drilling wells as vertical as they possibly could. Later

the drillers realized that deviated wells could actually help in dealing with some issues, e.g. to avoid problematic sections, the wells could be deviated, to side track around stuck pipes and drilling relief wells to avoid blow outs.
Today more than ten directional wells have been drilled in the Menengai geothermal field the strategic reasons for drilling directional wells include;

a. Drilling an optimum number of wells from a single location/ platform has helped by greatly reducing the costs and environmental impact on having to prepare additional wells pads.
b. Wells have been drilled directionally to reach production zones or targets that are not accessible.
c. Drilling multiple target zones is seen as a cost effective way of delivering highly productive wells from a single well pad.
d. Directional wells have also been employed to drill around obstructions such as stuck drill strings and or if requested by geologist, to orient the side track in a certain direction to anticipate a production formation.

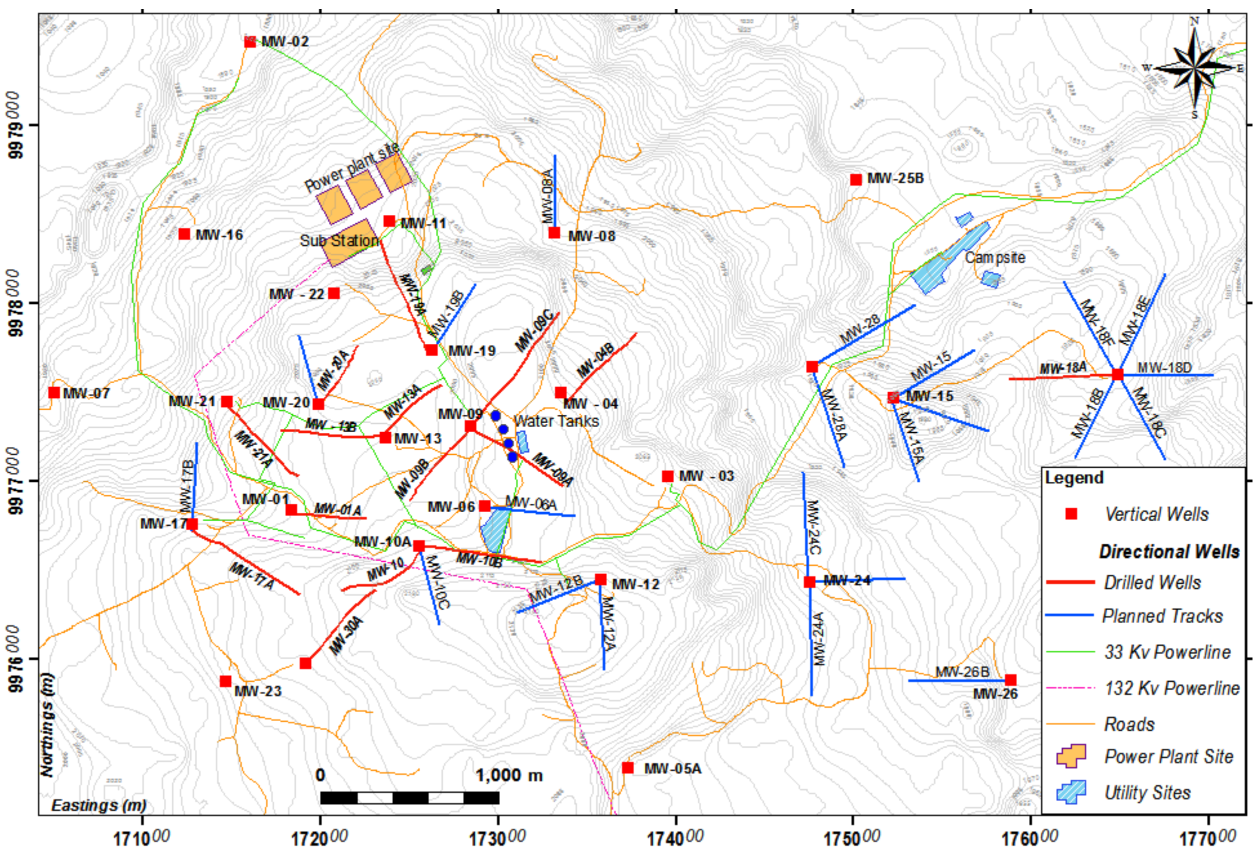


Figure 2: Directional well map of Menengai

3.2 Geological context/ Lithology of the directional wells drilled in Menengai

In Menengai geologists have been involved in the surface studies of the Menengai geothermal field from the onset and have therefore been tasked to site productive wells. The wells have been sited mainly to intercept structures that are expected to be carriers of hot steam normally between 250°C-350°C from the geothermal reservoirs to the surface. The first directional well drilled at Menengai was MW-01A, which is a highly productive well. The formation that is most penetrated in Menengai is trachyte lava, which varies from fresh to highly altered at the bottom of the wells. Hydrothermal alteration is controlled by temperature as we drill deeper. At shallow levels pyroclastic material is oxidized in most cases due to its interaction with shallow ground water. Syenite is also encountered mostly towards the bottom of the wells and varies from fresh to highly altered as we approach the bottom of the wells.

On MW-01 well pad the 1st exploration vertical well was drilled to a depth of 2195 m. The well proved existence of a geothermal reservoir (with temperatures greater than 250°C), which paved the way for the development of the Menengai geothermal field. The well is highly permeable and productive. It was therefore natural that the first directional well would be sited and drilled on the same well pad. MW-01A was drilled to a depth of 2200m oriented to the east with an azimuth of N85°E targeting the NNW-SSE structures. MW-01A is a very productive high temperature well. The formation encountered in these wells was mainly trachyte with thin lenses of tuff and pyroclastic with a deeper syenite intrusive underlain by a magmatic body. Following the success of MW-01A more directional wells were drilled in Menengai.

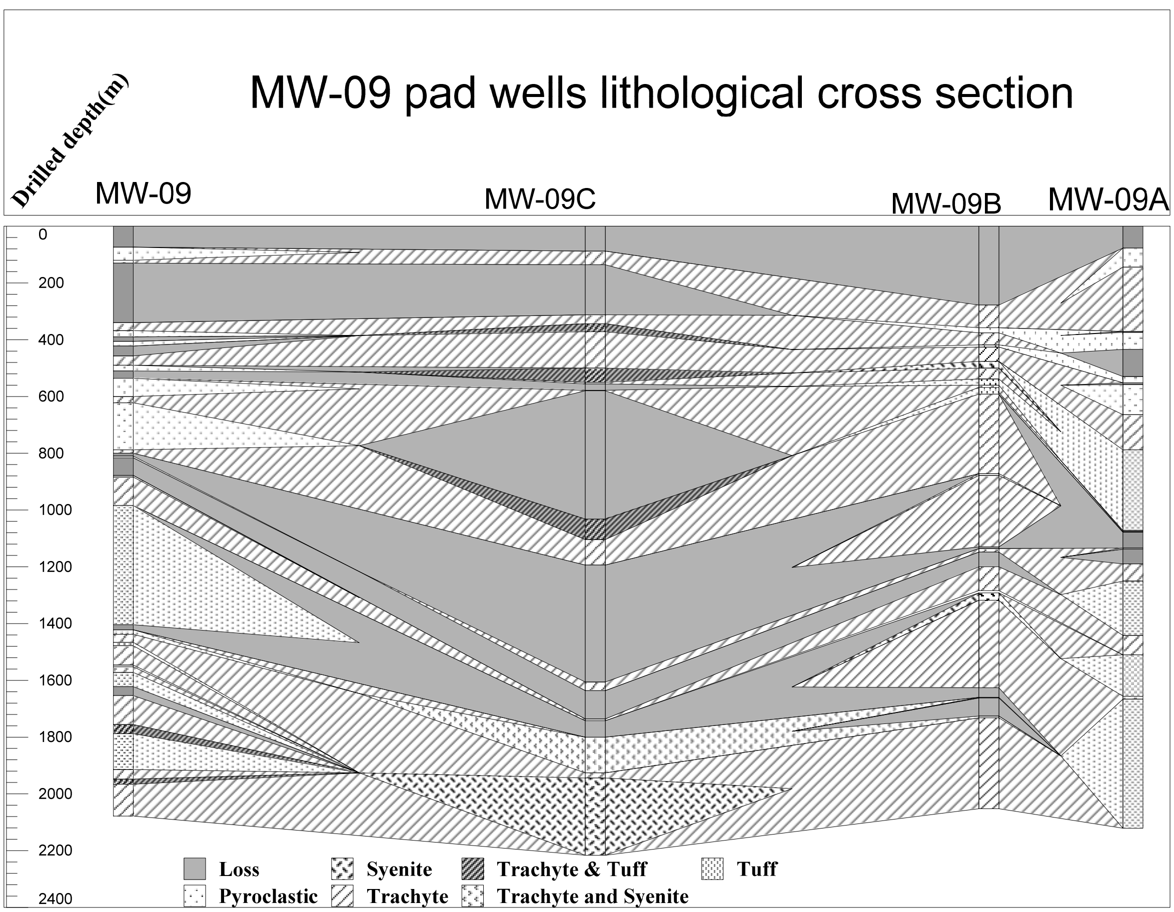


Figure 3: Lithology of wells drilled on MS-09 pad.

Four wells have been drilled on the MS-09 well pad (Figure 2) in different orientations aimed at tapping the NNW-SSE structures associated with the Molo tectono-volcanic axis (Molo TVA) and NNE-SSW structures associated with the Solai TVA. All the three directional wells are S-Type. Well MW-09A is the second directional production well drilled in the Menengai geothermal field. It is located at coordinates E 173295.5 N 9977107 at an elevation of 2105 m.a.s.l. The well was drilled towards an azimuth of N120^{o}E with an aim of intercepting the N-S structures. . The well was designed to tap the resource area between MW 04 and MW 06 (Figure 4)

Well MW-09B is located at coordinates E 173295.5 N 9977107 at an elevation of 2015 m.a.s.l. The well is deviated towards the southwest (Azimuth S215°W) with an aim of intercepting the NNW-SSE structures (Figure 1) The well is designed to tap the resource area between MW 01A, MW 10 and MW 06 (Figure 4) MW-09C is located at coordinates Easting: 172851.623 Northing: 9977307.83 at an elevation of 2015 m.a.s.l. and was drilled towards the northeast with an azimuth of N040^{o}E. The well was designed to tap the resource area between MW 4B and MW 13A (Figure 4). Trachyte is the dominant rock type in these wells occurring from the surface to the bottom of the well with intermittent tuff and pyroclastic intercalations and sometimes the a tuff Layer separates the trachyte formation like in MW-09, MW-09B and MW-09C (Figure 3). Trachyte varies widely in terms of grain size, color, texture and mineralogical composition this is attributed to the different eruption episodes; Pre-caldera (dominated by fine-grained trachyte and medium grained trachyte), syn-caldera (dominated by medium grained trachyte lava), post caldera (volcanics sequence is characterized by scarce syenitic dykes) Mbia et.al 2015. The syenite intrusive was mostly penetrated at the bottom of the wells; it was most prominent in MW-09C (Figure 3). These wells also encountered total loss of circulation; most notable was MW09C which encountered total loss of circulation from shallow depths to the bottom of the well mostly attributed to drilling parameters (Figure.3). In the in the other wells MW-09, MW09B and MW-09A, the total loss of circulation was attributed to feed zones. High differential temperatures are noted just before the production casing and towards the bottom of the well, sometimes resulting in blow outs.

3.3 Wellbore trajectory planning and drilling

Each directional well is designed to cut across as many structures as possible in a bid to increase well productivity. Both geologists and engineers have to agree on the best well trajectory that can achieve this.

The build-hold (J) directional well profile is the most common in geothermal applications. In Menengai both are used but the build-hold-drop (S) profile is popular. This is due to the fact that wellpads lie close to each other and to prevent reservoir interference, new wells have to be controlled from intersecting into reservoirs of already producing wells.

In Menengai an anti-interference policy of 300 m minimum distance between wellbores is applied to ensure no interference between neighboring wells. In a wellpad where the first well was vertical all subsequent wells must have their production casing shoe at >300m away from the vertical well production casing shoe. This at times translates into deeper casing depths or steeper inclination to achieve a vertical section of >300 m. After achieving the 300 m at the production casing shoe the wellbore is then controlled so as to be within 600 m of neighboring wells at TDed(well completion). This has necessitated the drop in angle after setting the production casing.

In Menengai directional wells are drilled from multicellars, to prevent collision between wellbores, wells are spudded at least 6 m apart at the surface. When planning the well azimuth, the arrangement of wells and the order in which they are drilled is considered to ensure that no wellbores cross paths in the future. In cases where an already existing well crosses the path of a proposed well, the new well is kicked off at a lower depth. An electronic single shot tool is used to take surveys, which are used to estimate the wellbore trajectory.

Wellpad MS-09

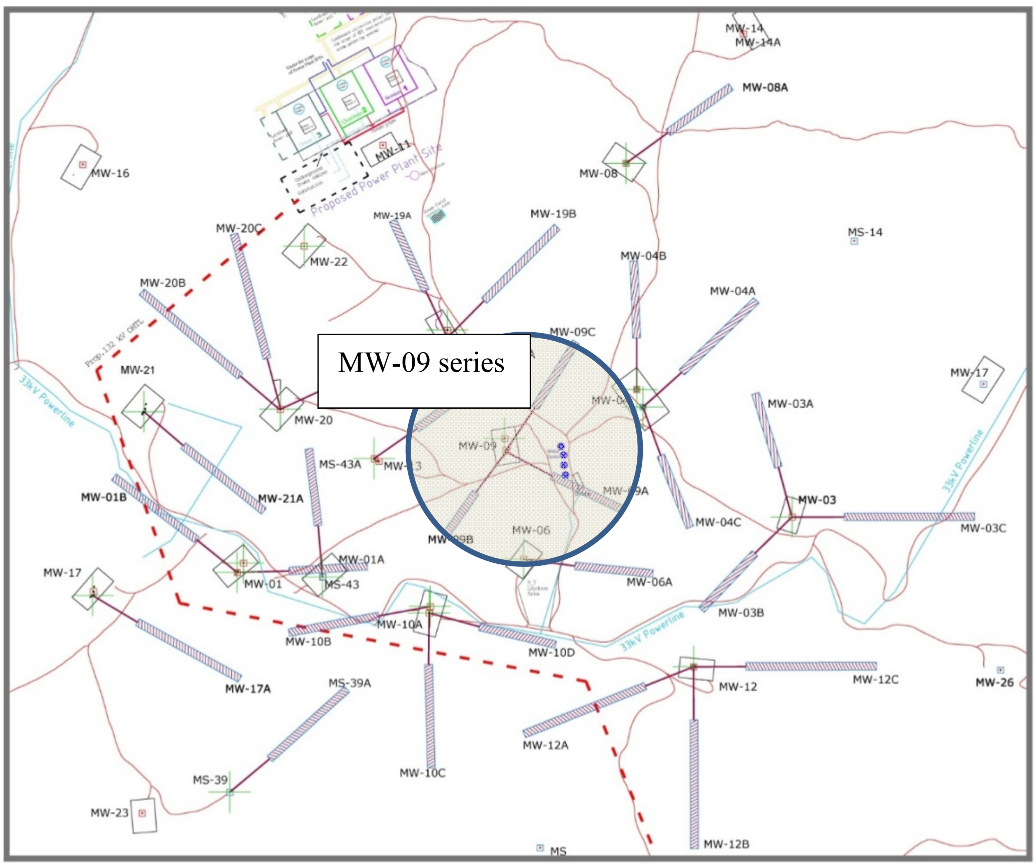


Figure 4: Map showing MW-09 Wells

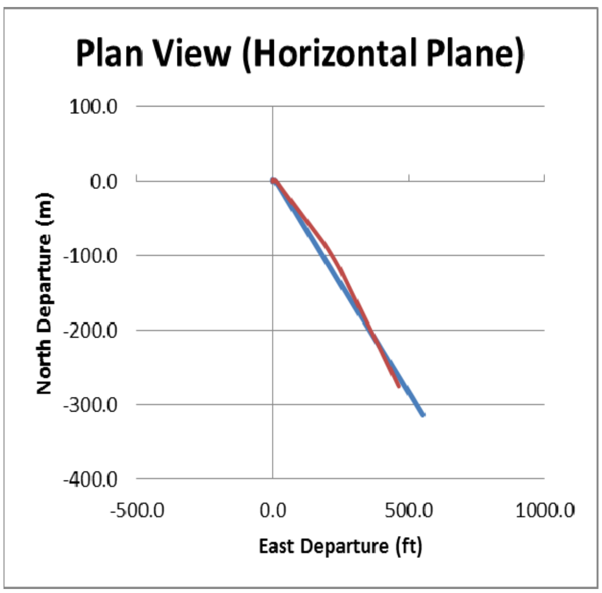
MW 09

MW-09 was the sixth appraisal well drilled in the Menengai prospect aimed at confirming the extent of the resource to pave the way for production drilling. It was the first well to be drilled on wellpad MS-09, and is vertical. On mapping out the resource area more wells were proposed on wellpad MS-09.

MW 9A

The MW-9A is a directional production well adding part of the steam for the 105MWe power plant under the Menengai Geothermal Development Program. It was the second well to be drilled on wellpad MS-09 and is located at coordinates E 173295.5 N 9977107 at an elevation of 2105 m.a.s.l. The well was kicked off at 450m in the 12 ¼'' section at an azimuth of S120^{o}E so as to intercept the N-S structures and a target inclination of 25^{o} at 600 m. The inclination was sustained throughout the well course with slight but allowable deviation as seen in Figure 4. Like its predecessor MW 09, massive lost circulation was encountered throughout the 12 ¼'' section even after using LCM (Loss circulation medium). Aerated foam drilling was employed as it was no longer economical to keep pumping mud into the hole. In the 8½'' hole, aerated water and foam was employed with full returns. Stiff soap was used to manage hole cleaning and high friction torque. Cuttings dispersed in the foam improving the lifting capacity of the fluid.

At a measured depth of 2131 m the drill string got stuck as a result of magma interception. Most of the drill string was fished successfully but the bit and near bit stabilizer were left in hole. The well was terminated at this point, Slotted liners landed in hole and the well was successfully completed.



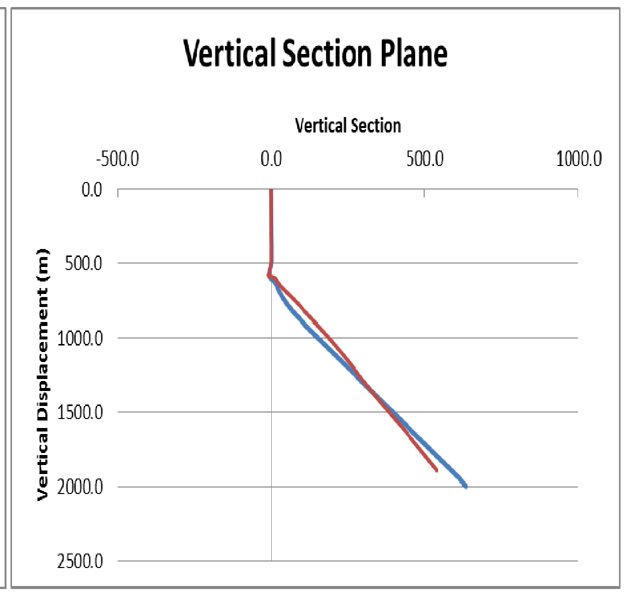
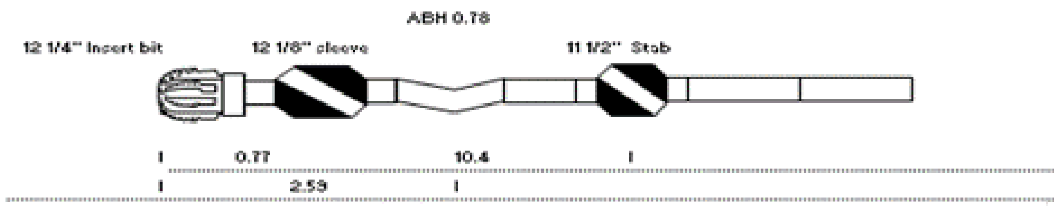


Figure 5: MW 09A planned trajectory (blue) and actual trajectory (red)

MW 9B

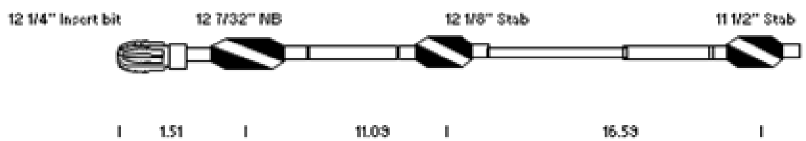
The MW-9B is a directional production well, also part of the steam production for the 105MWe power plant under the Menengai Geothermal Development Program. It was the third well to be drilled on wellpad MS-09. The well is located at coordinates E 173295.5 N 9977107 at an elevation of 2015 m.a.s.l. The well was kicked off at 370 m in the 12 ¼'' section at an azimuth of 215^{o} and a target inclination of 27^{o} at 700 m. It is deviated towards the southwest (azimuth of S215°W) with an aim of intercepting the NNW-SSE structures (Figure 1). The kick off BHA (Bottom Hole Assembly) (Figure 6) included a 12¼″ bit, 8″ mud motor, 11½″ string stabilizer, 8″ float sub, 8″ UBHO (Universal Bottom Hole Orientation Sub), 2x8″NMDC (Non-magnetic Drill Collar), 6x8″DC (Drill Collar), X/O (Cross-over) sub, 6x6½″ DC, and 12x5″HWDP (Heavy Weight Drill Pipe). An initial survey was conducted to help orient the tool face then slide drilling started from 370m to 578m. Surveys were conducted at intervals of 20m. At 578m, having attained an inclination of 21° and an azimuth of 226°, the mud motor was pulled out of hole due to its operational cost.



12¼″ BHA Kickoff BHA, 12¼″ BHA Number 2

Figure 6: 12 1/4" Kickoff BHA

A lock up BHA consisting of a 12¼″ bit, 12 7/32″ near bit stabilizer, 8″DC, 12 1/8’’ string stabilizer, X/O sub, 2x8″NMDC, 11½″ String stabilizer, 6x8″DC, X/O sub, 6x6½″DC, and 12x5″HWDP(Figure 7) was rigged in the hole. Drilling resumed in medium hard formation with aerated water and foam to a depth of 878m.



12¼″ Rotary holding assembly 1, 12¼″ BHA 2

Figure 7: 12 1/4" Holding BHA

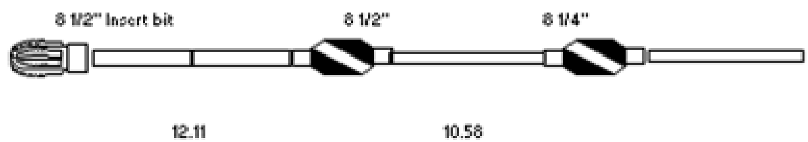
Due to the hard formation, increasing the weight on bit did not result in the desired build and so the BHA was pulled out of hole to install a build assembly consisting of a 12¼″ tricone bit, 8″bit sub, 8″ Pony DC, 12 1/8’’ string stabilizer (Figure 8), UBHO sub, 2x8″NMDC, 11½″ string stabilizer, 6x8″DC, X/O sub, 6x6½″DC, and 12x5″HWDP as shown in figure 7 below.

12¼″ Rotary holding assembly 1, 12¼″ BHA 3

Figure 8: 12 1/4 holding BHA

At 930m the target inclination of 27° was attained, and the 12 ¼'' hole section was TDed at 1181m. After conducting a wiper trip to the anchor casing shoe the hole was spotted with mud and POOH commenced in readiness to rig in hole 9⅝″ casing.

A dropping BHA consisting of an 8½″ tricone bit, 6½″ bit sub, 6½″ NMDC, 6½″ Pony NMDC, 8½″String stabilizer, 6½″DC. 8¼″string stabilizer, 6x6½″DC, and 12x5″HWDP (Figure 9) was installed to drill out cement and drop the inclination below the casing shoe from 27° at 1181m to 15° at 1700m. Very high temperatures were encountered below 1600m deep.



8½″ Dropping BHA, 8½″ BHA 1

Figure 9: 8 1/2 dropping BHA

At 2064 m the ROP reduced significantly, necessitating POOH to inspect the drill string. Upon POOH it was discovered that the string had sheared off at the box end of the non-magnetic drill collar, leaving in the hole the bit, bit sub and the sheared monel. After several unsuccessful fishing attempts the well was TDed at this depth and slotted liners were RIH.

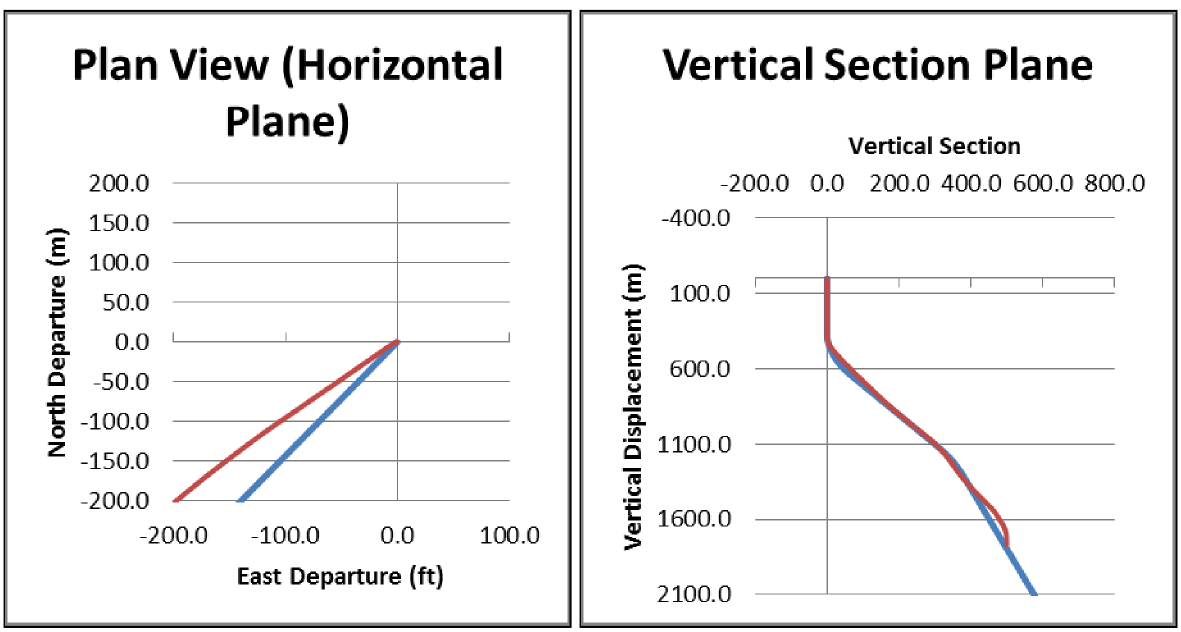


Figure 10: MW 09B planned trajectory (blue) and actual trajectory (red)

MW 9C

MW 9C was the third directional well to be drilled on wellpad MS-09. It is located at coordinates Easting: 172851.623 Northing: 9977307.83 at an elevation of 2015 m.a.s.l. The well was kicked off at 350 m in the 12 ¼'' section at an azimuth of 40° and a target inclination of 25° at the end of build section. The well is was an S-type with a targeted measured depth of 2300 m.

Slide drilling commenced at 374 m after conducting a tool face orientation confirmation survey using a singleshot electronic inclinometer. The kick-off BHA included a 12¼″ bit, 7 3/4″ mud motor, 8″ UBHO sub, 8″NMDC, 5x8″DC, X/O sub, and 15x5″HWDP. Slide drilling continued with aerated water and foam in medium hard formation with surveys conducted after every 20m. The survey at 541 m indicated an inclination of 25.78° and an azimuth of 36.38°. The sliding BHA was POOH and a holding BHA consisting of a 12¼″ bit, 12 ¼″ near bit stabilizer, 8″DC, 8" short DC, 12 ¼" string stabilizer, 8″NMDC, 5x 8″DC, Flex joint, 7 3/4″drilling jar, 2x8″DC, X/O sub, and 12x5″HWDP.

While RIH with the holding BHA, an obstruction was encountered at 340m and 380m, forcing the driller to lay down 5 stands and ream using singles. The hole was reamed down to 541m with aerated water and foam. Losses were encountered at 560m and the drill string got stuck at 566m for 10mins in soft formation.

At 725m a survey was conducted with an inclination of 23.59° and an azimuth of 36.49°. The inclination was dropping hence POOH to replace the 8" short collar with an 8" DC to achieve a slight build. Drilling continued with aerated water and foam in soft formation to section TD at 1018m. A wiper trip to anchor casing shoe was conducted followed by POOH in preparation to RIH with 9⅝" casing.

A slick BHA was used to drill out cement to 1030 m. A holding BHA consisting of an 8½″ tricone bit, 8½″ near bit stabilizer, X/O sub, 6½″ short DC, 8½″ string stabilizer, X/O sub, 6½″ NMDC, X/O sub, 6½″DC, 6½″DC (12), and 5″HWDP (12) was RIH. A tight spot was experienced at 1017m necessitating reaming to the bottom in singles. A survey at 1379 m indicated an inclination 35.40° and an azimuth of 31.39°. Too high an angle could lead to hole cleaning challenges, especially while drilling through soft formation. A dropping BHA consisting of an 8½″ tricone bit, bit sub, X/O sub, 6½″ short DC, 8½″ string stabilizer, X/O sub, 6½″ NMDC, X/O sub, 6½″DC, 12x6½″DC, and 12x5″HWDP was installed. A kick was experienced at 1465 m while conducting a well survey. The hole was circulated with cold line water for 2 hours to kill the kick. The well was then drilled ahead with aerated water and soap to TD at 2305 m. The final survey at 2280 m indicated an inclination of 19.42° and an azimuth of 35.63°, and the vertical section at this point was 851 m.

4. DISCUSSION

The structures that straddle the Menengai caldera mostly trend N-S, NNE-SSW and NNW-SSE. The major regional structures that control the Menengai geothermal system are the Molo tectonovolcanic Axis (TVA) and the Solai TVA. The Molo TVA has a NNW-SSE general trend while the Solai TVA, which is much younger than the caldera, trends in a NNE-SSW direction and cuts the caldera rim in the NE. Most of the wells sited in Menengai are sited targeting these structures that are deep seated and tap into the geothermal reservoir.

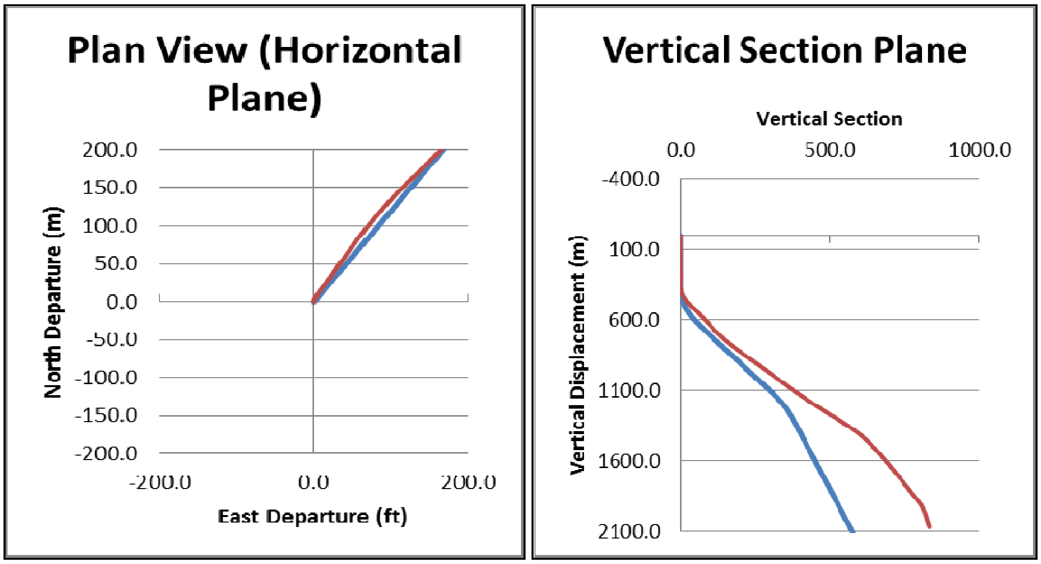


Figure 11: MW 09C planned trajectory (blue) and actual trajectory (red)

The build-hold (J) directional well profile is the most common in geothermal applications, however in Menengai the build-hold-drop (s) profile is popular. This is due to the fact that wellpads lie close to each other. An anti-interference policy of 300m minimum distance between wellbores is applied to ensure no interference between neighboring wells. Four wells have been drilled on the MS-09 well pad (Figure 2) in different orientations aimed at tapping the NNW-SSE structures associated with the Molo tectono-volcanic axis (Molo TVA) and NNE-SSW structures associated with the Solai TVA. All the three directional wells are S-Type. Trachyte is the dominant rock type in these wells occurring from the surface to the bottom of the well with intermittent tuff and pyroclastic intercalations. Trachyte varies widely in terms of grain size, color, texture and mineralogical composition this is attributed to the different eruption episodes. The syenite intrusive was mostly penetrated at the bottom of the wells; it was most prominent in MW-09C.

Several BHA configurations were used to control the well trajectory. The kick-off BHA included a mud motor, magnetic drill collar and a universal bottom hole orientation sub. A packed BHA would be used to hold the angle. Depending on the weight on bit applied, a packed BHA could be used to build or drop the angle. Control of the well trajectory is a big challenge as the rig team has to keep on switching the various BHAs to achieve the planned trajectory (Figure 5,10 and 11). With a holding BHA in the hole the driller can play around with the weight on bit to achieve a build, hold or drop in angle. High weight on bit results in a build in soft formation, but this can result in hole cleaning challenges as too much cutting accumulate in the wellbore as drilling progresses. The BHA runs reduced in each subsequent well as experiences from old wells were applied in new wells. In future better trajectory control can be achieved by using MWD (Measurement While Drilling) and a rotary steerable system.

Aerated foam drilling is very successful in Menengai. The fact that drilling detergent is readily available in the local market makes it cheap. Hole cleaning has been greatly improved and frictional torque has been reduced by applying foam drilling. Drilling detergent is less messy in application compared to mud however when applied in excess quantities returns can be chaotic with foam spilling into the environment. This makes it difficult to collect samples as cuttings are suspended on the foam and take time to settle making it hard for the geologist to obtain a representative sample.

5. CONCLUSION

MS-09 wellpad has four wells MW09 a vertical well, MW09A, MW09B, MW09C all directional S-Type. All the four wells are productive despite MW09A and MW09B having been terminated before reaching target depth due to drilling challenges. The wells have been drilled directionally to reach production zones or targets that would otherwise be inaccessible. This has proved that drilling multiple target zones is a cost effective way of delivering highly productive wells from a single well pad. Mudmotors and various BHA configurations have been employed successfully in Menengai to control wellbore trajectory in a predetermined path however better control with fewer hole runs can be achieved by employing MWD and a rotary steerable system.

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