UNITED NATIONS UNIVERSITY
UNU-GTP
Geothermal Training Programme

Orkustofnun, Grensasvegur 9,
IS-108 Reykjavik, Iceland

Reports 2016
Number 20

CHALLENGES OF DIRECTIONAL WELL DRILLING IN KENYA: CASE STUDY OF OLKARIA, KENYA AND THEISTAREYKIR, ICELAND GEOTHERMAL FIELDS

James Karanja Kahutu
Kenya Electricity Generating Company, Ltd. - KenGen
P.O Box 785-20117
Naivasha
KENYA
jkahutu@kengen.co.ke

ABSTRACT

Directional drilling in Olkaria geothermal field started in the year 2007. This was necessitated by the need to drill high productivity geothermal wells by intercepting multiple fractures as well as taking advantage of the benefits associated with directional drilling. These advantages include the ability to exploit geothermal resources in an area that would be difficult to access, the ability to drill multiple wells from the same well pad, thereby minimizing surface disturbance among others. Since then, over 100 directional wells have been drilled successfully. All the directional wells in Olkaria employ the build and hold (J shape) design with a target angle of inclination set at 20°. The kick-off point for the wells ranges from 300 to 600 mRKB. Kick-off is achieved by the use of a mud motor to build the required angle after which an angle holding BHA composed of two stabilizers is used to hold the angle to the total depth. Drilling of the wells is done using water based mud for the upper section of the wellbore down to 300 mRKB and then aerated drilling is employed for the remaining section. Directional drilling in Olkaria is facing a number of challenges. This report focusses on the different challenges with emphasis on the BHA design related challenges. Proper BHA design for directional wells is important as it ensures that the wellbore trajectory is contained within the acceptable dog-leg severity. Excessive dog-legs in drilling results in drill string problems such as fatigue failure and worn out tool joints due to excessive torque and drag. A comparison of the different BHA designs and their performance for two wells drilled in Olkaria, Kenya and two wells drilled in Theistareykir, Iceland is used to highlight these challenges and explore how some of them can be addressed.

1. INTRODUCTION

Directional drilling involves a technique of deviating a wellbore intentionally along a predetermined path to reach a given target (Vieira, 2009). Directional drilling can be done through various techniques that include the use sophisticated technologies like a mud motor with bent sub, measurement while drilling (MWD) integrated with in-field referencing, real time multi survey measurement, analysis that ensure that the target is reached accurately, use of steerable assemblies, logging while drilling (LWD) and finally the use of older drilling methods like the use of whipstocks, rotary assemblies and jetting techniques (Economides et al., 1998).

Currently, there are over 200 geothermal wells that have been drilled in Olkaria Geothermal Field with at least 100 of these being directional wells. While directional drilling offers numerous advantages, drilling of directional wells in Olkaria has been facing two main challenges which are formation related challenges and BHA (bottom hole assembly) design challenges. With the huge number of wells in the field, it is important to ensure that the directional wells plan is followed properly to ensure that wells do not target the same resource area. For this reason, there is need to ensure that the BHA design and formation related challenges are properly addressed to meet this objective efficiently and economically.

2. LITERATURE REVIEW

2.1 Directional drilling methodology

Directional drilling is a process that involves intentionally deviating a wellbore along a predetermined path to a target or location normally given by lateral distance and true vertical depths (TVD) from an originally known point (Bourgoyne et al, 1986). Historically, wells were drilled in vertical direction only, and this continued until 1934 when wellbore deviation became acceptable in the drilling industry after it was used to drill a directional relief well in Texas. With the adoption of directional drilling techniques, it became possible to drill multiple wells targeting different directions from the same well pad. Over the years there has been a tremendous improvement on how directional drilling is being conducted to improve the efficiency and accuracy with which the targets are hit. The use of measurement while drilling (MWD) tools, steerable mud motors and logging while drilling (LWD) tools has had the biggest impact on drilling of directional wells. When used together, these tools have made it possible to follow complex 3D well profiles without bottom hole assembly (BHA) change, and to measure the inclination and the direction of the well without running the wireline to log or survey (Economides et al., 1998). In addition to the sophisticated technology, older drilling practices such as the mud motors with bent subs, rotary assemblies, jetting technique, whipstocks and wireline steering tools to orient and survey are still being used for drilling directional wells.

2.2 Terminologies used in directional drilling

There are different terminologies used in directional drilling with reference to the well that has been drilled or is being drilled. These terminologies are important as they help identify the wellbore direction, wellbore trajectory and well design characteristics. The major terminologies used are listed below (Aadnoy et al., 2009):

a) Azimuth - The angle (in degrees) of a wellbore on a horizontal plane measured clockwise with reference to North. Azimuth can be referenced using magnetic North, grid North or true North. In directional drilling survey coordinates are normally represented with reference to true or grid North.
b) Kick off Point (KOP) - Any point below the surface where the initial deflection of the wellbore from vertical starts. KOP for many geothermal wells lie in 300 m - 600 m depth what is mainly dependent on the geometry of the wellbore, geological conditions and the location of the adjacent wells.
c) Build up Rate (BUR) - This refers to the rate with which the angle of inclination increases with depth, normally expressed in degrees/100 ft or degrees/30 m.
d) Drop off Rate - Rate with which the inclination angle is returned towards vertical, expressed in degrees per feet.
e) Inclination - The angle between the vertical line and the tangent line at a given point in a wellbore.

f) Hold - Tendency of maintaining a constant azimuth and inclination of a wellbore.
g) True Vertical Depth (TVD) - This is the vertical distance (meter or feet) measured from the rotary Kelly bushing (RKB) to the current or final depth of a wellbore.
h) Measured Depth (MD) - Depth of the wellbore measured along the well path from one known point to another. It is expressed in meters or feet.
i) Dog leg - Sudden change in angle or direction of a wellbore.

2.3 Application of directional drilling in geothermal wells

Adoption of directional drilling technology in the geothermal industry has made it possible to achieve a number of objectives as shown in Figure 1:

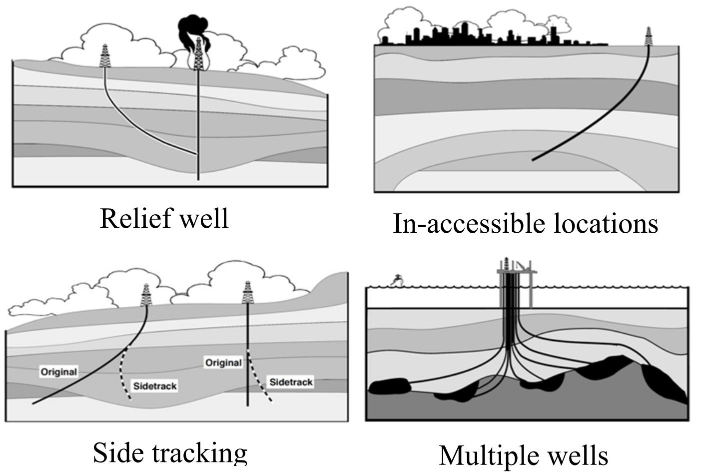

FIGURE 1: Applications of directional drilling (Baker Hughes INTEQ, 1995)

a) Accessing inaccessible locations - In geothermal drilling, it is possible that some of the target zones are located beneath areas with severe topographic features such as mountains where rigging up would be impossible. This means that the target resource can only be accessed by drilling a directional well (Devereux, 1998).
b) Drilling multiple wells from a single well pad - Traditionally, one well pad could only accommodate one well but with the adoption of directional drilling, it is possible to have multi-wells in a single platform. This is not only economical but also helps conserving the environment as it causes less disturbance on the surface both in drilling phase and steam gathering phase as less land is required to achieve both (Speith, 2015).
c) Side tracking - This involves deviating from the original well trajectory to avoid an obstruction such as a twisted off drill string that cannot be fished out. It is different from other types of directional drilling applications as it lacks a predetermined target and therefore cannot be defined as controlled drilling.
d) Targeting several faults - Directional drilling is employed in an effort to intersect as many faults as possible to improve productivity of a well.
e) Drilling a relief well - Directional drilling technology is used in drilling a directional well to relief another well when all the other well control mechanisms have failed and the rig has been damaged. To control the well, another directional well is drilled targeting the well which is out of control, after which high viscosity mud is pumped after intercepting the target (Adams, 1985).
f) Fault drilling - This involves drilling of a directional well in order to avoid having a vertical well going through an area with steeply inclined fault plane which could slip and shear off casings in case of fault movement.

3. DIRECTIONAL WELL TRAJECTORY PLANNING

In planning of any directional well, there are a number of factors that have to be considered. The first key factor that must be considered is the design of the wellbore trajectory with respect to the set target. The design should propose the different types of wellbore paths that can be drilled in the most economical way possible. The other factor that should be considered is the effectiveness of the desired bottom hole assembly in a given formation type and the influence of other factors on the desired well trajectory (Bourgoyne et al., 1986). In addition, it is important to consider the angle build up rate to avoid subjecting the drill pipes to fatigue when drilling, avoid key seats and minimize the effects of torque and drags generated when the angle of inclination increases. The wellbore profile selected has a very big influence on the torque and drags subjected to the drill string during drilling as well as the drag that occur when running casings and logs. Highly deviated wells with significant azimuth changes may cause serious problems due to the frictional forces generated. Other factors that should also be considered include the surface coordinates and how they have been defined, adjacent wells in the area, geological sequence of the area, performance of BHAs in adjacent wells and rig information among others (Devereux, 1998).

3.1 Types of wellbore trajectory

There are different types of wellbore path designs can be used in directional drilling. The most popular types include:

a) Build and hold trajectory/J-profile - It is the most common type of well path design in geothermal well drilling. In this design, the wellbore is kept vertical until a KOP is reached after which the well is deflected off and a desired angle built. When the required angle is acquired, the wellbore is kept straight and made to intersect the target at an angle that is equal to the build-up angle as shown in Figure 2a (Baker Hughes INTEQ, 1995).
b) Build, hold and drop trajectory/S-profile - For this design the wellbore is drilled just like in the build and hold design but instead of holding the angle to total depth after the tangent section is drilled the angle is then dropped to allow the wellbore intersect the target vertically as shown in Figure 2b.
c) Build, hold, partial drop and hold trajectory/modified S-profile - As the name suggest the design of this trajectory employs the same principle of the S-profile trajectory with the difference being that the wellbore is designed to intersect the target at an inclination angle which should be less than the maximum angle attained in the hold section.
d) Horizontal wells trajectory - In this design the well is kept vertical for the first section then the wellbore path inclination angle is allowed to reach 90° or more. Most of these wells are designed

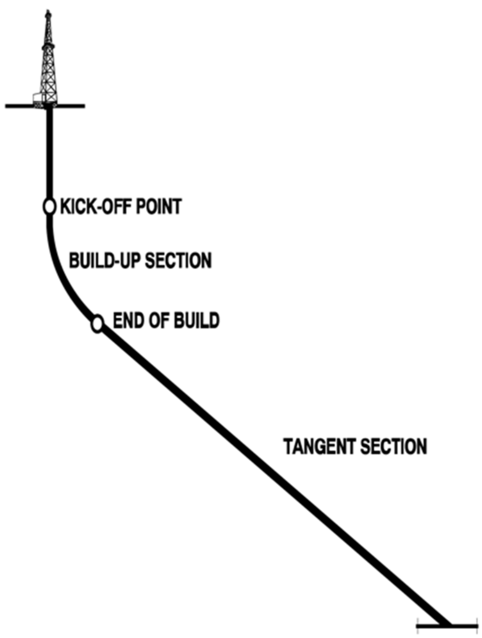

FIGURE 2a: Build and hold (J-type)
(Baker Hughes INTEQ, 1995)

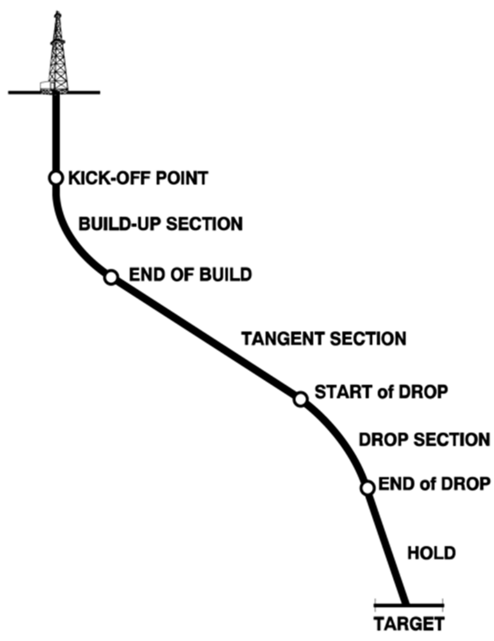

FIGURE 2b: Build, hold and drop
(S-type) (Baker Hughes INTEQ, 1995)

as production wells due to their increased flow rates due to increased reservoir exposure. This design is most popular in oil and gas industry (Economides et al., 1998).

4. TOOLS FOR DIRECTIONAL DRILLING

Drilling of directional wells unlike the vertical wells requires that the well path control be done in the best way possible as it is one of the most complex and important phases of drilling. For this reason, a lot of research has to be done to better understand how different variables affect the BHA behaviour. Such variables include the weight on bit, rate of penetration, geological conditions, rotary speed and hole inclination among others. In order to drill a directional well, the BHA can be manipulated to include different components to achieve the desired results. Currently, there are a number of equipment that have been developed to drill directional wells such as mud motors with bent subs, jetting bits, rotary steerable assemblies and whipstocks among others. The selection of the tool to use for well deflection is a very important exercise as it determines how well the predetermined path can be achieved as discussed below.

4.1 Basic rotary assemblies

The bottom hole assembly is the major portion of the drill string that affects the path of the bit and consequently the trajectory of the wellbore. The assemblies can be designed to either build or drop the angle of inclination or to steer the well either to the right, left or maintain the existing wellbore direction (Devereux, 1999). In directional drilling, the composition of BHAs ranges from a simple one consisting of the bit, collars and the drill pipes (Figure 3a) to a complex one integrating a drill bit, stabilizers, collars, reamers, shock subs, jars, subs, heavy weight drill pipes and the regular drill pipes as shown in Figure 3b.

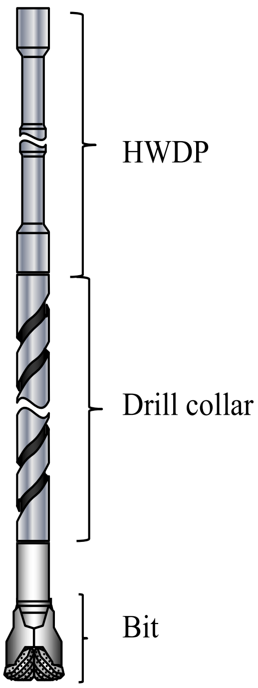

FIGURE 3a: Slick BHA (Simple)

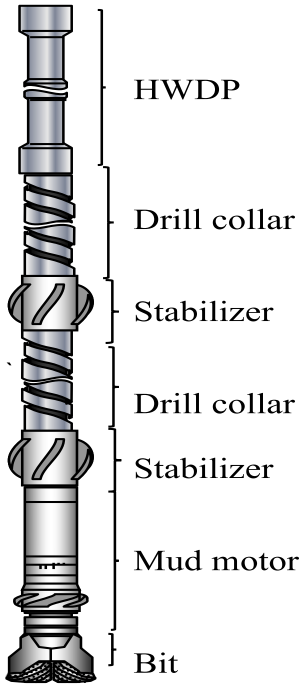

FIGURE 3b: Complex BHA

The tendency of any assembly to cause deviation when drilling is dependent on the flexibility of the drill collars and the forces acting on the BHA causing the drill collars to bend. The design of any BHA for directional drilling is based on principles that involve the active length of the drill collars. The point at which the collars get into contact with the low side of the wellbore is known as the tangent point while the distance from the tangent point to the bit is known as the active length. Active length of any BHA is dependent on the collar size, hole size, weight on bit, hole curvature and hole inclination (Computerlog Drilling Services, 2000). When the active length of the drill collars is short, it results in a fulcrum effect used in angle building and when the length is increased it results in a pendulum effect that is used in angle dropping. When these two principles are combined, they give rise to angle holding. All this can be achieved by placing the stabilizers at different positions. In addition, the directional tendency or behaviour of any bottom hole assembly is governed by a number of factors that include:

- Bit tilt
- Diameter and length of drill collars
- Rotary speed/Revolution per minute (RPM)
- Bit type
- Weight on bit (WOB)
- Flow rate
- Rate of penetration
- Bit side force
- Rock type/properties
- Hydraulics
- Formation dip

This report focuses more on the effect of bit side forces as a result of stabilizer placement in rotary assemblies as well as the effect of drilling parameters such as WOB and rotary speed and their impact on directional drilling.

4.1.1 Angle building BHA

The configuration of this BHA utilizes what is known as the fulcrum principle. Typical build assemblies consist of one to three stabilizers. The first one is the near bit stabilizer normally placed 3 to 5 feet from the bit face or connected directly to the bit followed by two to three drill collars and a second string stabilizer as shown in Figure 4. The near bit stabilizer acts like a pivot in the assembly, while the bending of the drill collars between the first and the second stabilizer causes the drill bit to press against the top side of the well bore. At lower inclinations, building assemblies with only one stabilizer are recommended as they generate more side forces (Bourgoyne et al., 1986). The bit side force generated determines the rate of build which can range from 2° to 5°/30 m. This is dependent on the distance between the first and the second stabilizer, increase in distance results in high build rates and vice versa. However, there is a limit with which the build-up rate is influenced by the increase in spacing between the two stabilizers. If the second stabilizer is more than 120 ft from the near- bit stabilizer (depending on the hole size and collar OD), the collars contacts the low side of the hole and any further increase in distance has no effect on the build rate. In addition, the rate of build is also influenced by the weight on bit application and the size of the drill collars in the assembly (Economides et al., 1998). Increase in WOB lowers the tangency point thus increasing the angle build up rate. The rate of build in this case is however not caused so much by the side force but by the bit tilt. Other factors that affect the build assembly include the inclination of the well bore and the rotary speed. If the rotary speed is too high the drill collars tend to be straightened up thus reducing the angle build rate. It is recommended that a rotary speed of 70-100 RPM is used for fulcrum assemblies. Unlike in the past, the build assemblies are currently composed of few drill collars and stabilizers. Heavy walled drill pipes can replace some of the drill collars thus reducing the need to have stabilizers that hold the collars off the walls of the wellbore (Bourgoyne et al., 1986).

4.1.2 Angle holding BHA

This assembly is also known as a packed assembly as it contains three to five stabilizers in close proximity. Normally, it consists of a full gauge near bit stabilizer, drill collar, string stabilizer, drill collar and another stabilizer as shown in Figure 4. Packed assemblies in directional drilling are normally introduced after achieving the required inclination. The series of stabilizers helps guiding the bit to drill straight ahead. Careful selection of the right BHA to be used above the bit should be done to ensure that the drill bit is forced to drill in the direction of an already drilled hole. If done properly, hole angle changes encountered are normally so gradual and wellbore problems like key seat, doglegs, ledges and offsets can be avoided. In addition, packed assemblies have a slight tendency to turn to the right. To compensate this the build section should be completed when it is slight to the left of the required azimuth to the target. In situations where the geology of the area causes a normal holding BHA to drop faster, an under-gauge second stabilizer is introduced in the assembly as it has a positive side force which results to a building tendency. The advantage of this assembly is that it allows optimum utilization of the drilling parameters like the weight on bit and the rotary speed (120-160+RPM) which have a direct impact on the drilling progress (Devereux, 1999).

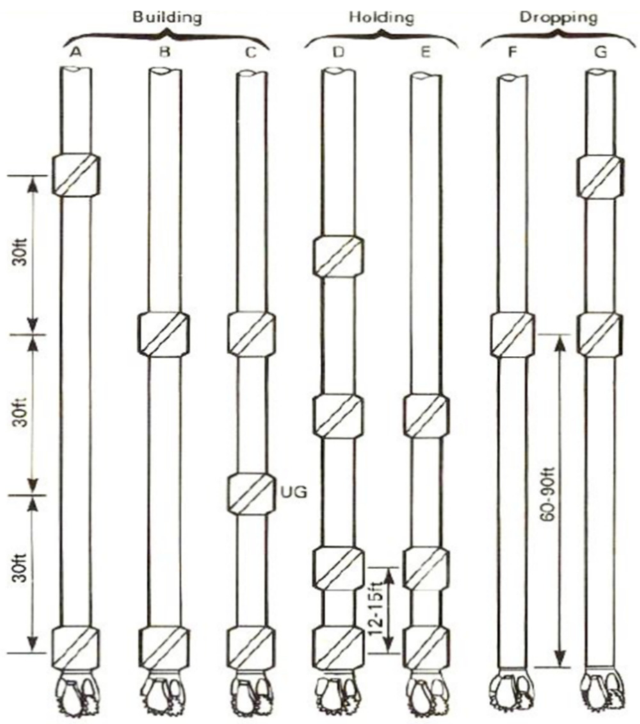

FIGURE 4: Building, holding and dropping assemblies (Economides et al., 1998)

Unlike other types of BHAs, holding BHAs are characterized by small changes in side forces as a function of WOB application (Bourgoyne et al., 1986). It should be noted that it is easy to control the direction using rotary assemblies if the angle of inclination is greater than 17° from the vertical (Devereux, 1998). The side forces generated by the BHA are dependent on the angle inclination of the well bore. A four stabilizer holding BHA shown in Figure 4 example D, normally shows the least change in side force as the angle of inclination increases what is the case especially in soft formation (Inglis, 1987). It has been proven that using more than five stabilizers to control deviation has no notable change in the neutrality of the BHA. Five stabilizers add too much torque at higher inclinations when used in rotary systems and that is why the three to four stabilizers BHA's are recommended for use (Bourgoyne et al., 1986). In geothermal drilling, the use of more than two stabilizers is avoided since drilling is normally done in total loss zones and it is too risky to have many stabilizers in the assembly especially because only water and polymer or aerated drilling is used in the production sections where the hold BHA is necessary. The factors listed below should be considered when selecting the BHA to use:

a) Length of the tool assembly

This is a very important factor as it determines the ability of an assembly to provide sufficient contact length to guarantee alignment with an already drilled hole. A single stabilizer above the bit cannot be used to maintain a straight path as it acts as a pivot point. It causes the bit to push to one side of the weight being applied, hence building an angle. If another stabilizer is added in the assembly, say 10 m above the bit, it will nullify some of the fulcrum effect experienced in scenario one as it provides another stabilizing point. This will reduce the tendency of the BHA to build angle but two stabilizing points are not enough as they can still follow a curved path. For this reason, a BHA with three stabilizing points is recommended as it forms a stiff assembly which makes it easy to maintain the path of an originally drilled hole. However, other factors like the stability of the well being drilled need to be considered since a packed assembly with many stabilizers poses a lot of challenges should a drill string get stuck.

b) Stiffness

The stiffness of the drill collars used in any BHA is a very important factor that should be taken into consideration. It is important to note the relationship between the drill collars diameter and stiffness; it has been found that doubling the diameter of a bar normally increases its stiffness by 16 times. This means that the diameter of a drill collar influences how much it can be deflected. For this reason, maximum diameter of drill collars should be considered for different BHA configurations since large diameter drill collars provide the required stiffness. For example, a 12¼" hole can be drilled using the following sizes of drill collars; 9½", 7" and 8". Since the relative stiffness of a drill collar is proportional to the collar radius to the fourth power the 9½" diameter drill collar for example, will be four times stiffer than 7" drill collars (Smith Services, 2001).

c) Hole clearance

Hole clearance plays a major role in determining the effectiveness of BHA in maintaining the required path. For smallest deviation, there should be a minimum clearance between the stabilizers and the walls of the wellbore. Hole enlargement also plays a very big role in determining how well the bottom-hole assembly is aligned in the hole to achieve its intended purpose. Good drilling practices and proper mud design should always be adopted in cases where hole enlargement due to unconsolidated formation is anticipated (Devereux, 1998). In addition, it is important to consider the wear on the contact tools.

d) Wall support and length of the contact tool

In order to ensure that the drill bit is stabilized and the drill collars are centralized, the surface area in contact with the bottom hole assembly should be adequate to ensure that the stabilizing tool does not dig into the walls of the hole. If the surface area is not sufficient, the stabilization is lost and the wellbore tend to drift. Formations that are strong, uniform and hard normally provide the best stabilization in comparison to soft and unconsolidated formations which may require the use of a long blade stabilizer to achieve stabilization (Smith Services, 2001).

4.1.3 Angle dropping BHA

The assembly uses the pendulum principle which is derived by removing the near bit stabilizer in the assembly and retaining the stabilizers in the upper section. Normally, a dropping assembly consists of two stabilizers, with the distance between the first stabilizer and the bit being around 30 - 90 ft as shown in Figure 4. With increasing distance between the bit and the first stabilizer, the bit is pulled towards the low side of the wellbore by gravity. This increases the bit tilt and bit side force and hence the angle drop. Hole inclination plays a very important role in determining the rate of drop for different dropping assemblies. Higher hole inclinations result in higher rate of drop and vice versa since the force that causes the dropping tendency is a sine function of the inclination angle (Computerlog Drilling Service, 2000). The dropping assemblies are normally used in S trajectory type wellbores which require planned drop in an angle. In addition, the assembly is used when the angle of inclination goes beyond the intended size and must be dropped to bring the well trajectory back on course.

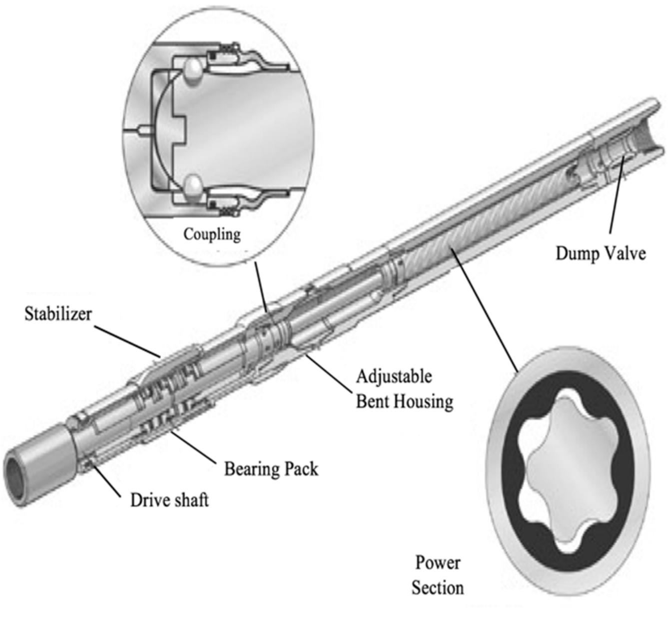

FIGURE 5: PDM assembly (Economides et al., 1998)

4.2 Positive displacement motors (PDM)

PDM refers to downhole mud motors that makes use of the Moineau pump principle to provide motion to the bit without rotating the entire drill string (Economides et al., 1998). Mud motors can be powered using different kinds of drilling fluids such as drilling mud, air and water. In order to deviate a well, PDMs contain a bent housing and if not a bent sub is run above the PDM. Figure 5 shows a PDM assembly which is made of the following four sections:

i) *Dump valve/by pass valve* - Makes it possible to fill up or drain the drill string during tripping in or out of hole.
ii) *Motor assembly* - Contains a rubber lined stator which contains a spirally shaped cavity of elliptical cross section. A solid steel shaft which is spiral in shape runs through the stator cavity with the lower end of the shaft fixed to a connecting rod.

iii) *Connecting rod* - It has a universal joint on both sides to accommodate the eccentric rotation of the rotor and transfer the rotation to the draft shaft.
iv) *Drive shaft and bearing assembly* - Contains bearings (thrust and radial) which allows free rotation of the drive shaft. The drive shaft is then connected to the bit sub, which is the only rotating external part of the mud motor.

4.3 Jetting technique

This is an old technique developed in 1950s that is used to deviate wellbores in soft formation. This method although not very popular today is still used frequently in some situations as it offers numerous advantages. To achieve the deflection a special jet bit can be used but also standard tri-cone bits with one very large nozzle and two small ones can be used (Baker Hughes INTEQ, 1995). This is however only possible if the formation is soft and can be easily eroded by mud exiting the largest nozzle and if the rig hydraulic horsepower is adequate to provide jetting enough to erode the formation. Figure 6 shows the jetting technique.

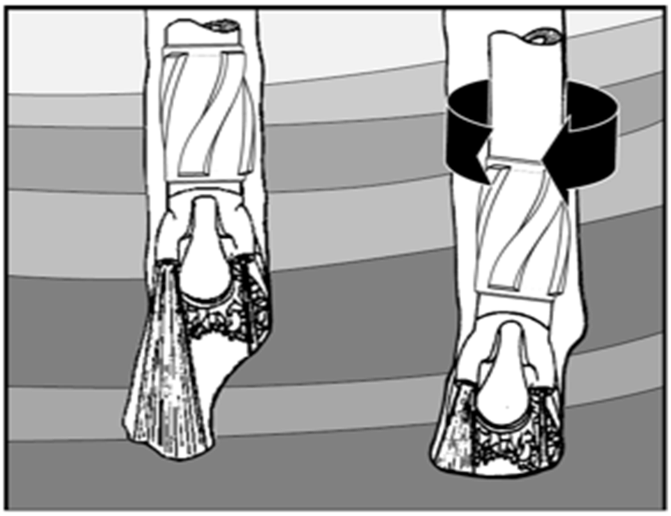

FIGURE 6: Jetting technique (Baker Hughes INTEQ, 1995)

4.4 Whipstock

A whipstock is a wedge with a concave face which is placed in a well with the face pointed to the direction that the well is meant to go to. These were the main deflection tools between 1930 and 1950. Although rarely used nowadays they are used in some special operations like coiled tubing drilling for work over jobs. There are three types of whipstocks that are used in directional drilling namely; standard removable whipstock which is mainly used for kick off and side-tracking, circulating whipstock and permanent casing whipstock which is designed to stay permanently in the well (Rabia, 2002).

5. DIRECTIONAL DRILLING CHALLENGES IN OLKARIA, KENYA

Directional drilling in Olkaria geothermal field started in the year 2007. This was necessary in order to drill high productivity geothermal wells and take advantage of the other benefits associated with directional drilling as discussed earlier in this report. Over 100 directional wells have been drilled in Olkaria and all of them employ the build and hold (J shape) design with the target angle of inclination being 20° (Munyoki, 2012). As shown in Figure 7, the kick off point for the wells is mostly done at 400 mRKB where the formation is competent or as advised by the geologists. The drilling media for the upper section of the wellbore is water based mud while aerated drilling is introduced from 300 m. Directional drilling in Olkaria poses a number of challenges. This report focuses on the different challenges faced in Olkaria, emphasising the BHA design related challenges. Data for 2 wells drilled in Olkaria, Kenya and 2 wells drilled in Theistareykir, Iceland will be used for analysis and comparison. The challenges discussed in this report represent typical problems faced while drilling directional wells in Olkaria geothermal field.

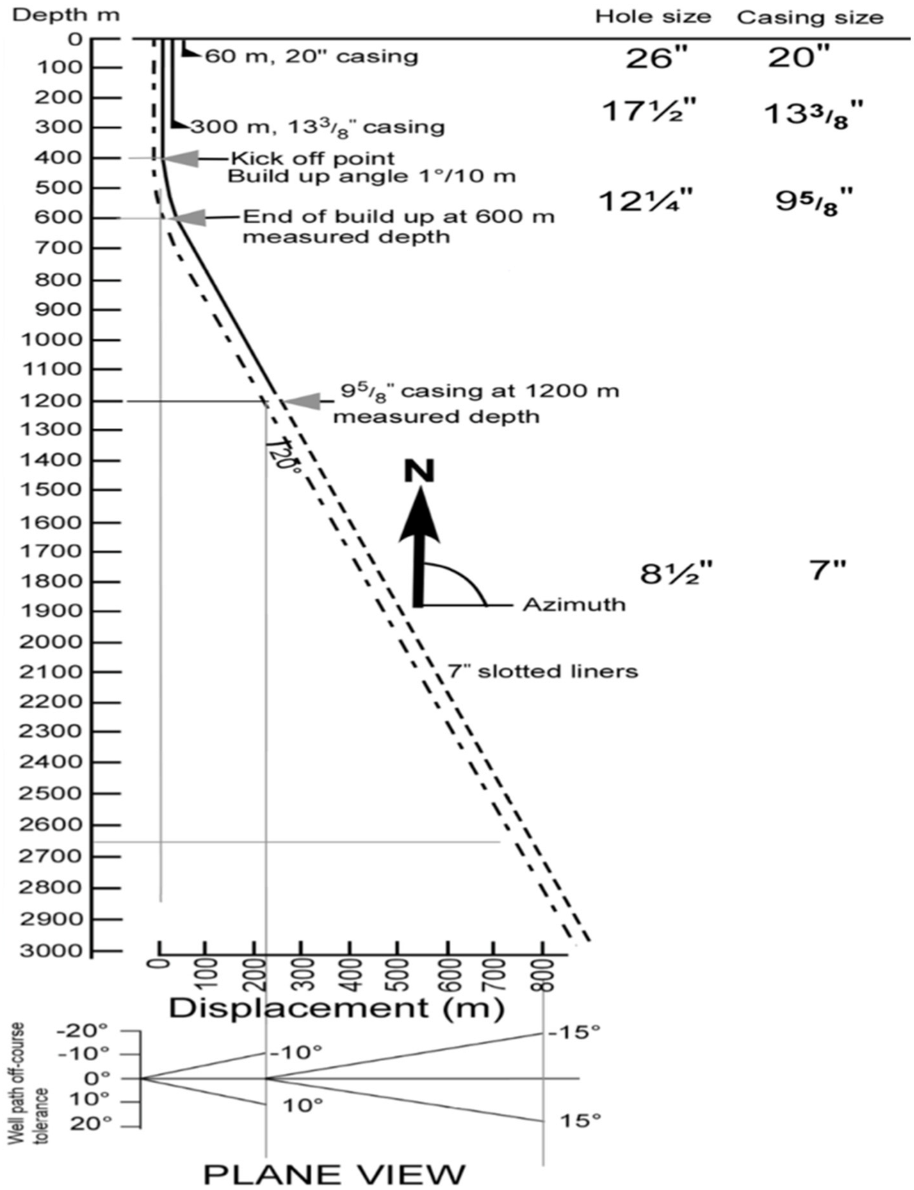

FIGURE 7: Typical Olkaria directional well profile (Munyoki, 2012)

5.1 Formation challenges

Olkaria geothermal field is primarily dominated by loose and unconsolidated rocks that are prone to collapsing or sloughing when drilling using a directional bottom hole assembly. This makes it hard to control the desired trajectory as the BHA tends to lie on the softer side of the wellbore, generating undesirable side forces which makes the drill bit follow a different path. The other danger that is caused by the unconsolidated formation is collapse that lead to hole pack-off which may result in a stuck drill string. The other challenge faced in drilling directional wells is possible poor hole cleaning. The efficiency of directional drilling operation is dependent on how well the hole cleaning is done. Due to numerous losses encountered in Olkaria field, sometimes hole cleaning is not efficient even when using aerated drilling. Poor hole cleaning especially during kick-off often results to low rate of penetrations which overworks the mud motor thus reducing its life time. Interbedded lithology consisting of alternating hard and soft rocks layers present another serious challenge in maintaining the course of a directional well. With this kind of formation, it is hard to optimize bit selection as the bit is made to drill through formations desired and undesired for its use. This kind of formation normally cause some deflecting forces that may lead to bit walk especially if the bit is damaged from drilling in formations it is not designed for (Devereux, 1998). This may lead to sudden increase or drop in angle of inclination which is not desirable in directional drilling. The other formation challenge is encountered when drilling through aquifer rich formations. Cases like this have been encountered in Olkaria. This normally causes the bottom hole assembly to hang down to vertical thus affecting the angle of inclination adversely. Other formation challenges include drilling in very soft formations which causes the angle of inclination to drop and drilling in clay rich formations which makes it very hard to build an angle by sliding the mud motor in clay.

5.2 Bottom hole assembly design challenges

In Olkaria the main wellbore trajectory design employed is the J-shape type. Drilling of a J-shaped type well is a process of two phases which are building the desired inclination after the kick off, and holding the angle to the target depth. The build section ranges from 400 m to 600 m RKB. Building the angle requires an angle building BHA and holding the angle requires an angle holding BHA. The design of these BHAs has presented some serious challenges in directional drilling as discussed below.

5.2.1 Angle building BHA

The BHA configuration normally consists of a 12¼" drilling bit, a 8" or 7¾" bent-housing mud motor, non-magnetic drill collar (NMDC), 4 drill collars, heavy walled drill pipes and drill pipes. The mud motor has an integral 12¼" stabilizer. The BHA is normally introduced at 400 m RKB or according to the drilling program and is required to build the angle of inclination of 20° at a rate of 3°/30 m. The build section is usually 200 m measured along the actual trajectory of the well. When using the BHA, the following challenges are encountered:

- Failure to achieve the desired results using the same BHA at times for the same geological conditions and hence the need to optimize the drilling parameters or BHA configuration
- Very hard formations lead to lower build up rate especially when sliding. This normally leads to exceeding the working life of the mud motor before the required inclination is achieved. The mud motor operating time is rated at 175 running hours.
- While sliding in alternating hard rocks in the upper sections of the hole, torque is induced in the string and cases of shear breakage on the tool joint of NMDC have been witnessed.
- Drill bit bearing failure has also been noticed while using this BHA especially when drilling through hard formation with consistent string vibrations.

5.2.2 Angle holding BHA

This BHA is normally introduced after achieving the desired angle of inclination and azimuth. It consists of a 12¼" or 8½" bit,a near bit stabilizer and a string stabilizer located after two drill collars. This BHA design has always presented the biggest directional drilling challenge in Olkaria. Due to unconsolidated formations that collapse easily, there is always a very big risk of getting stuck if a third stabilizer is introduced should the formation collapses on this packed BHA. Using two stabilizers in the configuration has given the following results:

- The angle of inclination usually drops.
- The azimuth shifts on either side of the desired path. This is due to bit walk.
- Minor doglegs start to develop and the torque rises. This causes a lot of resistance causing drill string rotation due to friction.
- When correcting the BHA to achieve azimuth, the inclination sudden changes can occur that make it difficult to maintain the intended trajectory.

For this reason, there is a need to optimize the BHA design for the angle holding as well as optimising the relevant drilling parameters such as revolution per minute (RPM), weight on bit (WOB) and pump strokes per minute (SPM) among other factors that may limit the effectiveness of this BHA.

5.2.3 Angle correction BHA

This BHA is used to correct the target direction or angle of inclination by either lowering or increasing based on the survey data. The following challenges are faced when using this BHA:

- BHAs expected to increase the angle can sometimes lead to a decrease in angle and also a noted shift in the azimuth.
- BHAs meant to hold the inclination usually do so for a short interval. The BHA will hold for about 100 m and then start to drop. The BHA may also lead to sudden increase in the inclination.

6. DATA ANALYSIS

In this section, data for the different BHA configurations and drilling parameters used is presented in tables. The tables provide the different BHA configurations used for the four wells which are considered here. The data provided in the tables will be used to analyse the effectiveness and the performance of different BHAs, when subjected to different drilling parameters. The analysis will focus on the BHAs used from the kick-off point to the target depth. The drilling parameters used for the analysis are the WOB and RPM. For the purposes of comparison, the average WOB in each well has been used instead of the instantaneous WOB.

6.1 Case studies – BHA design for directional drilling in Olkaria, Kenya and Theistareykir, Iceland

In this section, the effectiveness of different BHA configurations from kick off point to target depth when subjected to different drilling parameters (WOB and RPM) will be analysed. Data for four wells, two from Kenya and two from Iceland will be used for the analysis.

6.1.1 OW-710B in Olkaria field, Kenya

This well was drilled to cater for additional steam for Olkaria 1, unit IV and V. The KOP for the well was done at 500 m depth as planned and went well until 804 m when the drill string got stuck. Efforts to free it were unsuccessful and a back-off opted. The fish was plugged in hole using cement and a new kick off was initiated at 710 m using a kick off BHA. This BHA was meant to build an inclination angle of not more than 20° at a rate of 3°/30 m with deviation surveys conducted at different intervals as shown in Appendix I. As shown in Table 1, drilling of OW-710B was accompanied by several challenges related to angle holding BHA design.

The second kick off for the well was done successfully using two types of BHAs as shown in Table 1 from 710 m to 1,202 m attaining the required angle of 22.85° and an azimuth of 337.19°N. An average WOB ranging from 5.4 -7 tons and an average rotary speed of 43-50 rpm was used to build the angle of inclination from 5.1° to 22.85° within a measured distance of 376 m. As shown in Table 1, introduction of angle holding BHAs with the provided configuration from a depth of 1,202 m to 1,550 m and 1,856 m to 2,076 m leads to an angle decrease from 22.85° to 17.77° and 22.05° to 17.21° respectively. The angle drop may have been caused by a number of factors such as introduction of a new BHA in a section that had been drilled by a totally different BHA. Before the first holding BHA was introduced a slick BHA without stabilizers had been used to drill out cement and drill 7 m into the formation past the 9⅝" casing shoe. Normally, introducing a BHA in a section of the hole that has been created by a BHA of a

TABLE 1: OW-710B BHA data performance

BHA Type	Depth (m)		Metres drilled	Inclination (°)		Average angle drop/build (30m)	Av. WOB (tons)	RPM	Desired result	Achieved result
	In	Out		In	Out					
Kick-off BHA (12¼"hole) Bit- MM- O-SUB- NMDC-3/8"DC-xo-9/5"HWDP	710	826	116	1.55	5.1	0.92	5.4	-	Build angle	Build angle
Angle building BHA Bit- bit sub- STB- NMDC-1/8"DC- STB- 8/8"DC- Flex joint- jar- xo-9/HWDP	826	1202	376	5.1	22.9	1.42	7	43-50	Build angle	Build angle
Angle holding BHA (8½" hole) Bit- bit sub- STB- xo- short DC- xo- STB- NMDC- xo-15/6.5"DC- xo-9/5"HWDP	1202	1550	348	22.9	17.8	-0.44	5.8	47-48	Angle hold	Angle drop
Angle correction Bit- NB- xo- 2/short DC-xo- STB- NMDC- xo-15/6.5" DC- xo- 9/HWDC	1550	1600	50	17.8	14.3	-2.06	5.7	47	Angle correct	Angle drop
Angle correction Bit- bit sub- STB- NMDC-xo- 2/short DC- xo- STB-xo- 15/6.5" DC- xo-9/HWDP	1600	1858	258	14.3	22.1	0.90	6	47-66	Angle correct	Angle correct
Angle holding Bit- bit sub- STB- xo-2/short DC- xo- STB-NMDC- xo- 15/6.5"- xo-9/HWDP	1858	2076	218	22.1	17.2	-0.67	5.7	47-60	Angle hold	Angle drop
Angle correction Bit- bit sub- STB- NMDC-xo- 15/6.5"-xo-9/HWDP	2076	2509	433	17.2	22	0.33	5.2	47-60	Angle correct	Angle correct
Slick BHA due to high torque Bit- bit sub- NMDC- xo-15/6.5"- xo-9/HWDP	2509	3120	611	22	15	-0.34	6.5	45-50		

different configuration, the hole curvature may cause the new BHA to behave in an opposite manner to which it was designed for (Bourgoyne et al., 1986). Secondly, the other factor that may have resulted in the angle drop is the stabilizer placement in the BHA. Holding BHAs by design are meant to minimize the rate at which an angle of inclination builds or drops but they do not maintain the inclination angle entirely. It is difficult to maintain the angle of inclination using these assemblies due to the effects of formation and gravity. To overcome this, the packed assembly should be designed to provide sufficient length of contact to ensure alignment with an already drilled hole as discussed earlier in this report. Normally, three or more stabilizing points are necessary to ensure effectiveness of a packed assembly (Smith Services, 2001). The two angle holding BHAs introduced had only two stabilizing points with the second stabilizer placed 24 and 43 ft from the first stabilizer respectively. This means that there was no sufficient length of contact to hold the angle. Based on their configurations, the BHAs should have built the angle instead of dropping. The WOB application for these two assemblies may not have been sufficient to provide the right tangent length that would have resulted in angle build. In addition, if the stabilizers in the assembly were under gauge the assembly would decrease the angle (Bourgoyne et al., 1986). Other factors listed earlier in this report may have contributed to the angle drop.

To correct for the angle drop, another BHA was introduced at a depth of 1,550 m as shown in Table 1. This BHA was supposed to control the angle drop but instead led to a severe angle drop of 2.06° in only 50 m. This rapid angle drop may have been caused by the factors discussed above.

The angle drops in the two instances were corrected by the use of building BHA composed of just one near bit stabilizer. These BHAs were introduced at a depth of 1,600 m to 1,858 m and 2,076 m to 2,500 m and an average build-up angle of 0.9° and 0.33° per every 30 m respectively was achieved as shown in Table 1. Single stabilizer building assemblies are very effective at low inclinations since they can generate more side force as discussed earlier in this report. Due to high torque generated during drilling of the well, a slick BHA without stabilizer was used to drilling the well to 3,120 m RKB.

6.1.2 OW-49C in Olkaria field, Kenya

The well was drilled to provide steam for 560 MWe. The kick off for the well was done at 480 m RKB using a kick off BHA with a downhole motor. A build-up rate of 2.47°/30 m was achieved and by 677 m depth the angle of inclination was 17.8°. Drilling of the well was faced by several BHA design challenges just like OW-710B discussed earlier. Some of the challenges encountered are similar to those faced in OW-710B and will only be mentioned but not discussed in details in this case study.

An angle holding BHA shown in Table 2 was introduced after the build-up section. It was supposed to hold the angle but after drilling for only 70 m the angle dropped from 17.8° to 11.9°. Based on the configuration of the BHA, the two stabilizers with only 30 ft between them would have provided sufficient side forces to build the angle instead of dropping. Fulcrum assemblies with such configurations are affected greatly by the WOB application. The drilling parameters used to drill the section were not fully optimized, the WOB and the RPM used were too low as shown and may have contributed to the BHA behaviour. The angle correction was done by introduction of another BHA as shown in Table 2 with two stabilizers which were 60 ft apart. The WOB and RPM were also optimized what resulted in a good response. Other BHAs introduced while drilling the 12¼" hole section responded well based on their configuration and the drilling parameters used. However, to minimize the rate of build from a depth of 995 m, one of the short drill collars should have been removed. The distance from the near-bit stabilizer to the first drill string stabilizer is the main design feature of any fulcrum assembly that affects the build rate (Bourgoyne et al., 1986). This means that if the distance between the near-bit stabilizer and the string stabilizer is reduced from 20 ft to 10 ft by removing one short drill collar, the build rate would have dropped if all other factors would have been kept constant. The longer the fulcrum section, the more the bend which results in higher side forces being generated hence the build rate for the angle increases. In addition, the build rate can have been affected by the hole inclination as discussed earlier in this report.

In drilling of the 8½"section, similar angle holding challenges were encountered. A combination of pendulum and fulcrum assemblies were used to drill this section. From a depth of 1,372 to 1,872 m a fulcrum assembly consisting of two short drill collars was used. The angle rose steadily at a rate of 0.54°/30 m and the inclination angle rose from 20.6° to 29.6°. This means that the wellbore at this point was at a tangent point and with the right BHA configuration, it would have been easy to maintain the angle at this point. However, due to the well design requirement, the angle had to be dropped to 21.2° using an angle dropping BHA with the first string stabilizer placed 33 ft from the bit. With this pendulum BHA an angle drop-rate of 2.07°/30 m was hold for 122 m. The angle holding BHA introduced thereafter resulted in an increase in the angle of inclination from 19.5° to 27° within 248 m and had to be dropped again to 20° using a pendulum BHA. Due to these interchanging drops and increases in the angle of inclination, there was very high torque during drilling and a slick BHA without stabilizers had to be used to drill the wellbore from 2,517 m to 2,960 m. The well was terminated at that depth due to high torque and drag. In Appendix II, the survey data shows clearly that the Dog Leg Severity (DSL) was high at some occasions what possibly led to very high torque during the drilling of the well.

TABLE 2: OW-49C BHA data performance

BHA Type	Depth (m)		Metres drilled	Inclination (°)		Av. angle drop/build (30m)	Av. WOB (tons)	RPM	Desired result	Achieved result
	In	Out		In	Out					
Kick-off BHA (12¼"hole) Bit- MM-O-sub-NMDC-4/8"DC- xo- 7/HWDP	480	677	197	1.6	17.8	2.5	5		Angle build	Angle build
Angle holding Bit- bit sub- STB-NMDC- STB- 9/8"DC-xo- 12/HWDP	677	747	70	17.8	11.9	-2.5	5.5	35-40	Angle hold	Angle drop
Angle building Bit-NB-NMDC-8"DC-STB-5/8"DC-xo-15/HWDP	747	995	248	11.9	20.6	1.1	10.5	40-45	Angle build	Angle build
Angle holding Bit- bit sub- STB- 2SDC-STB- NMDC- 6/8"DC-xo-15/HWDP	995	1186	191	20.6	25.3	0.7	7	45-52	Angle hold	Angle build
Angle correction (8½" hole) Bit- bit sub- 2/6.5"DC-STB- NMDC -9/6.5"DC-15/HWDP	1186	1372	186	25.3	20.6	-0.8	6.6	45-60	Angle correct	Angle correct
Angle holding BHA Bit- STB- 2SDC- STB-NMDC- 12/6.5"DC-15/HWDP	1372	1840	468	20.6	29.2	0.6	7	55-70	Angle hold	Angle build
Angle correction BHA Bit- bit sub- 6.5"DC-STB- NMDC- DC- Stab-10/6.5DC- 15/HWDP	1840	1998	158	29.6	21.2	-1.6	6.8	50-60	Angle drop	Angle drop
Angle holding BHA Bit- STB- 2SDC- STB-NMDC- 12/6.5"DC-15/HWDP	1998	2057	59	21.2	19.5	-0.9	5	55	Angle hold	Angle drop
Angle holding BHA Bit- bit sub- STB-NMDC- STB- 9/6.5"DC-15/HWDP	2057	2305	248	19.5	27	0.9	5	50-60	Angle hold	Angle build
Angle correction BHA Bit- bit sub-2/6.5"DC-STB- NMDC- 9/6.5"DC-15/HWDP	2305	2517	212	27	20	-1.0	8	60	Angle correct	angle correct
Slick BHA Bit-bit sub-NMDC-STB-9/6.5"DC-12HWDP	2517	2960	443	20	12	-0.5	9.2	45-60		

6.1.3 THG-6 in Theistareykir, Iceland

THG-6 well design was based on the information obtained after drilling THG-3. The target azimuth for the well was planned to be 285°N ± 10° with the final angle of inclination at TD set at 30° ± 3°. The angle build-up rate for the well was planned to be 2°/30 m with the KOP set at 290 m. As planned, the kick off for the well was done at 288 m RKB using a kick off BHA composed of a mud motor and an MWD tool as shown in Table 3. The drilling of the 12¼" section of the well went well without any angle building challenges and by 663 m the angle of inclination was with 25.3° close to the target inclination. This continued until 846 m which was the target production casing depth, the angle of inclination at this depth was 30.5°. Only one BHA was used for drilling this hole section and the average WOB used was 12 tons.

Drilling of the 8½" section was done using the same BHA configuration as the one used for drilling the production section. The tangent section of this wellbore was drilled by a combination of rotation of the drill string and sliding to drill ahead. As shown in Table 3 and Appendix III the angle of inclination was maintained at 30° to a depth of 1,315 m using the angle holding BHA. The drill bit had to be changed at 2,161 m during which the MWD tool was laid down and replaced by a drill collar. With the absence of the MWD tool, it was not possible to monitor the angle change on real time and hence the angle of inclination rose from 31° to 37.9° by the time the target depth of 2,799 m was reached. Despite this, drilling of the main hole was done successfully with no BHA related challenges. An average WOB of 6.3 - 8 tons and an average rotary speed of 60 – 70 rpm was used to drill the production section.

TABLE 3: THG-6 BHA data performance

BHA Type	Depth (m)		Metres drilled	Inclination (°)		Av. angle drop/build (30 m)	Av. WOB (tons)	RPM	Desired result	Achieved result
	In	Out		In	Out					
Kick off BHA (12¼"hole) Bit -bit sub-mud motor-STB-MWD-STB-BT050-3DC-6 other	266	846	580	1	30.9	1.6	12	50-60	Angle build	Angle build
Angle holding BHA (8½" hole) Bit-mudmotor-STB-MWD-STB-5DC-jar-DC-3HWDP-wiper	846	2161	1315	30.9	31	0.0	6.3	50-80	Angle hold	Angle hold
Angle holding BHA Bit-mud motor-STB-DC-STB-5DC-Jar-DC-3HWDP-Wiper	2161	2799	638	31	37.9	0.3	8	60-70	Angle hold	Angle build

6.1.4 THG-07 in Theistareykir, Iceland

This well was drilled in order to study the geothermal reservoir conditions of the resource under Ketill mountain. Drilling the well would provide important data such as the heat condition, permeability and the characteristics of the geothermal fluid in the area as well as confirm the results from the previous studies showing that there is an upward flow in the area. The KOP for the well was done at 294 m RKB as planned in the drilling program. A BHA composed of a 9⅝" mud motor and an MWD tool as shown in Table 4 was used for the kick-off. The kick-off for the well was successful but several plug jobs had to be conducted before reaching a depth of 397 m due to losses and H_2S influx between 345 and 385 m. After the plug job the cement was drilled out using the kick off BHA and an inclination of 7.14° was attained. A fulcrum BHA with just one near bit stabilizer was introduced and used to drill up to 416 m. The WOB used on this BHA was around 11 tons and as discussed earlier, fulcrum assemblies respond highly to WOB application and hence the high build up rate. The earlier BHA used for kick off was then re-introduced and used to build up the angle from 9.03° to 34.94° with a build-up rate of 2.98°/30 m as shown in Table 4. As indicated in Appendix IV, the build-up rate was smooth for this hole section. An average WOB of 7 tons was used.

For the 8½" section, the same BHA configuration as shown in Table 4 was used to hold the angle of inclination from 776 to 1,573 m. Using that configuration, the inclination angle was maintained as required with the dog leg severity kept below 0.6° as shown in Appendix IV. After this the mud motor and the MWD tool were laid down and a fulcrum assembly consisting of two stabilizers placed 30 ft between them was introduced. The introduction of this BHA configuration resulted in angle rise of a total of 15.76° from 33.71° to 49.47° within 657 m with a build-up rate of 0.72°/30 m. This build up may have been the result of use of high ROP and WOB during drilling. The last BHA introduced in the well dropped the angle from 49.47° to 45.67° within 278 m as per the BHA design. The WOB application was also reduced to accelerate the angle drop.

TABLE 4: THG-7 BHA data performance

BHA Type	**Depth (m)**		**Metres drilled**	**Inclination (°)**		**Av. angle drop/build (30 m)**	**Av. WOB (tons)**	**RPM**	**Desired result**	**Achieved result**
	In	**Out**		**In**	**Out**					
Kick off BHA (12¼" hole) Bit -mud motor-STB MWD-UBHO-STB-4DC-9 other	270	397	127	0.7	7.1	1.5	6.5	50-60	Angle build	Angle build
Bit-STB-4DC-jar-2DC-wiper, 5 other	397	416	19	7.1	9.0	2.9	11	50-60		
Angle building BHA Bit -mud motor-STB-MWD-UBHO-STB-4DC-9 other	416	776	360	9.0	34.9	2.1	7	50-70	Angle build	Angle build
Angle holding BHA (8-1/2" hole) Bit-mudmotor-STB-MWD-STB-4DC-jar-7other	776	1573	797	34.9	33.7	-0.1	5.7	50-80	Angle hold	Angle hold
Angle holding BHA Bit-NBS-DC-STB-5DC-Jar-9other	1573	2230	657	33.7	49.5	0.7	5.3	50-80	Angle hold	Angle build
Angle dropping BHA Bit-BS-PC-STB-PC-DC-STB-3DC-9other	2230	2508	278	49.5	45.7	-0.4	3.8	65-80	Angle drop	Angle drop

7. DISCUSSION

As shown in the two case studies for the Olkaria wells, the fulcrum assembly introduced to build the angle responded very well to WOB application. As discussed earlier in the report, high WOB applications for these assemblies results in high angle build up rates. The major challenges encountered were mainly on angle holding. The angle holding BHA used in the two case studies consisted of two stabilizers. Two stabilizer assemblies can be used especially in areas where the formation is not properly consolidated like it is the case in Olkaria. However, the near bit and the string stabilizer should be full gauge. Should the near bit stabilizer be under gauge, an assembly that is meant to build an angle may cause an angle drop. It is also possible that with two stabilizer BHA configuration that the behaviour changes significantly when they reach a certain depth like shown in the two case studies. A BHA which was supposed to hold inclination may start decreasing the angle. Assuming that the near bit stabilizer is not under gauge, the angle drop may be caused by change in formation, change in formation dip or strike among others (Devereux, 1998). For this reason, it is important to have a very good geological database of the respective area so that such problems can be anticipated earlier and measures taken. In addition, when drilling the tangent (hold) section, the tangent inclination should be greater than 15°. It has been proven that the directional control problems are made worse if the drift angle is less than 15°. This is because a small drift angle increases the tendency of the bit to walk (change in azimuth) (Hole, 2008). Bit walk has been one of the challenges experienced in drilling directional wells in Olkaria and can be minimized by increasing the tangent inclination angle of the hold section.

From the two Olkaria case studies, it is evident that drilling parameters optimization for most BHA configurations is a very important factor. While drilling OW-49C for example, changes in drilling parameters WOB and RPM showed a very big impact on the behaviour of an angle correction BHA consisting of two stabilizers. This means that fewer trips to change the BHA can be made if the response of the BHA to the drilling parameters being used is fully understood. It is advisable to understand these variables as well as taking into account the kind of formation that is being drilled. If these two are combined, some of the challenges experienced could have been avoided or addressed more quickly.

Angle correction in directional drilling should be done sooner rather than later. In the two case studies for the Olkaria wells, in some cases the angle correction was done when it was too late. In OW-49C the BHA introduced at 1,372 m was supposed to hold the angle but it continued building the angle from 20.6° to 29.6° at 504 m before it was changed as shown in Table 2. Correcting the angle at deeper depths is a long process which is hard to control and should therefore be discouraged. In addition, dropping an angle at deeper depths is not recommended as it normally leads to serious drilling challenges. If the circumstances dictate that the angle has to drop, the choice of the BHA to use is very important. In most cases a pendulum assembly is preferred over downhole motors because when the tool face of a downhole motor is aligned to the low side of the hole, the tool normally flips over when reactive force is applied as the bit contacts the bottom. This makes it very hard to hold the motor in its position especially when the well is deep and dipping at a high angle. When using a pendulum assembly to drop an angle, the drilling parameters used should be selected carefully. Low WOB should be applied until the drop trend is established and the second stabilizer in the BHA is in the section of the hole that is dropping. Once this is established, the WOB can be brought up. When this is done, the ROP will improve and the drop rate may increase since the drill collars will be forced to bend outward due to the bend in the hole between the bit and the second stabilizer (Devereux, 1998).

The two case studies for the Icelandic wells drilled in Theistareykir show a different BHA configuration design from that used in Olkaria wells. The BHA used in drilling the two directional wells consists of a downhole motor and an MWD tool for relaying the survey data to the surface as the drilling continues. The down hole motor and the MWD tool are maintained in the BHA as much as possible and only removed if significant losses are encountered when reaching a certain depth. With this combination, it was possible to hold the angle of inclination while maintaining the target azimuth for the well. With mud motor and MWD tool in the assembly it is possible to follow the directional plan more closely since no frequent trips are required to change the BHA and corrections in the slide mode can be done when required. These corrections ensure that the wellbore is kept as close as possible to the planned path (Devereux, 1998). In addition, the use of this kind of BHA configuration for almost the entire well section from KOP to TD minimizes the number of trips to correct the BHA in comparison to when basic rotary assemblies are used as shown in the case studies. When angle or azimuth correction is required, the motor is oriented in the desired direction (tool face angle) and drilling is done in slide mode (without pipe rotation) until the correction is achieved. The change in azimuth or inclination is achieved by the bit tilt derived from bent housing in the motor assembly or from the side force exerted form the stabilizers. Drilling in rotary mode is then continued until another correction is required. In rotary mode, the bit tilt and side forces generated are cancelled out by the rotation of the drill string which causes the assembly to act like a stabilized rotary assembly (Carden and Grace, 2007). In addition, to save trip time, frequent motor corrections normally minimize the problem associated with key seats. Frequent BHA changes when using basic rotary assemblies can result to high dog leg severity if not properly monitored. This normally results in very high torque during drilling which has a direct impact on running of casings as well as the overall drilling progress. The two wells from Olkaria had to be terminated a few meters before reaching the target depth due to excess torque during drilling.

8. CONCLUSIONS AND RECOMMENDATIONS

As shown in the report, BHA design for directional wells plays a very important role for achieving the desired results. In Olkaria, the major BHA related challenges are experienced in the angle holding section. These challenges have led to numerous BHA changes that increase the number of days spent in drilling a well. In OW-710B for example, approximately 6 drilling days were spent on trips to change the BHA. This would have been minimized if the right BHA configuration was adopted for drilling the well. In addition, frequent BHA changes and lack of proper drilling parameters optimization lead to increased torque while drilling, making it impossible to drill to target depth in some wells. For rotary assemblies, stabilizer placement and drilling parameter optimization play a very important role in directional well drilling. The side forces generated by different assemblies determines the behaviour tendency relative to holding, building or dropping the angle of inclination. In order to benefit fully from BHA design optimization, an understanding of different BHA response to design and operating parameters is necessary. With this knowledge, it is possible to vary the BHA configuration or the drilling parameters to control the directional tendencies appropriately.

In Iceland, BHA related challenges have been minimized by the use of the downhole motor and MWD after the build-up section. Those two make it easy to follow the directional plan more closely and to avoid many trips to change BHA. In addition, it ensures that a smooth trajectory is achieved thus minimizing key seats and severe dog legs that can be brought about by frequent BHA changes. If this is done, the torque values while drilling can be maintained within normal range and hence the well can be successfully drilled to the target depth. In addition, a two stabilizer assembly with a short drill collar between them can be used for the tangent section of a directional well. This BHA has a slight building tendency which can be controlled by optimizing the drilling parameters. The near-bit stabilizer and the string stabilizer should however be full gauge. If the geology of an area is properly understood, a three stabilizer assembly can also be used for drilling the tangent section.

A consideration to increase the tangent inclination angle from 20° to 25-35° should be made. This will minimize bit walks experienced in drilling the tangent section which lead to constant BHA changes to control the azimuth and inclination. In addition, when drilling directional wells, either using rotary assemblies or by downhole motors, a key seat wiper should be included in the BHA. This is very important especially when dog legs are expected. The main purpose of the key seat wiper is to increase the key hole diameter by drilling it out when POOH. To be fully affective, it has to have an outside diameter (OD) that is greater than the OD of any other part of the BHA excluding the stabilizer blades and the bit. The key seat wiper rotates freely and does not have any reaming affect during drilling or when reaming downwards in the well. With a key seat wiper in BHA configuration, torque experienced when drilling due to dog legs is minimized.

ACKNOWDGEMENTS

My appreciation goes to the Mr. Lúdvík S. Georgsson, Director UNU-GTP, and Mr. Ingimar G. Haraldsson, Deputy Director for giving me the opportunity to undergo the six-month training program. Many thanks to UNU-GTP staff: Ms. Málfrídur Ómarsdóttir, Ms. Thórhildur Ísberg and Mr. Markús A. G. Wilde for supporting me during my stay in Iceland. I wish also to thank my company, KenGen for giving me this opportunity to learn and enhance my skills in geothermal technology.

I am grateful for all the support my supervisor, Mr. Arnar Bjarki Árnason, his fellow engineers at MANNVIT and Mr. Sverrir Thórhallsson gave me. Their encouragement and fruitful ideas kept me going during my project period. I would also like to thank my colleagues at work for providing me with data and support all the time.

My sincere gratitude goes to my family for their support and prayers during my stay in Iceland and Almighty God for protecting me and my family during my absence.

REFERENCES

Aadnoy., B.S., Cooper, I., Miska, S.Z., Mitchell, R.F., and Payne, M.L. (eds.), 2009: *Advanced drilling and well technology*. Society of Petroleum Engineers, Richardson, TX, 888 pp.

Adams, N.J., 1985: *Drilling engineering, a complete well planning approach*. Pennwell Books, Tulsa, OK, 849 pp.

Baker Hughes INTEQ., 1995: *Drilling engineering workbook, a distributed learning course*. Baker Hughes INTEQ Inc., Houston, TX, 410 pp.

Bourgoyne Jr., A.T., Millheim, K.K., Chenevert, M.E., and Young Jr., F.S., 1986: *Applied drilling engineering.* Society of Petroleum Engineers, SPE Textbook Series, 2, Richardson, TX, 502 pp.

Carden, R.S. and Grace, R.D., 2007: *Horizontal and directional drilling*. Petroskills, Tulsa, OK, 409 pp.

Computerlog Drilling Service 2000 (?): *Directional Drilling 1*. Houston, TX: Technology Services Group, 188 pp.

Devereux, S., 1998: *Practical well planning and drilling manual.* PennWell Corp., Tulsa, OK, 524 pp.

Devereux, S., 1999: *Drilling technology in nontechnical language.* PennWell, Corp., Tulsa OK, 337 pp.

Economides, M.J., Watters, L.T., and Dunn-Norman, S., 1998: *Petroleum well construction*. John Wiley & Sons, NY, 622 pp.

Hole, H., 2008: *Directional drilling of geothermal wells*. Petroleum Engineering Summer School, Workshop 26, Dubrovnik, Croatia, June 2008.

Inglis T.A., 1987: *Directional drilling, vol. 2.* Graham & Totman Ltd., London, 260 pp.

Rabia, H., 2002: *Well engineering and construction*. Entrac Consulting, 789 pp.

Smith Services., 2001: *Drilling assembly handbook*. Smith International, Inc., Houston, TX, 190 pp.

Speith J.G., 2015: *Handbook of offshore oil and gas operations*. Gulf Professional Publ. WY, USA, 444 pp.

Vieira, J.L., 2009: *Controlled directional drilling* (4^{th} edition). Petroleum Extension Service, Austin TX, 129-134.

APPENDIX I: OW-710B survey data

KOP	**752.0**	**Azimuth**	**337.5**					
Measured Depth (mRKB)	**Depth from KOP**	**Inclination (deg)**	**Azimuth**	**TVD**	**Displacement**	**North**	**East**	**Dog leg severity**
				752.00	0.00	0.00	0.00	0.00
739	-13	1.19	79.00	739.00	0.27	-0.05	-0.27	-2.79
758	6	1.55	72.34	758.00	-0.24	0.10	0.22	0.63
772	20	1.32	46.03	771.99	-0.57	0.33	0.46	1.50
789	37	1.75	344.78	788.98	-1.09	0.83	0.32	2.88
809	57	3.06	323.63	808.96	-2.15	1.69	-0.31	2.38
826	74	5.10	320.72	825.89	-3.66	2.86	-1.27	3.68
838	86	5.27	321.00	837.84	-4.77	3.72	-1.96	0.44
937	185	10.55	330.09	935.16	-22.89	19.43	-11.00	1.67
1071	319	15.78	332.52	1064.11	-59.33	51.76	-27.82	1.20
1229	477	22.85	337.19	1209.71	-120.69	108.31	-51.60	1.40
1284	532	21.79	338.66	1260.79	-141.10	127.33	-59.03	0.66
1379	627	20.46	338.18	1349.70	-174.28	158.13	-71.36	0.43
1529	777	17.77	337.19	1492.64	-220.09	200.35	-89.12	0.55
1598	846	15.93	332.21	1558.99	-239.02	217.11	-97.95	1.03
1645	893	14.33	335.27	1604.53	-250.66	227.67	-102.82	1.16
1691	939	14.66	335.90	1649.03	-262.30	238.30	-107.57	0.24
1739	987	16.36	337.09	1695.08	-275.82	250.75	-112.83	1.10
1829	1077	18.76	340.37	1780.30	-304.76	278.02	-122.56	0.88
1920	1168	22.05	345.58	1864.65	-338.93	311.10	-131.07	1.26
2000	1248	22.3	346.6	1938.66	-369.28	340.63	-138.10	0.17
2162	1410	17.21	346.77	2093.41	-417.22	387.29	-149.07	0.96
2229	1477	17.99	348.52	2157.13	-437.91	407.57	-153.19	0.43
2833	2081	16.31	334.51	2736.83	-607.53	560.68	-226.19	0.22
3120	2368	15.03	334.68	3014.01	-681.96	627.96	-258.02	0.14

APPENDIX II: OW-49C survey data

KOP	480.00	Azimuth	225	Planned				
Measured depth	**Depth from KOP**	**Inclination**	**Azimuth**	**TVD**	**Displacement**	**North**	**East**	**Dog leg serverity**
				480.00	0.00	0.00	0.00	0.00
495.00	15.00	1.80	173.60	494.99	0.47	-0.47	0.05	3.66
514.00	34.00	2.70	172.00	513.97	1.37	-1.35	0.18	1.45
523.00	43.00	2.60	191.60	522.96	1.77	-1.75	0.09	3.07
533.00	53.00	3.80	190.80	532.94	2.44	-2.41	-0.03	3.66
543.00	63.00	4.20	192.50	542.91	3.17	-3.12	-0.19	1.27
552.00	72.00	5.60	195.00	551.87	4.05	-3.97	-0.42	4.80
562.00	82.00	6.80	200.30	561.80	5.23	-5.08	-0.83	4.05
571.00	91.00	8.20	200.10	570.71	6.52	-6.28	-1.27	4.74
581.00	101.00	8.80	207.40	580.59	8.05	-7.64	-1.97	3.76
590.00	110.00	10.00	209.20	589.45	9.61	-9.01	-2.73	4.18
600.00	120.00	10.90	212.00	599.27	11.50	-10.61	-3.74	3.15
610.00	130.00	12.00	216.40	609.05	13.58	-12.28	-4.97	4.28
619.00	139.00	13.70	217.00	617.80	15.71	-13.99	-6.25	5.78
629.00	149.00	15.20	220.60	627.45	18.33	-15.98	-7.96	5.33
638.00	158.00	15.50	224.80	636.12	20.74	-17.68	-9.65	3.90
647.00	167.00	17.10	224.80	644.72	23.38	-19.56	-11.52	5.42
656.00	176.00	17.80	225.60	653.29	26.13	-21.49	-13.48	2.51
677.00	197.00	19.50	226.50	673.09	33.14	-26.31	-18.57	2.50
746.00	266.00	11.90	225.40	740.61	47.37	-36.30	-28.70	3.36
795.00	315.00	11.50	225.90	788.62	57.14	-43.10	-35.71	0.26
804.00	324.00	12.10	227.10	797.42	59.03	-44.38	-37.10	2.20
815.00	335.00	12.60	225.90	808.16	61.43	-46.05	-38.82	1.56
823.00	343.00	12.80	226.90	815.96	63.20	-47.27	-40.11	1.13
842.00	362.00	13.40	229.20	834.44	67.60	-50.14	-43.45	1.28
869.00	389.00	14.70	226.80	860.56	74.45	-54.83	-48.44	1.61
900.00	420.00	16.30	223.60	890.31	83.16	-61.13	-54.44	1.78
928.00	448.00	17.70	231.10	916.99	91.67	-66.48	-61.07	2.83
957.00	477.00	19.00	235.50	944.41	101.11	-71.83	-68.85	2.00
986.00	506.00	20.30	229.80	971.60	111.17	-78.32	-76.53	2.43
995.00	515.00	20.60	230.80	980.03	114.34	-80.32	-78.99	1.56
1031.00	551.00	23.50	232.60	1013.04	128.69	-89.04	-90.39	2.52
1051.00	571.00	23.60	230.30	1031.37	136.70	-94.16	-96.55	1.41
1153.00	673.00	24.80	233.30	1123.96	179.48	-119.73	-130.85	0.51
1190.00	710.00	25.30	225.60	1157.41	195.30	-130.79	-142.15	2.72
1295.00	815.00	28.10	244.40	1250.04	244.75	-152.16	-186.75	2.57
1353.00	873.00	25.00	247.10	1302.60	269.26	-161.70	-209.33	1.75
1372.00	892.00	20.60	217.60	1320.39	275.95	-166.99	-213.41	19.42
1418.00	938.00	22.10	222.20	1363.01	293.26	-179.81	-225.04	1.49
1514.00	1034.00	24.30	231.60	1450.50	332.76	-204.35	-256.00	1.37
1571.00	1091.00	24.70	239.50	1502.29	356.58	-216.44	-276.52	1.76
1725.00	1245.00	26.70	226.20	1639.87	425.77	-264.33	-326.46	1.21
1812.00	1332.00	29.20	224.60	1715.81	468.22	-294.55	-356.26	0.91
1862.00	1382.00	30.40	230.70	1758.94	493.52	-310.58	-375.84	1.99
1896.00	1416.00	29.60	227.10	1788.50	510.31	-322.01	-388.15	1.77
1970.00	1490.00	23.20	232.80	1856.52	539.47	-339.64	-411.37	2.83
2000.00	1520.00	21.20	234.40	1884.49	550.31	-345.95	-420.19	2.12
2022.00	1542.00	19.70	232.90	1905.20	557.73	-350.43	-426.10	2.20
2057.00	1577.00	19.50	231.80	1938.19	569.41	-357.65	-435.28	0.37
2104.00	1624.00	20.50	233.90	1982.21	585.87	-367.35	-448.58	0.80
2195.00	1715.00	23.80	232.10	2065.48	622.60	-389.91	-477.56	1.13
2217.00	1737.00	24.70	230.10	2085.46	631.79	-395.80	-484.61	1.69
2246.00	1766.00	25.30	226.80	2111.68	644.18	-404.29	-493.65	1.60
2290.00	1810.00	27.00	224.10	2150.89	664.16	-418.63	-507.55	1.44
2341.00	1861.00	26.80	227.60	2196.41	687.15	-434.14	-524.53	0.95
2398.00	1918.00	20.70	218.00	2249.73	707.30	-450.02	-536.93	3.85
2432.00	1952.00	19.50	219.30	2281.78	718.65	-458.80	-544.12	1.15
2476.00	1996.00	18.00	215.30	2323.62	732.25	-469.89	-551.98	1.37
2517.00	2037.00	20.10	218.70	2362.13	746.34	-480.89	-560.79	1.77
2698.00	2218.00	13.80	217.40	2537.90	789.51	-515.19	-587.01	1.06
2861.00	2381.00	12.10	222.60	2697.28	823.68	-540.34	-610.14	0.39

APPENDIX III: THG-6 survey data

Depth	Inclination (from Vert)	Grid Azimuth	Closure Direction	True Depth	Coordinates		Dogleg Severity	Closure Distance
					+N/ -S	+E/ -W		
930,0	28,97	293,27		0,00	0,00	0,00		0,00
1300,0	30,22	285,55	289,41	321,72	60,73	-172,35	0,33	182,74
1308,0	29,75	288,78	289,36	328,65	61,91	-176,17	6,30	186,73
1350,0	29,93	287,72	289,25	365,08	68,45	-196,02	0,40	207,63
1400,0	30,23	288,27	289,11	408,35	76,19	-219,85	0,24	232,68
1450,0	30,29	287,41	288,99	451,53	83,91	-243,83	0,26	257,87
1500,0	30,09	288,05	288,88	494,75	91,57	-267,78	0,23	283,00
1550,0	30,27	287,11	288,77	537,98	99,16	-291,74	0,31	308,13
1600,0	30,74	286,98	288,64	581,06	106,60	-316,00	0,28	333,50
1650,0	30,11	289,35	288,61	624,17	114,49	-340,06	0,81	358,81
1700,0	30,33	289,88	288,67	667,38	122,94	-363,76	0,21	383,97
1710,0	30,14	289,20	288,68	676,02	124,62	-368,51	1,18	389,01
1750,0	30,18	287,30	288,66	710,61	130,92	-387,59	0,72	409,11
1800,0	30,21	288,45	288,62	753,82	138,64	-411,53	0,35	434,25
1850,0	30,24	287,08	288,57	797,02	146,32	-435,50	0,41	459,42
1900,0	31,09	285,23	288,44	840,03	153,41	-459,99	0,76	484,90
1950,0	30,44	282,79	288,22	883,00	159,60	-484,80	0,84	510,40
2000,0	29,52	283,76	287,99	926,31	165,34	-509,12	0,62	535,29
2050,0	30,16	284,42	287,82	969,68	171,40	-533,25	0,43	560,12
2100,0	30,26	285,63	287,70	1012,89	177,92	-557,55	0,37	585,25
2150,0	30,97	287,32	287,65	1055,92	185,14	-581,96	0,67	610,70
2200,0	32,19	288,69	287,66	1098,51	193,23	-606,87	0,85	636,89
2250,0	33,21	287,73	287,68	1140,59	201,68	-632,52	0,69	663,90
2300,0	34,40	289,75	287,73	1182,13	210,61	-658,87	0,98	691,71
2350,0	35,83	290,83	287,83	1223,03	220,59	-685,84	0,93	720,44
2400,0	36,79	290,11	287,93	1263,33	230,94	-713,58	0,63	750,02
2450,0	37,76	291,10	288,04	1303,11	241,60	-741,92	0,68	780,26
2500,0	38,84	292,91	288,19	1342,35	253,21	-770,65	0,93	811,18
2550,0	40,01	292,88	288,37	1380,97	265,56	-799,90	0,70	842,83
2600,0	39,87	293,16	288,54	1419,31	278,12	-829,44	0,13	874,83
2650,0	39,14	298,07	288,78	1457,89	291,87	-858,12	1,92	906,40
2700,0	38,68	292,19	289,00	1496,80	305,20	-886,56	2,23	937,62
2750,0	37,98	298,19	289,19	1536,02	318,40	-914,62	2,27	968,46
2770,0	37,87	297,81	289,30	1551,79	324,18	-925,47	0,39	980,61

APPENDIX IV: THG-7 survey data

Survey Type	Meas. Depth	Inc.	Azimuth	TVD	Closure	Vertical Section	Coordinates N-S	E-W	D.L.S.
GMS	300,00	0,793	93,39	299,99	2,08	-0,12	S 0,1	E 2,1	0,079
GMS	330,00	3,619	72,31	329,97	3,19	0,15	N 0,2	E 3,2	2,893
GMS	360,00	6,192	70,63	359,85	5,70	0,98	N 1,0	E 5,6	2,577
GMS	390,00	6,709	65,49	389,66	9,01	2,24	N 2,2	E 8,7	0,775
GMS	420,00	7,134	58,62	419,45	12,55	3,94	N 3,9	E 11,9	0,930
GMS	450,00	9,026	46,55	449,15	16,56	6,53	N 6,5	E 15,2	2,531
GMS	480,00	11,675	40,20	478,66	21,59	10,46	N 10,5	E 18,9	2,880
GMS	510,00	14,801	37,47	507,86	28,06	15,83	N 15,8	E 23,2	3,187
GMS	540,00	18,574	39,61	536,59	36,39	22,55	N 22,5	E 28,6	3,822
GMS	570,00	21,307	40,00	564,79	46,44	30,41	N 30,4	E 35,1	2,736
GMS	600,00	24,265	41,18	592,44	57,96	39,22	N 39,2	E 42,7	2,993
GMS	630,00	27,189	42,65	619,47	70,93	48,91	N 48,9	E 51,4	2,993
GMS	660,00	30,377	44,41	645,76	85,36	59,37	N 59,4	E 61,3	3,298
GMS	690,00	32,920	46,41	671,30	101,10	70,41	N 70,4	E 72,5	2,752
GMS	720,00	34,942	47,77	696,19	117,84	81,81	N 81,8	E 84,8	2,158
GMS	750,00	35,210	48,02	720,74	135,07	93,37	N 93,4	E 97,6	0,307
GMS	780,00	34,914	48,03	745,29	152,30	104,89	N 104,9	E 110,4	0,296
GMS	810,00	34,925	47,88	769,89	169,46	116,40	N 116,4	E 123,2	0,086
GMS	840,00	33,974	48,02	794,63	186,43	127,76	N 127,8	E 135,8	0,954
GMS	870,00	33,930	47,89	819,52	203,18	138,98	N 139,0	E 148,2	0,084
GMS	900,00	34,234	47,12	844,36	219,99	150,34	N 150,3	E 160,6	0,528
GMS	930,00	34,666	46,16	869,10	236,96	161,99	N 162,0	E 172,9	0,693
GMS	960,00	35,224	46,03	893,69	254,14	173,91	N 173,9	E 185,3	0,563
GMS	990,00	34,856	46,08	918,25	271,37	185,86	N 185,9	E 197,7	0,369
GMS	1.020,00	33,866	46,26	943,02	288,30	197,59	N 197,6	E 209,9	0,995
GMS	1.050,00	34,489	46,57	967,84	305,15	209,21	N 209,2	E 222,1	0,647
GMS	1.080,00	34,241	46,92	992,60	322,08	220,81	N 220,8	E 234,5	0,315
GMS	1.110,00	34,374	47,35	1.017,38	338,99	232,31	N 232,3	E 246,9	0,277
GMS	1.140,00	35,122	47,24	1.042,03	356,09	243,91	N 243,9	E 259,4	0,751
GMS	1.170,00	35,759	47,20	1.066,47	373,48	255,72	N 255,7	E 272,2	0,638
GMS	1.200,00	35,411	47,52	1.090,87	390,94	267,55	N 267,5	E 285,0	0,394
GMS	1.230,00	35,147	47,44	1.115,36	408,27	279,26	N 279,3	E 297,8	0,267
GMS	1.260,00	35,035	47,85	1.139,91	425,51	290,88	N 290,9	E 310,6	0,260
GMS	1.290,00	34,930	47,94	1.164,49	442,71	302,41	N 302,4	E 323,3	0,116
GMS	1.320,00	34,832	48,22	1.189,10	459,86	313,87	N 313,9	E 336,1	0,185
GMS	1.350,00	34,769	48,76	1.213,73	476,98	325,22	N 325,2	E 348,9	0,315
GMS	1.380,00	34,871	48,83	1.238,36	494,10	336,51	N 336,5	E 361,8	0,110
GMS	1.410,00	35,176	49,01	1.262,93	511,31	347,82	N 347,8	E 374,8	0,321
GMS	1.440,00	34,817	49,22	1.287,51	528,50	359,08	N 359,1	E 387,8	0,380
GMS	1.470,00	34,802	49,11	1.312,14	545,62	370,28	N 370,3	E 400,7	0,067
GMS	1.500,00	34,923	49,22	1.336,75	562,76	381,49	N 381,5	E 413,7	0,136
GMS	1.530,00	35,137	49,52	1.361,32	579,97	392,71	N 392,7	E 426,8	0,275
GMS	1.560,00	35,745	49,31	1.385,76	597,35	404,03	N 404,0	E 440,0	0,619
GMS	1.590,00	33,711	48,95	1.410,41	614,43	415,21	N 415,2	E 452,9	2,045
GMS	1.620,00	33,927	49,18	1.435,34	631,13	426,15	N 426,1	E 465,5	0,253
GMS	1.650,00	34,260	49,30	1.460,18	647,93	437,13	N 437,1	E 478,3	0,339
GMS	1.680,00	34,997	49,48	1.484,87	664,97	448,22	N 448,2	E 491,2	0,744
GMS	1.710,00	36,009	49,63	1.509,29	682,39	459,53	N 459,5	E 504,5	1,016
GMS	1.740,00	35,927	49,76	1.533,57	700,00	470,92	N 470,9	E 517,9	0,113
GMS	1.770,00	36,811	49,88	1.557,73	717,77	482,40	N 482,4	E 531,5	0,887
GMS	1.800,00	37,507	50,14	1.581,64	735,88	494,05	N 494,0	E 545,4	0,714
GMS	1.830,00	37,820	50,48	1.605,38	754,19	505,75	N 505,8	E 559,5	0,375
GMS	1.860,00	38,733	50,84	1.628,93	772,76	517,53	N 517,5	E 573,9	0,941
GMS	1.890,00	39,671	50,40	1.652,18	791,70	529,56	N 529,6	E 588,5	0,980
GMS	1.920,00	40,607	50,33	1.675,12	811,02	541,90	N 541,9	E 603,4	0,937
GMS	1.950,00	41,362	50,38	1.697,76	830,68	554,46	N 554,5	E 618,6	0,756
GMS	1.980,00	42,104	50,83	1.720,15	850,63	567,13	N 567,1	E 634,0	0,802
GMS	2.010,00	43,088	51,78	1.742,23	870,91	579,82	N 579,8	E 649,8	1,176
GMS	2.040,00	43,716	51,50	1.764,03	891,49	592,61	N 592,6	E 666,0	0,657
GMS	2.070,00	44,880	51,42	1.785,50	912,41	605,67	N 605,7	E 682,4	1,165
GMS	2.100,00	46,025	50,92	1.806,55	933,76	619,07	N 619,1	E 699,0	1,200
GMS	2.130,00	46,884	50,25	1.827,21	955,49	632,88	N 632,9	E 715,8	0,984
GMS	2.160,00	48,091	50,27	1.847,49	977,60	647,01	N 647,0	E 732,8	1,207
GMS	2.190,00	49,050	50,32	1.867,34	1.000,08	661,38	N 661,4	E 750,2	0,960
GMS	2.220,00	50,122	50,78	1.886,79	1.022,91	675,90	N 675,9	E 767,8	1,128
GMS	2.250,00	49,473	50,75	1.906,15	1.045,80	690,39	N 690,4	E 785,5	0,649
GMS	2.280,00	49,121	50,46	1.925,71	1.068,53	704,83	N 704,8	E 803,1	0,417
GMS	2.310,00	48,583	50,50	1.945,45	1.091,11	719,20	N 719,2	E 820,5	0,539
GMS	2.340,00	47,748	49,88	1.965,46	1.113,46	733,51	N 733,5	E 837,7	0,953
GMS	2.370,00	47,786	49,79	1.985,63	1.135,67	747,84	N 747,8	E 854,7	0,077
GMS	2.400,00	47,385	49,86	2.005,86	1.157,81	762,13	N 762,1	E 871,6	0,404
GMS	2.430,00	46,529	49,39	2.026,34	1.179,74	776,33	N 776,3	E 888,3	0,924
GMS	2.460,00	46,314	48,86	2.047,02	1.201,47	790,55	N 790,6	E 904,7	0,436
GMS	2.490,00	45,668	49,33	2.067,86	1.223,04	804,68	N 804,7	E 921,0	0,726