BREAKTHROUGH ON A ROTARY STEERABLE SYSTEM FOR GEOTHERMAL DRILLING IN A WEST JAVA FIELD

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ABSTRACT

Geothermal wells are often deviated and most of the directional work is generally performed in the intermediate hole section (17 ½”), conventionally using a mud motor. However this has some limitations, such as a small RPM range available for cleaning the hole while rotating and the risk of getting stuck due to pack-off (especially in the presence of total losses while sliding (particularly for inclinations around 35 degrees and above) in the formations of high heterogeneity encountered in the volcanic environment).

To overcome these drilling challenges, a Rotary Steerable System (RSS) has been utilized, specifically a RSS Xceed900. This is a “point the bit” system which ‘directs’ the bits in the desired direction, either through bending a shaft or having a built in offset, as opposed to a “push the bit” system, which utilizes “pads” to allow steering. This is the first time a “point the bit” RSS has been used in a geothermal well, worldwide.

To allow the successful deployment of this new technology in a geothermal application, a thorough technical/commercial analysis and several simulations and iterations were performed, which included:

- Gyro and Magnetometer drilling modes due to the expected cross-magnetic interference from the formation.
- IDEAS (Integrated Dynamic Engineering Analysis System - Schlumberger proprietary software) simulations to ensure both directional and dog-leg capabilities in the anticipated drilling conditions.
- Well plan optimization targeting a dog-leg severity (DLS) below 3 deg/30m.
- Flow rate optimization during aerated drilling together with survey considerations (downlink).

The actual field results can be summarized as follows:

- Higher on bottom ROP (15%).
- Optimization of parameters for hole cleaning - RPM 100-140, flow rate 900-1100 gpm.
- Minimization of back reaming.
- Optimization of Hi-Vis pills usage.
- Smoother T&D trend (including micro dog-leg avoidance).
- Implemented surveying strategy and QuikSurvey application.

The RSS Xceed900 showed several benefits that offset its higher cost compared to conventional mud motors in directional wells. This technology proved, in meeting specific drilling challenges, to be a viable alternative to mud motors for improving both performance and hole cleaning.

1. SPECIFIC CONSIDERATIONS FOR RUNNING A ROTARY STEERABLE SYSTEM IN GEOTHERMAL AREAS

1.1 Well Trajectory and BHA Design

When steering with a mud motor, the drill-string remains stationary (no rotation) for the period of time equivalent to the sliding intervals. The consequent risk of drilled cuttings accumulating around the BHA and potentially packing off the BHA (resulting in a stuck pipe) increases during the sliding intervals, and in particular if total losses are encountered because the drilling cuttings are not circulated out of the hole.

To mitigate this problem, a “point the bit” RSS Xceed900 was introduced, for the first time worldwide in a geothermal well: the drill-string rotates while the directional plan is executed without the need to stop the rotation for sliding purposes.

In this application, shown in Figure 1, the kick-off and the directional work were both planned in the 17 1/2” hole section and the well trajectory was simplified to reduce the amount of directional work at foreseen total loss depths and in anticipated swelling clay formations

Likewise, the DLS was planned to be as low as possible and below 3 deg/30m, thus maximizing the chance of running casing to hole section TD.

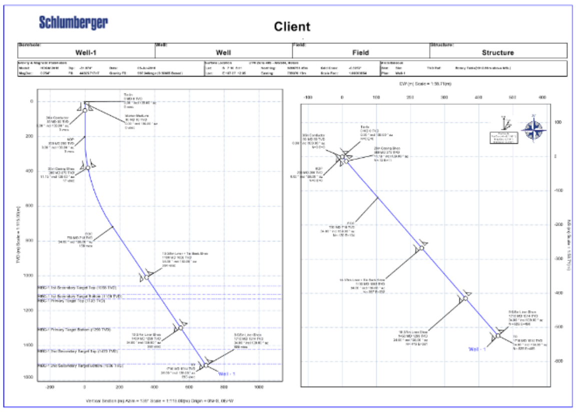

Figure 1 Geothermal Well Profile

Several considerations were made while designing the RSS directional BHA. Each component of the BHA was selected to:

- Meet the directional plan (trajectory and DLS).
- Reduce the risk of cuttings accumulating around the BHA.
- Enable pumping at a high flow rate for improved hole cleaning.
- Minimize drill-string magnetic interference.
- Provide jar sufficient impact in the event of a stuck pipe.

A typical BHA configuration for the 17 1/2” hole section utilizing RSS Xceed900 is shown in Figure 2 below.

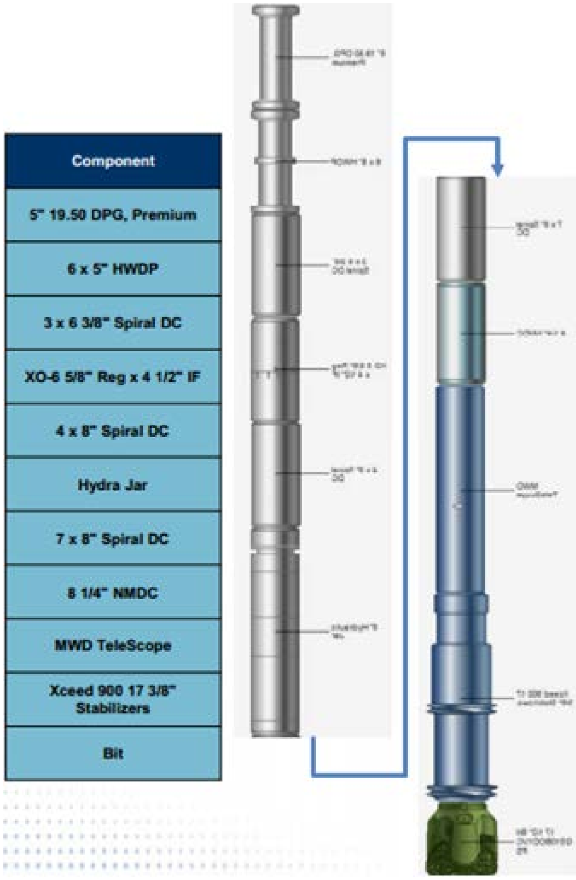

Figure 2 Typical BHA configuration for a 17 1/2” hole section utilizing RSS Xceed900

RSS Xceed900 is suitable for different bit types including bi-center bits. A PDC bit will have more of a side cutter effect, compared to roller cone bits. The most appropriate bit was selected based on a simulation using IDEAS. The choice was a Tungsten Carbide Insert (TCI) bit, IADC code 435. TCI bits of various grades and geometries have been developed to produce a durable and effective cutting structure and an integrated drill bit design platform was used to optimize the cutting structure, so that loads are more evenly distributed over the inserts of all three cones, producing a well-balanced bit with reduced risk of bearing failure.

The specific bit selected has a center jet feature to maximize fluid flow and inserts and back leg protection to minimize bit wear while drilling the hard and often abrasive volcanic formations.

1.2 Smith IDEAS Time Based Simulation

Dynamic Finite Element Analysis (FEA) modeling utilizing IDEAS software, was performed to compare the drilling dynamics behavior of several BHA configurations and to identify the best option for the RSS application based on stability and directional tendency. Drill-string components, including the BHA as well as the bit’s cutting structure design/pattern, were modeled in detail to get as accurate a simulation result as possible (see Figure 3 below).

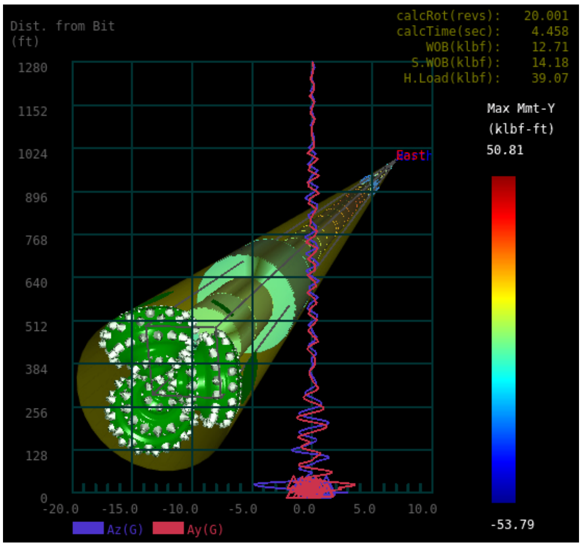

Figure 3 Dynamic FEA modelling

The nodes in the finite element mesh that represent the cutting structure of the bit are governed by rock mechanics and behave in a highly nonlinear manner. Rock mechanics data are empirically derived in a laboratory test program and implemented within the model to establish an accurate rock/bit dynamic output.

The objective of the simulations were:

- Select the best BHA configuration.
- Optimize the stabilization by selecting the stabilizer blade OD size.
- Identify the directional tendency was well as DLS capability of the BHA.
- Provide a stable drilling parameters roadmap.

The BHA selection is based on the following criteria:

- Stability – The most stable BHA with the lowest axial, lateral and torsional (stick/slip) vibration at all critical BHA components (bit, RSS, MWD).
- Directional capability – The BHA drop/build tendency in rotating mode and the DLS capability needs to satisfy the well trajectory requirement.

As volcanic formations are hard and generally abrasive, IDEAS simulation was done for two scenarios: ‘in gauge’ showing a DLS capability of ~5 deg/30m, and ‘worn out’ with the Xceed lower stabilizer worn out to 17 1/8” and a DLS capability that dropped to an average of ~2.5 deg /30m (see Figures 4 and 5).

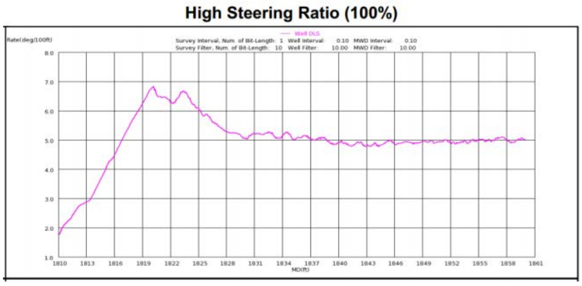

Figure 4 DLS simulation with normal in gauge stabilizer

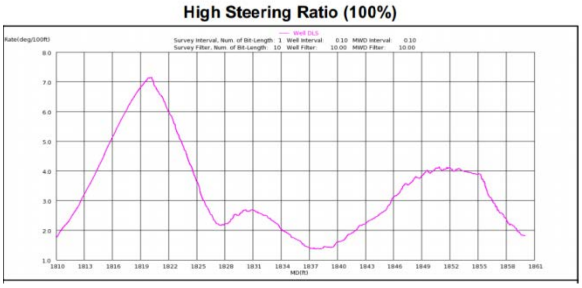

Figure 5 DLS simulation with worn out stabilizer

From the directional analysis, it was found that a worn out lower stabilizer can reduce the directional capability, and therefore two distinct IDEAS simulations were done: one with both top and bottom stabilizer in gauge and the other with a worn out bottom stabilizer. The results are summarized in Table 1 where 100% SR represents continuous steering.

Scenario	Parameter	30 klbs WOB / 100 RPM	
		100% SR	50% SR
Scenario-A BHA-2a	Well DLS (deg/100ft)	4.9 - 5	3 - 3.2
	Well Build Rate (deg/100ft)	4.9 - 5	3 - 3.2
	Well Walk Rate (deg/100ft)	0 - 0.2	(-) 0.75 - (-) 0.5
Scenario-B BHA-2b	Well DLS (deg/100ft)	1 - 4	2 - 2.8
	Well Build Rate (deg/100ft)	1 - 4	2 - 2.8
	Well Walk Rate (deg/100ft)	(-) 1.5 - 0.4	(-) 0.5 - 0

Table 1 BHA DLS simulations for two scenarios

Drilling parameters are very important with respect to drill-string stability: applying a certain WOB and RPM combination can trigger a drill-string resonance which causes vibration, and it might harm the integrity of the down-hole tools, leading to failures. Therefore, a stable parameters road map has to be created along with a stable BHA design. Figure 6 shows an example of such a road map with stable drilling parameters highlighted in the ‘light green’ zone.

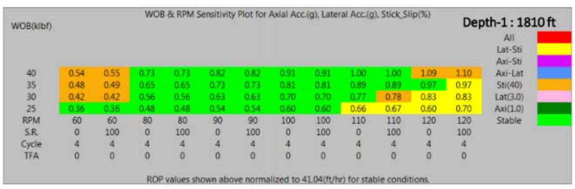

Figure 6 Road map for stable BHA design

1.3 RSS Steering Mode

The experience with this geothermal field shows that the MWD surveys recorded were out of FAC (Field Acceptance Criteria) from the top section until well TD. This is due to the ferrous materials in the volcanic formations, also observed in other geothermal projects in Indonesia. A Software called DMAG (Drill String Magnetic Correction, used to correct for magnetic interference) was able to partially correct the surveys. However, to account for the high magnetic interference typical of the geothermal environment that inevitably will affect the magnetometer, this has been coupled and supplemented with a gyro sensor to minimize deviations from the planned well trajectory.

In general, the gyro sensor will allow the following improvements which are related to magnetic interference:

- Steering ability within the ZOE (Zone of Exclusion).
- Control out of the casing and in the zone close to the casing shoe.
- Control when drilling close to offset wells.

Also such a configuration of the Xceed900 provides RPM sensor redundancy.

Table 2 summarizes the major differences between magnetometer and gyro drilling mode.

In **Magnetometer Drilling Mode**, Xceed uses magnetic field measurements (Hy, Hz and accels) to control its toolface and to navigate well trajectory.

Tool Positions	CRPM	TF
Non-vertical tool position (Incl > 4°)	Hy & Hz	dGTF from MTF and AngleX (Hy & Hz)
Vertical tool position (Incl < 2°) in manual mode	Hy & Hz	MTF (Hy & Hz)
Hold vertical (Incl < 5°)	Hy & Hz	dGTF from MTF and AngleX (Hy & Hz)

The new **Xceed Gyro Drilling Mode** uses y and z axis accelerometers (Gy and Gz) and a rate gyroscope sensor (not a north-seeking gyro sensor) to steer the Xceed tool.

Tool Positions	CRPM Source	TF Source
Non-vertical tool position (Incl > 4°)	Gyro	rGTF (Gy & Gz)
Vertical tool position (Incl < 2°) in manual mode	Gyro	MTF (Hy & Hz)
Hold vertical (Incl < 5°)	Gyro	dGTF from MTF and AngleX (Hy & Hz)

Table 2 RSS steering mode – Gyro and Magnetometer

1.4 Surveying Strategy

RSS Xceed900 uses a system called "downlink" to communicate with the tool by making a variation in flow rate (high flow and low flow). This is the same downlink system of the standard Xceed, and the only difference is that in the RSS version, the tool uses a Gyro sensor board.

There are two main downlink (DL) types based on the amount of time needed for sending the command to the tool: 18 and 60 seconds. For the former type, the total time for the measurement cycle is 5:06 minutes, meanwhile for the latter, the total time required is 13:30 minutes. DL can be done while on-bottom or off-bottom and as such, it will not hinder the drilling operations.

In case aerated mud is used, DL to the tool can still be done as long as the flow mixture between mud and air (Qmix) is within the tool specification (600-1200 GPM) and it is possible to adjust the flow rate (low/high flow). Figure 7 shows the flow rate sensitivity to air concentration.

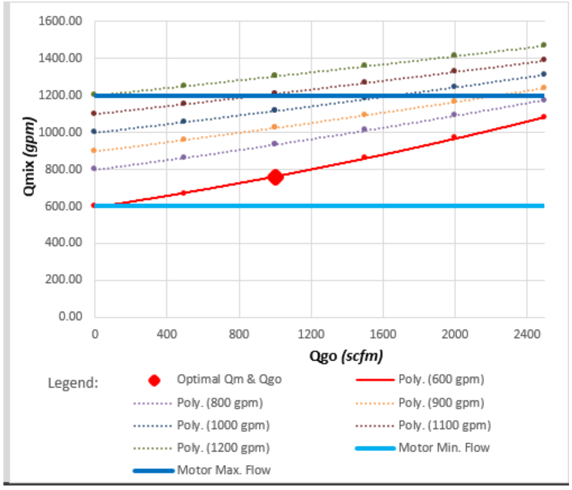

Figure 7 Aerated drilling mixture flow sensitivity

The selection of the MWD system to be used, pointed to the "Telescope" together with the QuikSurvey application that allows continuous pumping while surveying. This permits having real time communication with the RSS Xceed900 and allows the taking of surveys based on the drill-string rotation, without the need to shut off the mud pumps. The benefits of continuous pumping compared to recycling the pumps are illustrated in Figure 8; in general, it takes 3.5 minutes for a survey (as opposed to ~6 minutes when stopping pumping).

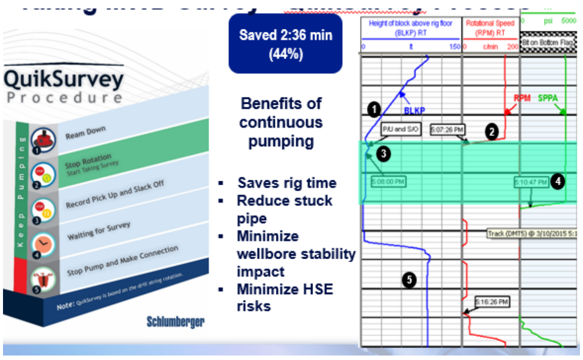

Figure 8 MWD QuikSurvey procedure

In addition to the MWD survey, RSS Xceed900 has the capability to record surveys that are used for steering purposes: this allows the directional control to be based on the information acquired independently by the two tools thus permitting comparison and redundancy (the Xceed survey has higher tolerance on FAC – Htot tolerance 1000 nT, Dip Tolerance 1.7 degree).

2. REAL EXECUTION IN 17-1/2" SECTION

2.1 Main Drilling Challenges

Drilling geothermal wells is technically challenging, because of the frequency of stuck pipe events, which is high both in terms of likelihood and severity, often resulting in fish/junk left in hole and a consequent side-track which is costly as the

Non Productive Time (NPT) associated with it can be substantial.

While drilling, total losses may be encountered that greatly affect hole cleaning efficiency and the actual removal of cuttings leading to stuck pipe events.

Stuck pipe events can also be associated with swelling clays and formation breakouts which, however, are often related to severe or total losses.

This is of paramount importance, especially in big hole sections with relatively high inclination as both these features have detrimental effects on hole cleaning.

2.2 Torque and Drag Consideration

The objective of this part of the project was to continue building inclination below the 20” casing shoe until the end of curve, with a maximum inclination of 30 degrees and maintaining a tangent section thereafter. Prior to this step, cement and the shoetrack were drilled out with the same RSS BHA.

Drilling commenced with 1000 gpm, 30-35 klbs WOB, 30-40 RPM at the bit and 120-140 RPM at the drill-string. The total drilled interval was around 600 meters. Steering was 20-30% and delivered DLS 1.5-2.5 deg/30m as required for trajectory control. Meanwhile, BHA DLS capability was 4.5 to 5 deg /30 m with 100% steering ratio.

In terms of steering, both the gyro sensor and the magnetometer were used (switching between them) with positive results as no major difference was observed.

Figures 9 and 10 show the torque and drag simulation together with the actual well results. For the torque and drag simulation, a friction factor of 0.50 was used, based on the field experience (drilling with total losses and aerated mud impacting the drilling parameters). The actual torque and drag values during execution with RSS Xceed900, showed a friction factor between 0.4 - 0.5 with smooth trends, and values consistent with the ones modelled.

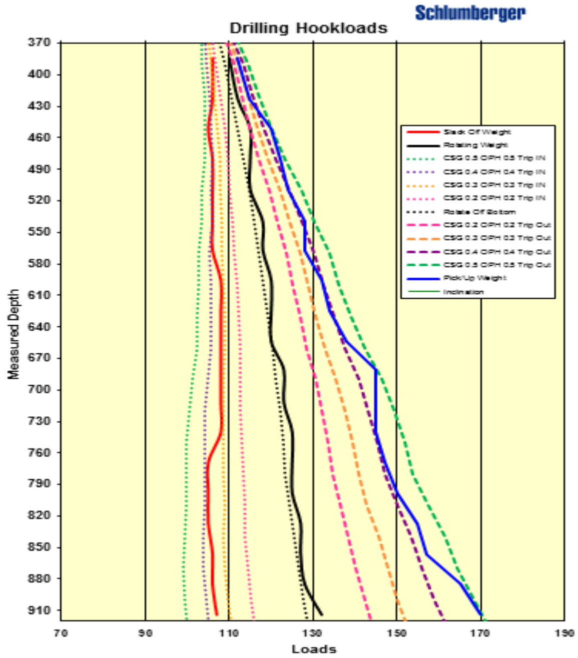

Figure 9 Hookload Broomstick plot

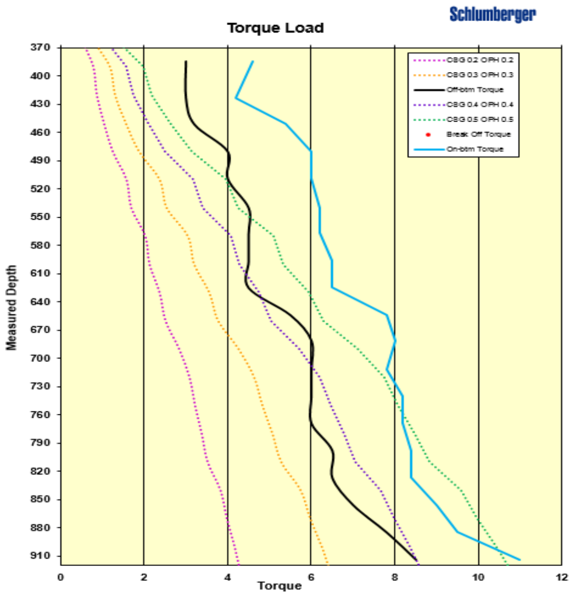

Figure 10 Torque plot

Regarding the borehole tortuosity, RSS Xceed900 produced a smooth borehole in terms of continuous inclination (red curve) as shown in Figure 11. This, in turn, translated to reduced over-steering in formations with walking tendencies and reduced micro dog-legs.

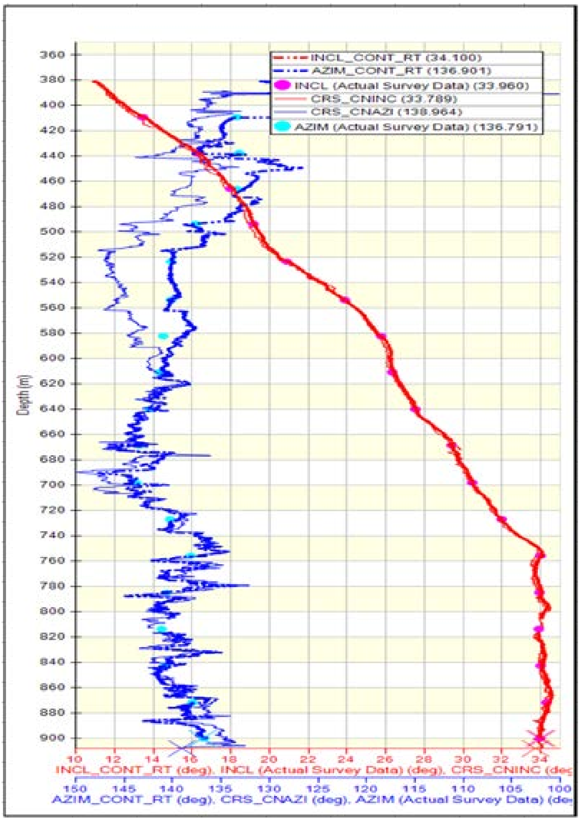

Figure 11 Perform Tool Kit chart of continous inclination and azimuth

2.3 Hydraulics Consideration

Concerning hydraulics, generally in the 17 1/2" directional section with a maximum flow rate of 1,200 gpm, the annular velocity is below the required theoretical value of around 150 ft/min necessary to effectively clean the borehole. Also, from simulations carried out and shown in Tables 3 and 4, the annular velocity is not high enough to carry the drilling cuttings into the annular flow, i.e. is below CTR (Critical Transport Rate).

The use of the RSS Xceed900 allows drill-string rotation aiding hole cleaning, especially relevant in case of total losses. Bit HSI was designed to be above 2 to help preventing bit balling and that proved to be effective while drilling.

Element	String OD in	Ann OD in	Length m	Meas.Depth m	TVD m	Inclination deg	Ann Vel ft/min	Flow Regime	Reynolds Number	CTR gal/min	HCI	Ann Flow gal/min
17 1/2 " (RR1) TCI	8.750	17.500	0.43	914.00	854.25	34.00	115.2464	Laminar	344.0	1455.50	19.69	1080.00
Xceed 900 17 3/8" Stabilizers	9.000	17.500	8.50	913.57	853.89	34.00	117.5168	Laminar	353.8	1503.10	20.08	1080.00
MWD TeleScope	8.250	17.500	8.41	905.07	846.84	34.00	111.1337	Laminar	326.6	1354.99	20.17	1080.00
8 1/4" NMDC	8.125	17.500	9.21	896.66	839.87	34.00	110.1868	Laminar	322.6	1329.11	20.26	1080.00
7 x 8" Spiral DC	8.000	17.500	31.69	887.45	832.24	34.00	109.2700	Laminar	318.8	1303.04	20.26	1080.00
7 x 8" Spiral DC	8.000	17.500	31.69	855.76	805.96	34.00	109.2700	Laminar	318.8	1303.04	20.26	1080.00
8" Hydraulic Jar	8.000	17.500	9.77	824.07	779.69	34.00	109.2700	Laminar	318.8	1303.04	20.26	1080.00
4 x 8" Spiral DC	8.000	17.500	35.49	814.30	771.59	34.00	109.2700	Laminar	318.8	1303.04	21.22	1080.00
XO-6 5/8" Reg x 4 1/2" IF	6.375	17.500	1.29	778.81	742.17	34.00	99.6601	Laminar	280.0	977.44	21.22	1080.00
3 x 6 3/4" Spiral DC	6.750	17.500	27.68	777.52	741.10	34.00	101.5417	Laminar	287.4	1046.80	21.75	1080.00
6 x 5" HWDP	5.000	17.500	55.87	749.84	718.15	33.99	94.6987	Laminar	259.3	771.50	21.35	1080.00
5" 19.50 DPG, Premium	4.855	17.500	52.33	693.97	670.91	30.54	94.3201	Laminar	257.6	716.23	20.91	1080.00
5" 19.50 DPG, Premium	4.855	17.500	52.33	641.64	625.12	27.30	94.3201	Laminar	257.6	667.29	20.49	1080.00
5" 19.50 DPG, Premium	4.855	17.500	52.33	589.31	577.97	24.07	94.3201	Laminar	257.6	624.24	20.15	1080.00
5" 19.50 DPG, Premium	4.855	17.500	52.33	536.99	529.61	20.83	94.3201	Laminar	257.6	580.46	19.86	1080.00
5" 19.50 DPG, Premium	4.855	17.500	52.33	484.66	480.20	17.60	94.3201	Laminar	257.6	535.08	19.58	1080.00
5" 19.50 DPG, Premium	4.855	17.500	52.33	432.33	429.90	14.36	94.3201	Laminar	257.6	488.95	19.35	1080.00
5" 19.50 DPG, Premium	4.855	18.750	54.29	380.00	378.87	11.13	81.2084	Laminar	199.9	439.27	19.12	1080.00
5" 19.50 DPG, Premium	4.855	18.750	54.29	325.71	325.33	7.77	81.2084	Laminar	199.9	382.09	18.98	1080.00
5" 19.50 DPG, Premium	4.855	18.750	54.29	271.43	271.36	4.42	81.2084	Laminar	199.9	320.05	18.90	1080.00
5" 19.50 DPG, Premium	4.855	18.750	54.29	217.14	217.14	1.06	81.2084	Laminar	199.9	252.08	18.87	1080.00
5" 19.50 DPG, Premium	4.855	18.750	54.29	162.86	162.86	0.00	81.2084	Laminar	199.9	252.08	18.87	1080.00
5" 19.50 DPG, Premium	4.855	18.750	54.29	108.57	108.57	0.00	81.2084	Laminar	199.9	252.08	18.87	1080.00
5" 19.50 DPG, Premium	4.855	18.750	54.29	54.29	54.29	0.00	81.2084	Laminar	199.9	252.08	18.87	1080.00

Table 3 Hydraulics Summary

Parameter	Bit
Nozzle Flowrate: gal/min	**1080.0**
Nozzle Pressure Drop: psi	**1024.6**
Jet Velocity: m/s	**112.1**
Jet Imp.Force: lbf	**1853.6**
Hydraulic Power: hhp	**646.1**
HSI: hp/in2	**2.7**

Table 4 Hydraulics at the bit

Again in terms of hole cleaning, an easy rule of thumb that gives a feel of how far the top of the pipe is from the top of the hole, is the Pipe-Hole Area Ratio. For P-HAR > 3.25, 'Big hole' rule applies; for P-HAR < 3.25, 'Small hole' rule applies.

In this particular RSS Xceed900 application, 17 1/2" hole section (Rh) and 5" drillpipe (Rp), the P-HAR is following the 'Big hole' rule, as per the calculation below:

$$\text{P-HAR} = R_h^2 \div R_p^2$$

> **3.25** = **"Big Hole" Rules**
< **3.25** = **"Small Hole" Rules**

P-HAR = 17.52/52 = 12.25 (>3.25 – Big Hole rule)

- **Rotary Speed**
  - P-HAR > 6.50 – >120 minimum, 180 rpm ideal
  - P-HAR 3.25 – 6.50 – >120 rpm minimum
  - P-HAR < 3.25 – 60-70 rpm minimum, 120 rpm ideal
- **Annular Velocity**
  - 200 ft/min (1.00 m/sec) – **Ideal**
  - 150 ft/min (0.75 m/sec) – **Minimum** (for *efficient* hole cleaning)
  - 100 ft/min (0.50 m/sec) – **Poor Cleaning + Barite Sag Problems**

In this case, a minimum of 120 RPM is required for good hole cleaning and this is provided by the RSS Xceed900 overcoming the limitations of the mud motors used in previous wells (50 RPM in the curve section and 100 RPM in the tangent section). Also, the RPM capability of RSS Xceed900 enables it to operate at the higher end RPM of the Big hole P-HAR ratio rule and in this case the top drive speed capabilities is the limiting factor.

The RSS Xceed900 stabilizers were 17 3/8” for both the upper and the lower one and although hard Andesite was drilled, they came out of hole in gauge as opposed to previous runs where the mud motor had experienced worn out sleeve stabilizers.

While drilling, as can be seen in Figures 12 and 13, the parameters were relatively smooth with WOB 20-30 Klbs, surface torque 5-9 kftlbs, flow rate 900-1100 gpm, RPM 100-120. The curve section was drilled without any major issues in terms of hole cleaning and torque and drag.

Also, this allowed minimizing the working of the pipe after each stand drilled and back-reaming operations, with consequent time savings together with Hi-Vis pills optimization.

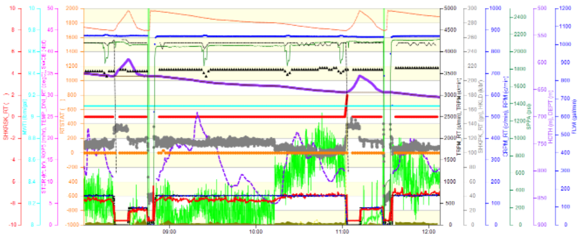

Figure 12 Real time drilling parameter snapshot -1

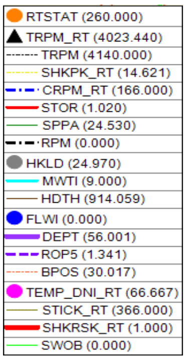

Figure 13 Real time drilling parameter snapshot -2

Looking at the drilling performance in Figures 14 and 15, well-B drilled with a mud motor, was the fastest in terms of ROP at 7.59 m/hr. However this well did not experience total losses nor was andesite present, which can reduce the ROP to as low as 1 m/h.

RSS Xceed900 was run in Well-D and successfully accomplished all its objectives while enhancing performance: the average on-bottom ROP improved by 15% with a total meterage of 600 meters.

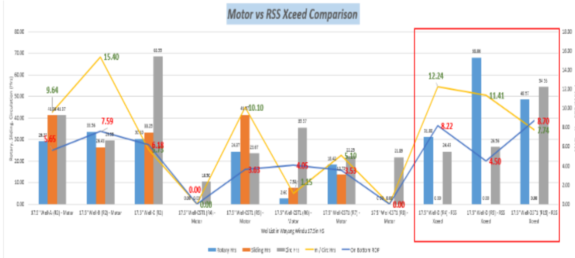

Figure 14 Drilling performance chart -1

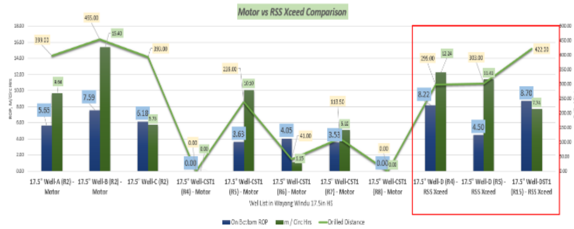

Figure 15 Drilling performance chart -2

2. CONCLUSION

The RSS Xceed900 drilled successfully the 17 1/2” hole section achieving all the planned objectives and introducing a number of performance improvements compared to previous conventional mud motor BHA runs.

The actual field results can be summarized as follow:

- Higher on bottom ROP (15%).
- Optimization of parameters for hole cleaning - RPM 100-140, flow rate 900-1100 gpm.
- Minimization of back-reaming.
- Optimization of Hi-Vis pills usage.
- Smoother T&D trend (including micro dog-leg avoidance) thus it will be easier to run the liner.
- Implemented surveying strategy and QuikSurvey application.
- Since the RSS is fully rotating, the touching point on the stabilizer is evenly distributed, thus there is no significant damage / wear on the stabilizer. With motors it is a known issue that the stabilizer easily gets worn out; when a thick andesite lava formation is encountered at the low side part and causes the DLS to drop.
- Even though the presence of iron oxide causes magnetic interference at the top section, the RSS magnetometer was still able to steer. As part of mitigation, Gyro Sensor steering is also built into the tool.
- Note that since the tool is more advanced compared to a conventional mud motor, LIH (Lost in Hole) risk / cost needs to be considered in advance.

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NOMENCLATURE

BHA : Bottom Hole Assembly

DOX : Drilling Office X

DLS : Dogleg Severity

DPMOP : Drill Pipe Margin of Overpull

ECD : Equivalent Circulating Density

EOU : Ellipsoid of Uncertainty

FAC : Field Acceptance Criteria

FEA : Finite Element Analysis

GT : Greater Torque

GLR : Gas Liquid Ratio

GPM : Gallon per Minute

HF : Hard Facing

ID : Inner Diameter

IDS : Integrated Drilling Services

JMOP : Jar Margin of Overpull

MW : Mega Watt

MWD : Measurement While Drilling

OD : Outer Diameter

OSF : Oriented Separation Factor

ROP : Rate of Penetration

RPM : Revolutions Per Minute

SCFM : Standard Cubic Feet minute

SRPM : Surface RPM

TC : Travelling Cylinder

TCF : Thermal Calibration Factor

TCI : Tungsten Carbide Inserts

TLC : Total Lost Circulation

TS : Tuffaceous Siltstone

TD : Total Depth

UCMPS : Unconfined Compressive Strength

Q-Mix : Flow Rate Mixture

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