Overcoming Drilling Challenges With Rotary Steerable Technology in Deep Geothermal Wells in the Molasse Basin of Southern Germany

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ABSTRACT

Several geothermal wells have been drilled successfully in the Southern German Molasse Basin within the last years. Some of them have reached depths of 4500 m with a horizontal displacement of up to 3000 m. However, as the wellpaths have become deeper and more complex, drilling has emerged as extremely challenging and cost-intensive, which can be critical for geothermal projects due to the high cost pressure.

Usually conventional steerable motor systems were used to drill directionally, but the drilling performance was not sufficient. Penetration rates while sliding were typically 50-60% less than those obtained when rotating. Lower than the optimum weight on bit (WOB) was often applied to maintain direction. Poor weight transition, motor stall outs, high bit wear and low penetration rates were getting progressively worse with depth. In addition, weak drilling performance could have been a major factor for severe tectonic breakout in time-sensitive shales causing over gauge hole, stuck pipe and inadequate cementation.

In order to avoid these problems, rotary steerable systems (RSS) have been deployed in two recently drilled wells. The result was a step change in well delivery time and reduced drilling cost. Moreover, no borehole stability problems have been encountered since drilling with RSS. This paper presents a case study demonstrating that the change from conventional systems to RSS has been both, technically and commercially successful.

Introduction

Erdwerk GmbH is an independent planning office in the field of geology and drilling engineering for the development and implementation of geothermal projects. Between the years 2002 and 2011 Erdwerk GmbH planned and supervised 16 wells in the vicinity of Munich in close cooperation with the client, the drilling contractor and the service contractors. The wells are drilled into the karstified dolomites and limestone of the Upper Jurrassic which form the most productive thermal aquifer in the Southern German Molasse Basin. Depending on temperature and production rates, the thermal energy is used for power generation coupled with heating or, in case of lower temperatures, for heating only. Temperatures between 80 - 140°C and production rates beyond 7000 m³/day are common.

The wells are typically 2500 to 4500 m deep and are divided in 4 sections of different bit diameters. It can be distinguished between two categories: (CAT 1), where the first section begins with 17.1/2" followed with 12.1/4", 8.5" and 6.1/8" bit diameter; and (CAT 2), where the first section begins with 23" followed by 17.1/2", 12.1/4" and 8.5" bit diameter. The first 3 sections are cased and cemented. The reservoir section–although the formations are

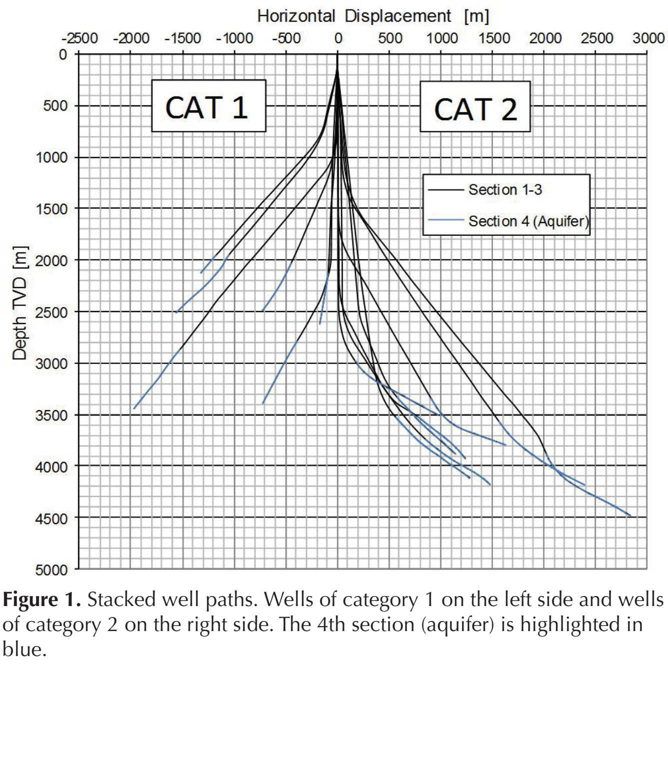

Figure 1. Stacked well paths. Wells of category 1 on the left side and wells of category 2 on the right side. The 4th section (aquifer) is highlighted in blue.

generally competent–is completed with a pre-holed liner which assures wellbore stability, whilst allowing high flow-rates without too much pressure losses.

The well paths are always deviated due to following reasons:

- (a) the optimal target position highly depends on facies type and the degree of faulting and therefore might be far off the well site, whose location is also constrained by several factors.
- (b) the producer and the injector need to have a certain distance between one another to avoid a hydraulic short circuit.
- And (c) the inclination of the well should be high in the aquifer to optimize the productivity.

Figure 1 shows the well paths stacked together at one starting point. Wells of Category 1 are on the left and wells of category 2 are on the right. The 4th section (aquifer) is highlighted in blue.

Traditionally, conventional steerable systems with a downhole motor and bend sub have been used for directional control. The results have not always been satisfactory, but alternatives such as rotary steerable tools were not considered to be economical due to their high price. Consequently they could not enter the geothermal drilling market in Germany for a long time, although the benefits were well publicized at the time.

However, as the well paths have become deeper and more complex, conventional directional drilling has emerged as too inefficient and cost-intensive. Therefore, in 2009 the first rotary steerable assembly was applied to address the steering problems. It successfully drilled the last two sections (build-up and tangent) in a 4500 m deep CAT 2 well. The performance improvement was remarkable and besides the technical advantages the economic success was outstanding as well. Consequently, in 2011 the system was applied in a second well (CAT 2) which finally became, by far, "best-in-class".

Working Principle of Conventional Directional Drilling

Conventional steerable systems use downhole motors which are placed close to the drill bit. They work according to the Moineau principle and are driven by the drilling mud. A bend is included at the motor bearing housing, which deflects the bit axis at a certain angle relative to the borehole centerline. The steering process is divided into intervals of "sliding" and "rotating".

In sliding-mode the direction of the bend sub, the so called toolface angle, is oriented after which the drill pipe is locked from further rotation. The bit rotation is now only derived by the downhole motor driven by the hydraulic power of the mud flow. Due to the constant orientation of the bend the assembly drills a curve.

In the rotary-mode the drill pipe is rotated at a constant speed. The bend on the downhole motor now changes its direction continuously and the assembly drills straight. This alternation of sliding and rotating leads to the desired buildup rate. Although this process is conceptually very simple, it can often be difficult and inefficient to implement, especially when wellbore trajectories are complex.

Experienced Problems with Conventional Steerable Systems

Decreased ROP While Sliding

The main disadvantage of drilling with steerable motors is that the drilling process includes intermittent intervals of sliding. Drilling performance depends very much on bit rotation speed and the applied weight transferred to the bit. Rotation speed while sliding is reduced by the absence of drill pipe rotation and sufficient weight transfer is often difficult because of the friction of the non-rotating drill string lying on the borehole wall. In addition, often lower than optimum WOB is applied to maintain direction: The toolface orientation is strongly influenced by the reactive torque generated between bit and formation. Therefore, variation of WOB is used to compensate for formation effects whilst keeping the toolface angle constant. Consequently, this does not leave much room for performance optimization.

Another issue which limits the application of optimum WOB is motor stall-out. In sliding-mode it is difficult to advance the drill string smoothly. Consequently, an abrupt downward movement and a sudden increase of WOB, which subsequently increases the torque, cannot be avoided. If the torque exceeds a critical limit the motor will stall. To avoid excessive high torque at the motor, directional drillers often tend to apply a priori lower WOB.

Figure 2 shows an example dataset of a well drilled with a conventional drilling assembly. The blue line depicts the revolutions per minute (RPM) of the drill string. A value of zero indicates the sliding-mode, which is highlighted in red, whereas a value unequal zero indicates the rotary-mode. The black line shows the depth against the drilling time and indicates the ROP: the steeper the line, the higher the ROP. It clearly shows the reduced ROP in sliding-mode (red interval) and the sudden increase of ROP in rotary-mode (white intervals). If the sliding-intervals are interpolated with the neighboring performances of rotary intervals, the time which has been lost while sliding can be estimated. This is indicated by the dashed line. In this example, which is representative for most build-up sections in this depth, the intermittent sliding intervals led to an increase of drilling time of almost 100%.

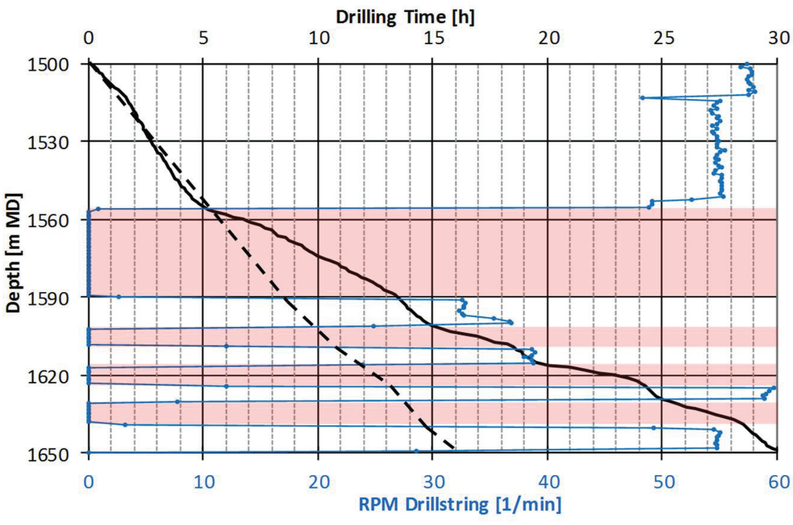

Figure 2. Example of the ROP behavior while "sliding" (red intervals) and "rotating" (white intervals).

Compromises in Bit Selection

The problem of tool face orientation and motor stalls can also be reduced by using less aggressive bits. Thus, roller cone bits have been often preferred for use on steerable motors instead of polycrystalline diamond compact (PDC) bits. Although roller cones have usually a shorter lifetime and most formations can be drilled faster with PDC-bits. Fig. 3 shows a comparison between the ROP achieved with roller-cone bits and with PDCs in the third section of 5 geothermal wells where both bit types have been used. The graph only shows data of intervals drilled in the rotary-mode to eliminate the effects of sliding on ROP. Although ROP depends on many factors and the graph doesn't quantify the exact influence of bit selection, it clearly indicates that ROP is higher with PDCs in these formations.

Human Factor

Drilling operations with conventional systems involve many processes which are typically controlled by the rig driller following verbal instructions of the directional driller. As already mentioned, the reactive torque between bit and the formation has a major influence on the tool face orientation. Variations of weight on bit or formation properties influence the reactive torque, which has to be controlled by the directional driller to maintain orientation. The rig driller and the directional driller have to work together to adjust the tool face and compensate for changes in reactive torque. Consequently the efficiency of the directional drilling process is strongly influenced by their experience and skills.

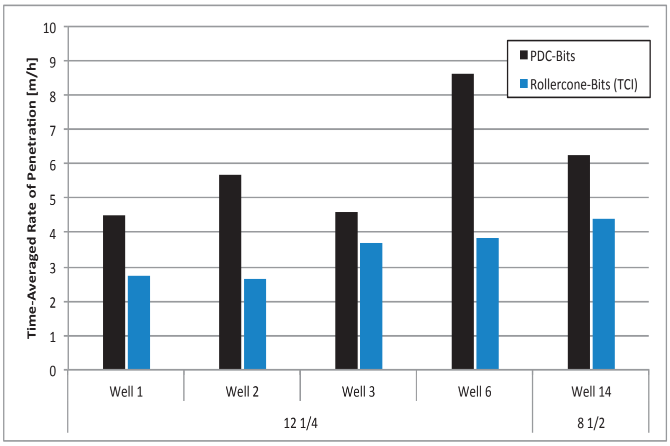

Figure 3. Time-averaged rate of penetration of different bits used in the third section of 5 geothermal wells where both bits have been used in comparable geological sequences.

Overview of RSS Technology

Rotary steerable directional drilling systems do, as the name suggests, allow guidance of the well trajectory while continuously rotating the drill string. Using a sequence of mud pulses, the RSS settings can be changed from the surface. Once configured, the RSS automatically (closed loop feedback) steers with a defined buildup rate in the desired direction or holds the inclination and azimuth in a tangent section.

Modern RSS-Technology was first introduced in the late 1990s. According to their working principles, there is a distinction between different systems. The system we used was a rib steering system. Therefore, other systems will not be discussed any further in this paper. Fig. 4 shows the main components of a rib steering system. Mud-powered pads (steering ribs) are situated close to the bit. The pads do not rotate and are pushed unequally against the wellbore wall to steer the bit in the desired direction (Fig. 5). This section of the tool is also called the steering head. This steering head is connected with a control unit via a non-rotating stabilizer sleeve which contains sensors, control electronics and turbines to generate power from the mud flow. It controls the direction and magnitude of force applied by the actuator pads. Although a downhole motor isn't necessary any more for the purpose of steering, it can be used optionally in combination with RSS to simply increase the rotation speed of the bit.

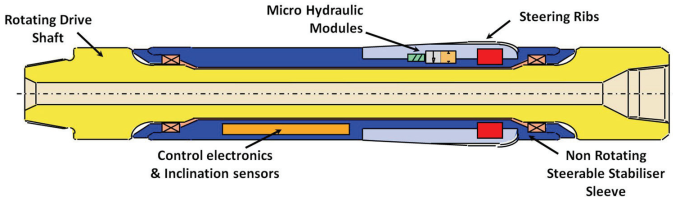

Figure 4. Main components of a RSS push-the-bit system (Source: Baker Hughes).

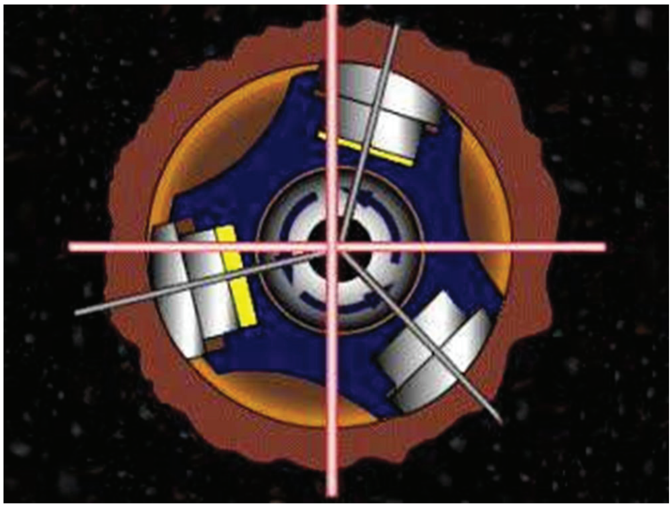

Figure 5. Cross-section through the steering ribs (Source: Baker Hughes).

Case Study: RSS Experience in Geothermal Wells

There are multiple papers which describe the success of rotary steerable applications in different geological provinces: For example South Texas (Akinniranye, 2007), the Persian Gulf (Molayee, 2006), Barmer Basin in India (Peytchev 2010), the Middle East (Pratten, 2003) and many other places. However, rotary steerable systems have proven to deliver a broad range of technical advantages; also in terms of the cost constrained geothermal market in the Southern German Molasse Basin. This case study will show the experience Erdwerk GmbH has made with RSS and will highlight the differences compared to conventional systems.

As already mentioned before, the RSS has been used in the 3rd (12.1/4") and 4th (8.1/2") section of two wells (CAT 2). The system was applied in combination with a downhole motor to increase the rotation speed of the bit.

ROP Improvement

The most significant advantage of the rotary steerable system was the increase in the rate of penetration. Figure 6 shows the relative overall gross ROP for 8 CAT 2 wells drilled between 2007 and 2011 in chronological order. The overall gross ROP include all operations between spud and reaching of final depth. The wells were drilled within a radius of 10 km and the geology is absolutely comparable. Nevertheless, the overall performance variations are enormous: Well 1 and 6 are negative outliers due to major problems with borehole instability in the 12.1/4" section, which will be discussed later in this paper. In Well 4, lost circulation was an issue which was not to be stopped over a long period of time. Finally, in Well 7 and 8 RSS was used which led to the highest overall gross ROP. This graph gives a good impression of the possible impact of a RSS on the overall performance. However, as the system was only applied in the last 2 sections, it does not clearly represent the effective increase of rate of penetration gained with the application of the RSS.

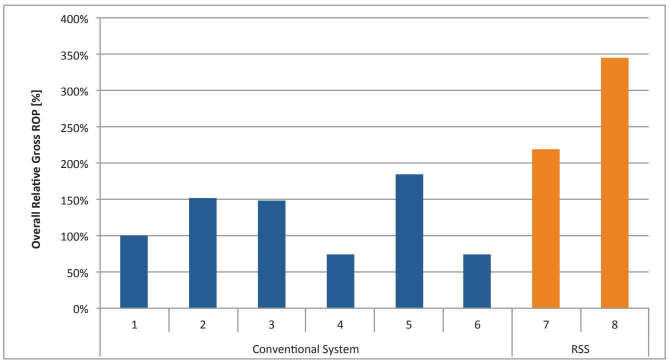

Figure 6. Overall relative gross ROP of 8 wells (CAT 2) in chronological order.

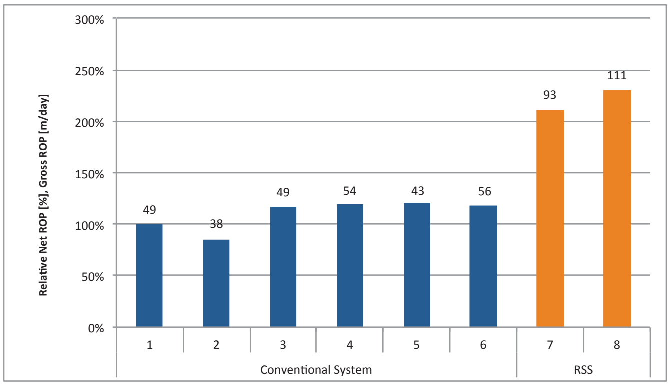

Figure 7. Relative net ROP of the 3rd section (12.1/4" bit diameter) of 8 wells in chronological order. The gross ROP in m/day is given above the bars.

Figure 7 shows the relative net ROP of the 3rd section (12.1/4" bit diameter) of the same 8 wells in chronological order. The net ROP includes only drilling without any other operations. It clearly shows that the drilling performance was relatively constant until RSS was applied (Well 7 and 8). The net ROP achieved with RSS (orange bars) was approximately 145% higher compared to conventional systems (blue bars). This is even higher than the value which was derived from the estimation in Fig. 2. However, for a following economic evaluation the gross ROP of the section is relevant, which is given above the bars in meters per day. The average gross ROP with a conventional system in this section was 48 m/day compared to 102 m/day with RSS. The decrease in time for non-drilling operations is caused by fewer check trips due to better borehole quality, no flat time for adjusting the tool face and fewer trips for changing the drill bit. The result in the 4th section was similar: The average gross ROP increased from 60 m/day to 105 m/day.

Risk Reduction of Potential Wellbore Stabilities in Time Sensitive Shales

As mentioned above, borehole instabilities have been a major problem in two wells. Stuck pipe, fishing operations and sidetracks have led to enormous delays and costs. Furthermore, as a consequence of severe over-gauged hole, cementation hasn't always been sufficient along the whole section, which can be critical in geothermal wells: If a water pocket in the annulus is heated up during production, the pressure will increase dramatically. Exceeding the collapse strength of the casing will then lead to failure.

The causes for the wellbore stabilities are not fully understood yet and measures like increasing the mud weight or changing the mud properties have not been successful in the past. However, the time-sensitiveness of this critical formation is well-known. Fig. 8 shows two caliper measurements at different times in the same well. One measurement was taken after 19 days open hole (blue line) and another after 36 days open hole (red line). The breakouts were already severe after 19 days and the wireline logging tool stood up at approximately 4175 m MD before the final depth could be reached. The second log after 36 days showed a significant

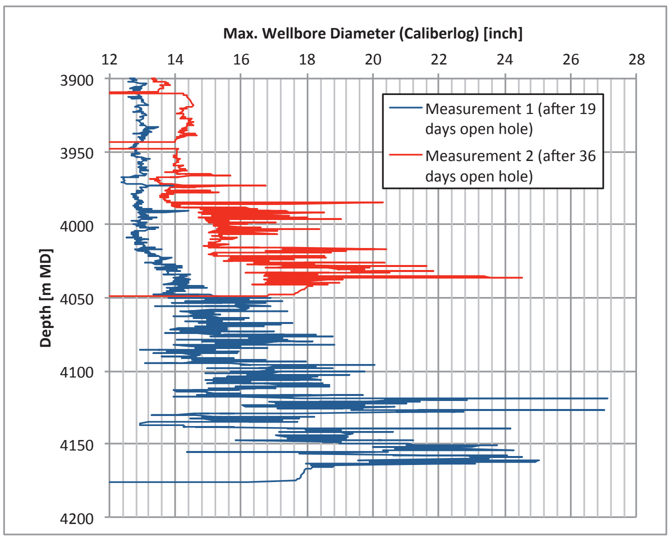

Figure 8. Maximum Wellbore Diameter vs. depth, measured at two different times (19 days and 36 days open hole).

increase in wellbore diameter and this time the tool became stuck even earlier at approximately 4040 m MD. The diameter of the wellbore at this point was approximately 18 inches compared to 13 inches in the first run (Bit diameter: 12.1/4”).

Consequently, minimizing open-hole time is most important in this section to reduce the risk of potential wellbore instabilities. Considering the ROP improvement with RSS it would be recommendable to apply this tool to avoid such problems. In the two wells drilled using RSS, no wellbore instability problems have been encountered.

Economic Evaluation

Besides the technical aspects, an economic analysis is most important to assess the value of a RSS application. Table 1 shows an economic comparison between a conventional steering system and the RSS for the 3rd section of well 8. As the absolute values are not to be published, they are given relative to the rig day rate X. The directional service costs depend on the directional drilling system and the difference is immense. The RSS assembly cost about 1.06 X/day compared to 0.38 X/day, which a conventional system would cost. Therefore, using the RSS, the total day rate increased from 1.38 X to 2.06 X by 49%.

However, as the offset data showed, the gross ROP for this section can be increased by 112% from 48 m/day to 102 m/day. Consequently it would have taken 23 days to drill the 1100 m long section with a conventional system, which would have led to approximately 31.6 X in total (time-dependent cost). Using RSS it took 11 days and the costs were 22.2 X. The saving achieved in this section was 9.41 X, which is a reduction of time dependent costs of approximately 30%.

	Conventional Steering System	**RSS with downhole motor**	
Dayrate (Rig, Mud Logging, Mud Engineering)	X	X	€/day
Directional Service	0.38 X	1.06 X	€/day
Total Dayrate	**1.38 X**	**2.06 X**	**€/day**
Section Length	1,100	1,100	m
Gross ROP	48	102	m/day
Days to Drill	23	11	days
Total Cost	**31.63 X**	**22.22 X**	**€**
Saving		**9.41 X**	**€**

Table 1. Economic evaluation of RSS application in the 3rd section.

Conclusions

This paper highlighted the most important aspects of the change from conventional steerable systems to RSS in the cost constrained geothermal market of the Southern German Molasse Basin. In recent years, drilling with conventional directional systems was, insufficient and cost-intensive, especially in deeper sections. Because of the intermittent sliding intervals, the ROP was reduced by 50% in build-up sections. Frequently, roller cone bits were preferred instead of PDCs for steering, although their performance is weaker. Additionally, the efficiency of the overall directional drilling process was strongly influenced by the experience and skills of the directional driller and the rig driller.

With the change to RSS, the net ROP as well as the gross ROP doubled in the 3rd and 4th section. The impact in the overall well delivery time was remarkable. The risk of wellbore instabilities in time-sensitive shales was reduced and no major troubles were faced. An economic evaluation has shown that the time-dependent section costs decreased by 30%. The application was a technical and economic success.

Nomenclature

RSS	Rotary Steerable System
ROP	Rate of Penetration
PDC	Polycrystalline Diamond Compact
WOB	Weight on Bit
BHA	Bottom Hole Assembly
RPM	Revolutions per Minute
DLS	Dog-Leg Severity
MWD	Measurement While Drilling
MD	Measured Depth
TVD	True Vertical Depth

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