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

Automated Geothermal Drilling with NOVOS

Kjartan Thor Birgisson, Khim Chhantyal, Akash Padir and Stephen Pink*

10000 Richmond Avenue, Houston, Tx, United States

kjartan.birgisson@nov.com, khim.chhantyal@nov.com, akash.padir@nov.com

*Correspondence: stephen.pink@nov.com

Keywords: Geothermal Drilling, Automatic Drilling, Autonomous Drilling, Stuck Pipe, Making Connections, W2W, Friction Tests

ABSTRACT

Geothermal environments are some of the harshest conditions known in the drilling industry. High temperature, naturally fractured formations, low-pressure zones, and corrosive environments are some of the challenges the geothermal drilling industry faces. Stuck pipe is one of the most frequently stated problem within geothermal literature. Research within Oil and Gas (O&G) industry has underlined the human factor involved in getting stuck. National Oilwell Varco (NOV) has developed an Automatic Drilling System, NOVOS that with its 4 series release, is now capable of Autonomous Drilling. NOVOS operates the drilling machinery and maintains well limitations, thus transferring the driller from an operator to a supervisor of the process. This enables the driller with the ability to monitor important drilling parameters in detail and minimizes the potential for human errors. NOVOS increases the consistency and efficiency of making connections across drilling crews and drilling rigs, thus reducing the risk of getting differentially stuck or running into pack-off situations due to improper hole cleaning. NOVOS is also capable of performing standard drilling processes such as friction tests in the most consistent manner, providing the driller with accurate readings required to determine the hole cleaning efficiency. NOVOS has been successfully implemented on nearly 100 O&G installations globally and with the experience gained so far, is now ready for the harsh conditions of geothermal drilling.

1. INTRODUCTION

1.1 NOVOS Process Controller

An Automatic Drilling System is a process controller that as minimum, is capable of drilling a stand by simultaneously controlling all applicable drilling machinery while maintaining both machine and wellbore limits. The system in its own is not smart and requires input from a driller for both drilling parameters and drilling limits. When such a system provides a platform for expert wellbore process control software to dynamically take control of those drilling parameters and limits as well as automatically detect and mitigate events such as pack-off, the whole system can be referred to as Autonomous Drilling System. For this purpose, National Oilwell Varco Operating System (NOVOS) was developed.

NOVOS is a software platform that transforms a standard drilling rig into an automated drilling rig. The software enables the driller to complete many common repetitive drilling procedures, automatically, with little to no direct interaction with the rig control system itself. As expected with any automation system, NOVOS exhibits far superior performance when compared to humans at executing repetitive tasks. With NOVOS in control, the process happens in an identical manner with minimal variance until such time as a change is needed and the process controller is updated with the required changes. Since the driller is no longer required to manipulate joysticks, press buttons, or interact with HMI screens to drill ahead, the drillers attention then can be placed on more operationally critical matters such as safety and wellbore condition, personnel, planning, and resource management. As drillers become conversant with the system and its response to the drilling environment, they can easily tune the system to improve the process making the process safer and or more efficient.

NOVOS comes as equipped with interface and applications for controlling processes such as drilling, reaming, friction tests, etc. However, its full potential is realized when its combined with advanced control functions for drilling optimization by means of applications. Some of the examples are as follows: Stick and slip mitigation, surge and swab protections, autonomous drilling optimization apps such as NOV’s Kaizen and other automatic systems such as Managed Pressure Drilling (MPD) and automated pipehandling. These innovative and intuitive functions can deliver to next level by integrating and utilizing real-time downhole data. NOVOS can be interfaced with NOV’s wired drill pipe, a real time downhole telemetry system.

In addition to its core functionality the system allows for third party control of the drilling process using applications. The NOVOS application interface is standardized and is an open platform where developers can write applications to control drilling parameters independent of control system platform. Thus, allowing any service company, operator or contractor to impart their specific process to any rig in the world that has NOVOS. The use of applications is standard across NOVOS installations, so users will interact with the application in NOVOS the same way, regardless of the type of rig. So, a rig operating in remote parts of Iceland would have the same look and feel as rigs drilling in the East African rift. If you use equations, define all symbols, either after the equation, or in a Nomenclature section at the end of the paper.

1.2 Geothermal Drilling and Stuck Pipe

Geothermal wells often drill through igneous and metamorphic rocks compared to the sedimentary formation in O&G. In general, geothermal reservoirs are under-pressured and prone to loss circulation causing differential sticking, making it challenging during tripping, casing, and cementing. In addition, a high bottom hole temperature of up to 400 °C makes it further challenging to drill. Thereby geothermal well drilling can cost up to 30% to 70% of the overall project cost (Finger and Blankenship 2012; Saleh et al.

2020). A comparative study by Denninger et al. (2015) shows a geothermal well drilled to a depth of 8,065 feet in 58 days, whereas it took only 11 days to drill 13,250 feet for an O&G well. The study shows roughly 13.9 million dollars was spent on non-productive time (NPT) in geothermal wells compared to 1.3 million dollars spent on O&G wells. The fluid loss, stuck pipe, and time required to mitigate these problems are major causes of NPT while drilling. This study will focus on issues related to the stuck pipe.

In a drilling process, a stuck pipe is a state when a drill pipe (string or casing) cannot be pulled out or moved forward in a wellbore with the designed working load (Oketch 2014). Broadly, there are two mechanisms for stuck pipe: differential sticking and mechanical sticking. Due to a pressure gradient existing to maintain bore hole stability and minimize hoop stresses, the higher-pressure drilling fluid applies a hydraulic pressure against the borehole. In geothermal wells which are typically in areas of tectonic movement, significant in situ fracturing can occur. This can lead to very high levels of permeability which change suddenly, leading to a sudden increase in overbalance and the pipe being hydraulically pulled on to the wall. This is the typical differential sticking method observed in geothermal applications. Abnormal permeability and low in situ formation pressures can elevate the risk of differential sticking under normal drilling conditions (Dupriest 2011). A high permeable formation will result in a high rate of pressure drop in the mud cake and can cause differential sticking. The primary reason for mechanical sticking is hole pack off, which can occur due to loss of well balance or change in stress regime, settled cuttings, avalanching, shale instability, fractured rocks, and cement collapse in drilling shoe track and rat hole (Oketch 2014). The wellbore geometry and formation types issues like key seating, mobile formations, under-gauge hole, tight hole, micro doglegs, and ledges can also lead to mechanical sticking (Oketch 2014). The formation permeability affects the rate of differential pressure decline (Dupriest 2011).

In O&G drilling, the stuck pipe resulted mainly due to differential sticking (25%), hole pack off (42%), and jammed pipe (20%) (Skalle et al. 1998). The stuck pipe occurred during steady drilling operations (14%), during tripping/reaming (56%), and during the drill string at stationary (30%) (Skalle et al. 1998). In addition, the study presented that 36% of the stuck pipe is related to crew change. The numbers (in percentage) on the causes and events of the stuck pipe are from 1998 and does not fully valid for today's O&G drillings. However, the numbers can be referenced in geothermal drilling as the overall drilling process is more than two decades behind the O&G drilling. There has been steady development with the new automated technologies introduced to the petroleum drillings (Nygaard et al. 2010). The geothermal drillings have the privilege to acquire these technologies from O&G drillings.

In some of the recent studies, (Chmela et al. 2014; Abrahamsen et al. 2015) demonstrates how an automatic repetitive sequence (for example, friction test and pump start-ups) can be consistent, faster, and safer. This leads to a reduction in invisible lost time and saving up to 10% rig time per well. The study also claims to detect pack-off well ahead in time before a driller takes action (7 minutes before, as highlighted in (Bergerud 2016)). These automatic sequences can reduce the connection time and help to reduce the probability of the stuck pipe.

2. METHODS

2.1 Making Connections

In the last two decades, automatic data logging and analyzing tools have evolved to allow for an unbiased real-time evaluation of the drilling process (Andersen 2009). The offshore drilling industry has been leading in utilizing these tools for the continuous improvement of its processes. One such process is making connections. There are several reasons why making a connection has such a high focus within offshore drilling. The inconsistencies in drilling a well are many and make for a difficult comparison between the performance of different drilling crews. However, this is not true for making connections. If well conditioning and other activities are not included in the comparison, then monitoring making connections can provide a good indication of how well the drilling crew is doing. More importantly, minimizing the time it takes to make a connection saves money. Not only in the minutes saved during each connection, but by minimizing the time spent with the drill bit stationary and drilling fluid flow off. Therefore, not allowing the mud cake additional time to drop in pressure and cuttings to collect on the BHA. Ultimately, reducing the risk of getting stuck (Equinor 2018).

The Key Performance Indicator (KPI) used for making connections is called Weight to Weight (W2W) and represents the time from when the string is lifted off bottom until the bit is on bottom again. W2W consists of three smaller segments, also referred to as KPIs, these are:

- Bottom to Slips (B2S) the time from when the string is lifted off bottom until weight has been set in slips
- Slips to Slips (S2S) the time from when weight has been set in slips until the weight has been taken off slips
- Slips to Bottom (S2B) the time from when weight has been taken off slips until the bit is on bottom drilling again

It is important to understand that the automatic/autonomous drilling system does not take care of pipe handling. An autonomous drilling system is given control as soon as a new stand has been added to the zone. The system starts by spinning in and making up the connection, take weight of slips, gel break, ramp up and as soon as a survey has been completed, tag bottom and drill the stand. As the elevator reaches the drill down stop position, the system lifts the bit off bottom, ramps down flow and rotation, and sets weight into slips before breaking up and spinning out. The system then gives control back to the driller or an automatic pipe handling system. The system does all this, in the most efficient and consistent manner, between rigs and drilling crews. This makes any unnecessary inconsistencies within W2W solely dependent on the pipe handling. Figure 1 below shows the most basic W2W, as used for comparison in the O&G.

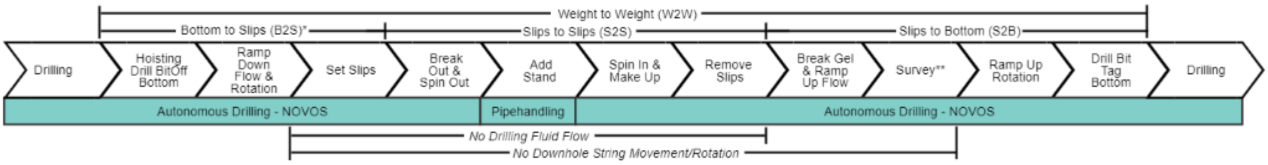

Figure 1: Comparable W2W. *Friction Test, Reaming and Off Bottom Hole Cleaning (not shown on figure) during B2S should be subtracted from W2W for better comparisons. **Special Surveys should be subtracted from W2W.

2.2 Friction Tests

Friction tests are required to create and evaluate torque and drag roadmaps. These roadmaps provide the driller with the evolution of friction in the well. Any deviation from the roadmaps should be taken seriously as they can be an indication of changes in hole cleaning efficiency (Equinor 2018). Friction tests are performed in a frequency based on hole requirements at the end of a stand as demonstrated on Figure 2, or if included in W2W KPI, at the middle of a stand as demonstrated on Figure 3. No matter when in the process a friction test is done, it is important the test is done in the most consistent manner, as readings are dependent on block speed, rotation and flow. Inconsistency in test processes can result in readings outside predicted values within the torque and drag roadmap, which can lead to either less efficient drilling, or increased risk of getting stuck (Equinor 2018).

Friction tests can be performed in a few different ways, however the goal is to obtain the following values: free rotating weight, pick-up weight while hoisting and slack-down weight while lowering. Figures 2 and Figure 3 show simplified friction test processes.

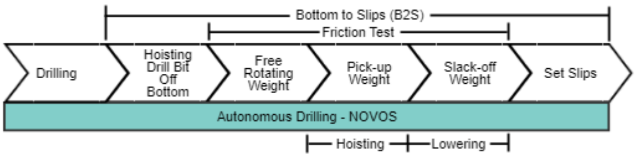

Figure 2: Friction test done at the end of stand.

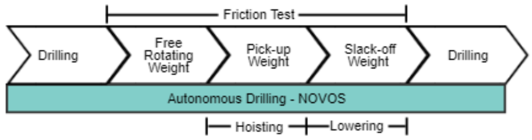

Figure 3: Friction test done at middle of stand, common method when friction tests are not subtracted from W2W.

3. RESULTS

3.1 Making Connections

The data presented below are from two offshore rigs, drilling in the North Sea in November and December of 2020. The two rigs are not identical, so major contributions to the KPIs' comparison between the two rigs are shown in Table 1.

Table 1: Comparison of the two rigs[1].

	NOVOS Version	Section Diameter ["] / Depth [m]	Rig Type	Driller's Previous NOVOS Experience	Drilling Stands
Rig 1	V 3.6.3	8.5 / 2700 to 3150	Jack-Up	Limited	Triple, Range 3
Rig 2	V 4.2	17.5 / 1050 to 1985	Semi-Sub	Limited	Triple, Range 3

- NOVOS version 4.2 has improved efficiency on S2B compared to NOVOS version 3.6.3.
- Smaller section/deeper hole increases time to: bleed off SPP, unwind residual torque from string, and required survey time.
- Semi-Sub is a floating rig that affects KPIs in the following way:
  - Heave compensation equipment increases the inconsistency and time to complete B2S slightly.
  - Heave compensation increases the inconsistency of tagging bottom, and therefore, S2B.
- NOVOS is an automation platform with built-in base functionality. If used by itself that is, without 3rd party envelope protection, it relies on the driller for configurations related to processes such as tagging bottom. As the drillers get more familiar with NOVOS, these configurations get less conservative, thus resulting in better KPIs.
- Total height of drilling stands affects S2S, as the travelling block needs to be hoisted the total length of the stand.

The KPIs for each NOVOS connection are shown on Figure 4 and Figure 5.

[1] There are more factors that can affect W2W, only major factors are stated here.

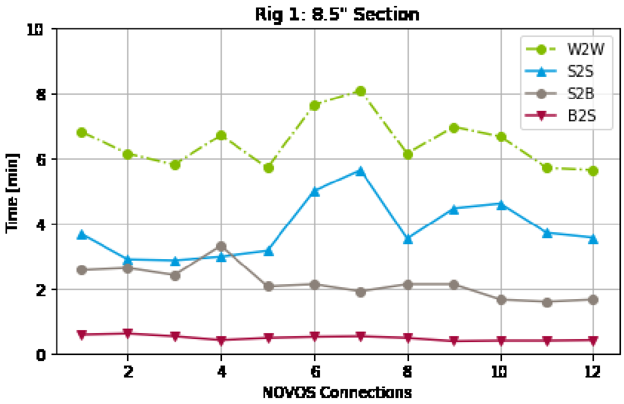

Figure 4: KPIs from NOVOS Connections on Rig 1 drilling an 8.5" section.

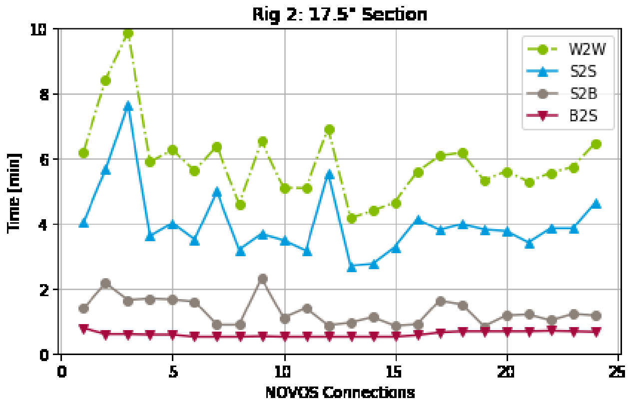

Figure 5: KPIs from NOVOS Connections on Rig 2 drilling a 17.5" section.

As can be seen on both Figure 4 and Figure 5, B2S is the most consistent KPI, while S2S is the least consistent one. Consistency in B2S is due to limited configurational requirements from the driller. S2B is between the other two KPIs in consistency. This is due to two parameters that rely on input from the driller, those are survey time and tagging bottom parameters. On both figures, S2B time decreases with connections as the drillers get more familiar with NOVOS. There are a few connections on each figure that require explanation. Connection 4 in Figure 4 has an increase in S2B due to a software bug. Figure 5 has inconsistencies in S2B due to rig heave affecting the tagging bottom process. On both Figure 4 and Figure 5, it is the human factor within S2S that is responsible for most inconsistency. On rig 1 (Figure 4), connections 2 to 5 were done by the dayshift while the remainder of the connections were done by the night shift. On rig 2 (Figure 5), the day shift did the first 14 connections and the night shift the last 10. However, it is difficult to determine which shift did better. The day shift was affected by harsher weather conditions, that made it difficult to stab the pipe during adding of stand.

Figure 6 shows a comparison between each W2W KPI for both rigs. Consistency of B2S is similar between both rigs, with rig 1 having a 7 s confidence interval vs a 10 s confidence interval on rig 2. The average B2S is also slightly better on Rig 1 then Rig 2, 28 vs 36 s. Both are the result of the heave compensation equipment, although the effect is less visible as rig 1 was drilling a smaller section in a deeper hole.

Rig 2 had a 53 s better average time on S2B then Rig 1, which can mostly be contributed to the NOVOS version. Inconsistencies during S2B on both rigs were due to limited NOVOS usage, as tag bottom parameters were being updated. However, heave compensation also contributed to inconsistencies on rig 2. For both rigs, there are no outliers on B2S and S2B based on Tukey's original definition of box plots (Mcgill 1978).

The average and median S2S is close on both rigs, however the confidence interval is bigger on Rig 1, as connections for Rig 1 are sparse compared with Rig 2. Rig 2 has 4 outliers, but only two of them result in outliers on W2W due to NOVOS performance on B2S and S2B.

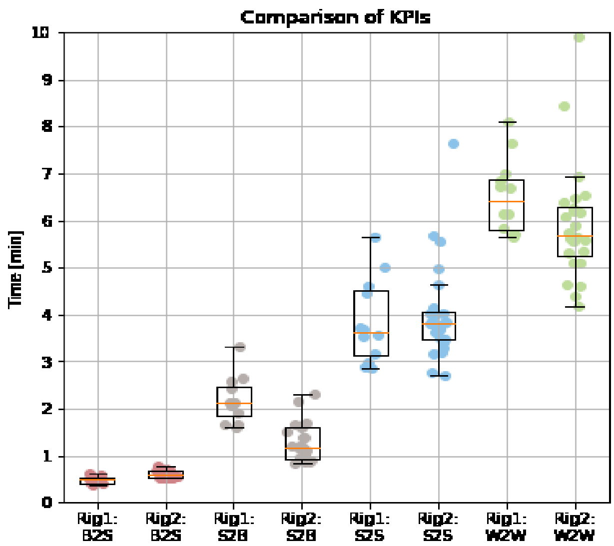

Figure 6: For each KPI: Median shown with orange line. Boxes are average ± standard deviation. Whiskers at 1.5.

3.2 Friction Test

The following friction tests were each done at an end of stand for a depth range from 2950 to 3930 m while offshore drilling in July 2020. Figure 7 and Figure 8 show 5 samples of friction test each, performed with a different block speed. The initial elevator position during a friction test is dependent on a driller configured NOVOS parameter, "Off Bottom Distance". Test duration is dependent on how long it takes to achieve stable load value during hoisting/lowering. The "flat top" seen on some of the tests is a result of a driller configurable NOVOS parameter "Stationary Time", which is the time the block should remain stationary after pick-up phase.

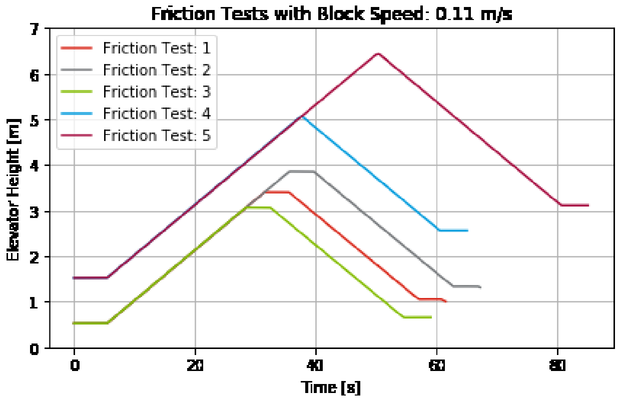

Figure 7: Friction tests done with a Block Speed of 0.11 m/s. Tests 4 and 5 are done with 0 stationary time and at a different "Off Bottom Distance" the tests 1 to 3.

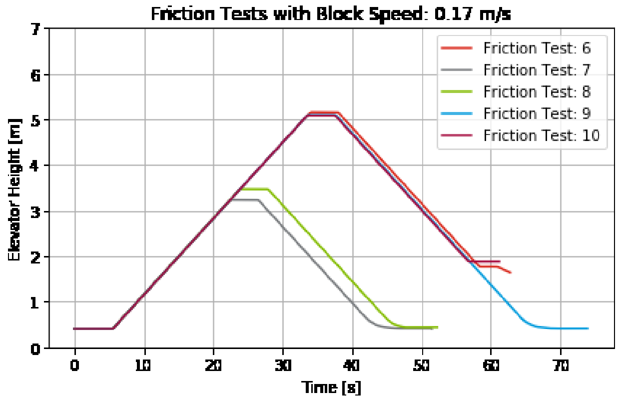

Figure 8: Friction tests done with a Block Speed of 0.17 m/s. All 5 tests are done with the same configured "Stationary Time" and "Off Bottom Distance".

While over-pull or set down weight is within the driller configured limits, NOVOS will maintain a constant block speed as can be seen on all tests in Figure 7 and Figure 8. However, NOVOS will regulate the block speed to be within these limits and notify the driller in that case. Figure 9 and Figure 10 show friction tests from the same section as the previous friction tests, where NOVOS had to limit the block speed to stay within the configured over-pull and set down weight limit.

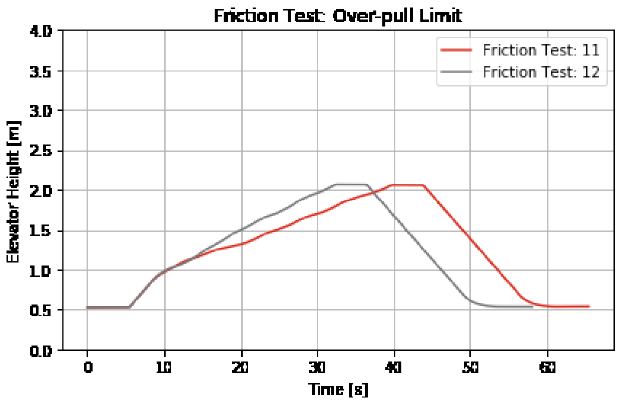

Figure 9: Two friction tests where NOVOS regulated block speed during pick-up phase to not violate the driller configured over-pull limit.

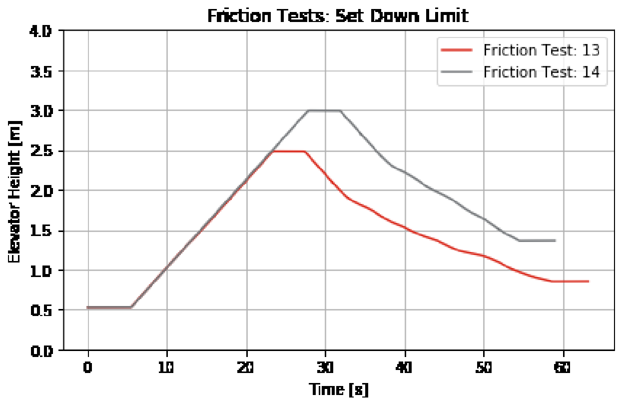

Figure 10: Two friction tests where NOVOS regulated block speed during slack-off phase to not violate the driller configured set down weight limit.

4. CONCLUSION AND FUTURE DEVELOPMENTS

4.1 Conclusion

Geothermal drilling phases many of the same challenges as O&G drilling in a different magnitude. Stuck pipe is one of the most commonly identified challenges within the geothermal drilling industry. High permeability of geothermal formations causes faster pressure drops in the mud cake, making it even more important to reduce the time the drill string is stationary. That is done by minimizing connection time. An automatic drilling system has the advantage of reducing the human factor to pipe handling only, that is if the rig is not equipped with automatic pipe handling. The consistency within friction tests achievable with an automatic drilling system, eliminates any error caused by manual control. Providing the driller with accurate values to maintain optimal drilling rate based on hole cleaning efficiency and further reducing risks of getting stuck. Automatic drilling systems provide the platform for 3rd party apps from where autonomous drilling can be done. Autonomous pack-off detection and mitigations have already been proven in the field and are commercially available.

4.2 Future Developments

The introduction of new technologies, such as NOVOS to the Geothermal industry opens enormous potential performance gains and significant cost reductions. To maximize the ROI of the technology, applications / software needs to be fed with data from the right sources. Traditionally surface data has been the primary source of data for many geothermal applications due to the temperature constraints. As of today, work is being done to develop electronics and battery solutions for high temp and ultra-high temp applications. This would enable gathering of memory or RT data for drilling dynamics and mechanics that could then be used to develop detailed drilling roadmaps for specific rock strengths, lithologies that could be preprogrammed into process controllers such as NOVOS so as to improve all aspects of the drilling process. This would have the effect of reducing downhole failures of tubulars, tools and bits and a net reduction in drilling cost. In addition, if appropriate telemetry systems can support the data in real time, incorporation of this data into autonomous algorithms such as Kaizen™ could lead to massive improvements in vibration management on bottom and significant improvements in on bottom ROP while protecting the integrity of the drilling system.

ACKNOWLEDGMENT

The authors would like to thank NOV's NOVOS team, Marketing team, Wellbore team, and Robotic Control team for the collaboration. Special thanks to Moatasim Amer, Guido Van Den Bos, Matthew Jackson, Henning Jensen, Amanda Parks, Tony Pink, Njål Sama, Jianghui Zhang, and Morten Ørevik.

ABBREVIATIONS AND DEFINITIONS

B2S	Bottom to Slips
BHA	Bottom Hole Assembly
KPI	Key Performance Indicator
MPD	Managed Pressure Drilling
NOV	National Oilwell Varco
NOVOS	National Oilwell Varco Operating System
NPT	Non-Productive Time
O&G	Oil and Gas
ROI	Return on Investment
ROP	Rate of Penetration
RT	Real-time
S2B	Slips to Bottom
S2S	Slips to Slips
SPP	Standpipe Pressure
W2W	Weight to Weight

REFERENCES

Abrahamsen, E., Bergerud, R., Kluge, R. and King, M.: Breakthrough in Drilling Automation Saves Rig Time and Safeguards Against Human Error, Abu Dhabi International Petroleum Exhibition and Conference, Society of Petroleum Engineers (2015). https://doi.org/10.2118/177825-MS

Anderson, E.R.: Aluminum Alloy Drill Pipe in Geothermal Drilling, *Proceeding*, World Geothermal Congress 2010, Bali, Indonesia (2010). https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/2102.pdf

Bergerud, R.: Drilltronics Drilling Process Automation - Statfjord C, Sekal (2016). https://sekal.com/wp-content/uploads/2018/02/2608_2016_Sekal_DrillTronics_final.pdf

Chmela, B., Gibson, N., Abrahamsen, E. and Bergerud, R.: Safer Tripping Through Drilling Automation, IADC/SPE Drilling Conference and Exhibition, Society of Petroleum Engineers (2014). https://doi.org/10.2118/168018-MS

Denninger, K., Eustes, A., Visser, C., Baker, W., Bolton, D., Bell, J., Bell, S., Jacobs, A., Nagandran, U., Tilley, M. and Quick, R.: Optimizing Geothermal Drilling: Oil and Gas Technology Transfer, *Geothermal Resources Council Transactions*, **39**, (2015). http://pubs.geothermal-library.org/lib/grc/1032147.pdf

Dupriest, F.E., Elks, B. and Ottesen, S.: Design Methodology and Operational Practices Eliminate Differential Sticking, IADC/SPE Drilling Conference and Exhibition. Society of Petroleum Engineers (2010). https://doi.org/10.2118/128129-MS

Equinor: Drilling Practice Quick Reference Guide, Revision 4, (2018).

Finger, J. and Blankenship, D.: Handbook of Best Practices for Geothermal Drilling, Sandia National Laboratories, Albuquerque (2012). https://doi.org/10.2172/1325261

Mcgill, R., Tukey, J. W. and Larsen, W. A.: Variations of Box Plots, The American Statistician, **32:1**, 12-16, (1978). https://dx.doi.org/10.1080/00031305.1978.10479236

Nygaard, G., Gjeraldstveit, H. and Skjæveland, O.: Evaluation of Automated Drilling Technologies Developed for Petroleum Drilling and their Potential when Drilling Geothermal Wells, *Proceedings,* World Geothermal Congress, Bali, Indonesia (2010). https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/2138.pdf

Oketch, B.A.: Analysis of Stuck Pipe Incidents in Menengai, UNU-GTP, Reykjavik (2014). https://orkustofnun.is/gogn/unu-gtp-report/UNU-GTP-2014-27.pdf

Saleh, F.K., Teodoriu, C., Ezeakacha, C.P. and Salehi, S.: Geothermal Drilling: A Review of Drilling Challenges with Mud Design and Lost Circulation Problem, *Proceedings,* 45th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (2020). https://pangea.stanford.edu/ERE/db/GeoConf/papers/SGW/2020/Saleh.pdf

Skalle, P., Aamodt, A. and Sveen, J.: Case-Based Reasoning, a Method for Gaining Experience and Giving Advise on How to Avoid and How to Free Stuck Drill Strings, *Proceedings of IADC middle east drilling conference,* **1**, (1998). https://folk.idi.ntnu.no/agnar/publications/iadc-98.pdf