Hot dry granite drilling optimization through iterative bit selection and mechanical specific energy management

Alexis Garcia[1], Andre El-Alfy[2], S. Noynaert[3], Prabhakaran Centala[1], Dawid Wojaczek[5], Stefan Moldoveanu[4]

[1] NOV, Conroe, Texas, USA

[2] Geo-Energie Suisse, Zurich, Switzerland

[3] Texas A&M University, College Station, Texas, USA

[4] NOV, Negoiesti, Romania

[5] NOV, Warsaw, Poland

Alexis.Garcia@nov.com

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ABSTRACT

As companies increasingly view geothermal energy as a vital component of their decarbonization strategies, the need to reduce costs and enhance efficiency in hot hard rock drilling is becoming significantly important.

The lessons from the Frontier Observatory for Research in Geothermal Energy (FORGE), a US Department of Energy geothermal project in Utah that began in 2020 with a five-well program, were implemented using physics-based workflows and practices developed by a group at Texas A&M University. These practices aimed to reduce flat time caused by key performance limiters, such as bottomhole assembly (BHA) whirl, insufficient weight transfer, resonant RPM, and other parameters that accelerate drilling dysfunctions.

To reduce the drillability uncertainty in hard rock in the Switzerland project, the evaluation of core samples extracted from three different offset wells yielded conclusive results. The lithologies included Monzonite, Metapelite, and Granite, representing different grain structures. These were analyzed in the laboratory for single polycrystalline diamond compact (PDC) cutter testing at different depths of cut. One of the three samples required 10-15% higher forces both axially and tangentially, suggesting a higher compressive strength compared to the granite found at FORGE.

Rapid bit iterations were critical to extend the cutting structure longevity and rate of penetration based on the dull conditions seen in each run. These included different body configurations and PDC cutter grades and shapes that would perform optimally under typical higher weight on bit (WOB) using high torque motor and rotary assemblies.

The combination of a good BHA design, the use of aggressive bits with shaped cutters, and maximizing WOB resulted in reduced vibration levels, as recorded in the mechanical specific energy (MSE) trends and bit dulls, ultimately leading to better drilling performance. Physics-based practice training and re-training for all people involved played a significant role in achieving such results.

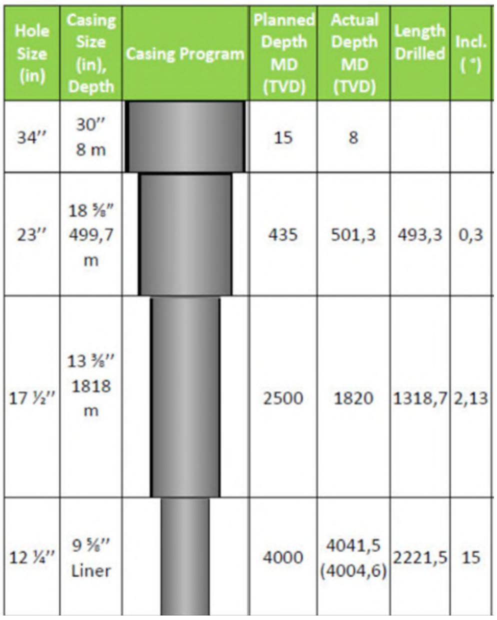
1. INTRODUCTION

Since 2012, Geo-Energie Suisse has been developing the Haute-Sorne geothermal pilot project in northwest Switzerland. The project involves constructing a geothermal power station with a maximum capacity of 5 megawatts (MW), capable of providing heat for district heating, industry, and agriculture, and supplying electricity to around 6,000 households. This project aims to demonstrate the technical feasibility of deep geothermal energy in Switzerland, producing renewable energy that is CO_2 emission-free, local, and available 24 hours a day.

In 2024, the Glovelier-1 (GVL-1) exploration well (Fig. 1) was drilled in the Republic and Canton of Jura, targeting a geothermal reservoir at a depth of 4 to 5 km (2.5 to 3 miles) below the surface. Lithologies consisted of crystalline basement, primarily consisting of granite and gneiss. This site was chosen to maintain a safe distance from faults that could pose a seismic risk.

Figure 1: Location of the GVL-1 exploration well.

The GVL-1 well (Fig. 2) consisted of a vertical conductor pre-installed at 8 m (26 ft), and 23-in., 17½-in., and 12¼-in. sections drilled vertically, with the corresponding casing strings of 18⅝ in., 13⅜ in., and 9⅝ in., respectively. While drilling the 17½-in. section, the wellsite geology team observed a notable increase in crystalline material in the cuttings at 1,787 m (5,863 ft), coinciding with a sudden drop in the rate of penetration (ROP) due to the hardness of the formation. The crystalline fragments consisted of quartz, alkali feldspars, and a fraction of mafic minerals.



Hole Size (in)	Casing Size (in), Depth	Casing Program	Planned Depth MD (TVD)	Actual Depth MD (TVD)	Length Drilled	Incl. (°)
34"	30" 8 m		15	8		
23"	18 ⅝" 499,7 m		435	501,3	493,3	0,3
17 ½"	13 ⅜" 1818 m		2500	1820	1318,7	2,13
12 ¼"	9 ⅝" Liner		4000	4041,5 (4004,6)	2221,5	15

Figure 2: Design of the GVL-1 well.

Many measurements have enabled the team to characterize the rock at 4,000 m (13,123 ft). As expected, the crystalline base consisted of gneiss and granite. Borehole measurements showed that numerous natural fractures crisscross these rocks, and preliminary temperature measurements at 4,000 m show a normal temperature gradient. No induced seismicity was measured during drilling or cementing operations.

For the 12¼-in. section, the final total depth (TD) was reached at 4,041.5 m (13,260 ft) MD. The 9⅝-in. liner was set and cemented at 4,033 m (13,232 ft) MD. The liner was tied back to the surface from 1,707.6 m (5,602 ft) MD and dressed to 3,992.5 m (13,099 ft) MD, which is the current hold up depth. The drilling fluid was displaced with a completion fluid.

Although a vertical well was planned, a building tendency was observed in the 12¼-in. section. A certain degree of build-up was tolerated to maintain drilling performance in the crystalline rock (Fig. 3). This section, expected to consist primarily of granite rock, was considered the most critical part of the project and is the focus of the physics-based limiter redesign and bit design optimization efforts.

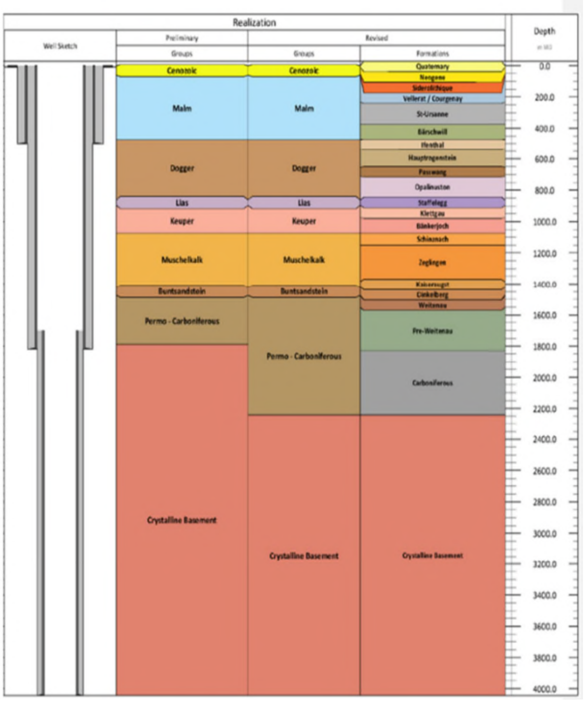


Figure 3: Stratigraphy drilled in the GVL-1 well.

2. PHYSICS-BASED LIMITER REDESIGN PROCESS

The physics-based limiter redesign approach to improving drilling performance has succeeded in various applications, including geothermal and hard rock drilling (Mann et al. 2016; Valenta 2014; Dupriest and Noynaert 2022 and 2024). The workflow is based on the question: "What is limiting us in this interval, meter of hole, minute of drilling, etc.?"

Typically, the limiter is one of a few inputs: weight on bit (WOB), flow rate, or revolutions per minute (RPM), which the driller can change in real time. WOB is the most common parameter because it has a known and linear correlation with ROP when a drilling system operates efficiently. When the response becomes non-linear, the system is dysfunctional. At this point, the team identifies what is limiting them and either implements a real-time response if possible or plans a redesign of the next run (Fig. 4).

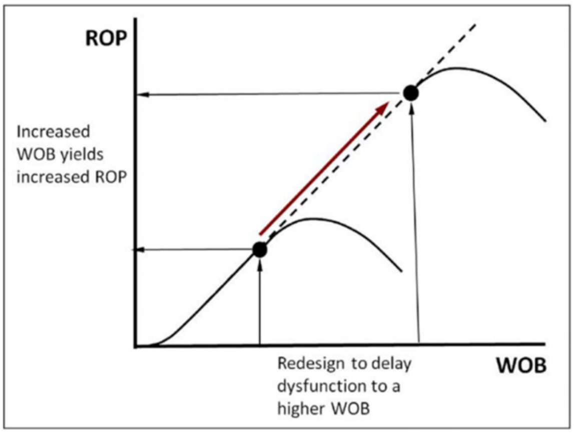


Figure 4: A physics-based limiter redesign workflow is based on the fact that there is only one limiter to increasing the WOB (or RPM or flow rate) in a given foot of hole. Identifying the limiter or dysfunction then becomes a manageable process if the drilling team understands the physics of the process and works deterministically, not empirically. Once a limiter is addressed through either real-time response or redesign, the onset of dysfunction for that point in the well is elevated, and performance improves (Dupriest 2006).

Either response type is deterministic, not empirical, and based on an understanding of the physics of the limiter, as well as the physics behind the real-time response and redesign. The key is the understanding of the physics of both on and off-bottom drilling operations, as well as topics such as wellbore quality. Once a team knows the physics of the drilling process, it no longer needs to work in an empirical manner. Instead, the team can work far more effectively, implementing the correct solution the first time or when needed, iterating much more rapidly than would be possible through empirical solutions.

The key to any effective physics-based limiter redesign effort is knowledge of how the drilling process works. This is not an ivory tower initiative; rather, it focuses on the operations team and the wellsite team, which are both necessary and central to the process's success. Training is essential for the entire team, not just engineers and supervisors.

Training usually consists of two parts. The first is several days of formal training on the physics of the drilling process and the identification, real-time response, and engineering redesign solutions to expected limiters (Dupriest and Noynaert 2022). The second part allows the team to apply the knowledge gained from the initial training.

For the GVL-1 well, the rig crew, service providers, and operator personnel—from the drilling engineer to the CEO—participated in the training. While drilling, training continued in the form of daily limiter design meetings, reviewing limiters observed and expected, and the response to these limiters.

In addition, the training provided tangible processes and procedures for the wellsite team to implement while drilling. One of the primary processes discussed was step tests. The team was able to implement WOB, RPM, and flow rate step tests throughout the drilling of the GVL-1 well to identify limiters and evaluate the effectiveness of real-time or redesign responses. Moreover, the step tests served to reinforce the concepts discussed in the training, as well as show the potential economic value of a potential change.

3. EARLY ROP DECLINE

Early ROP decline in hard rock is a well-documented phenomenon (Dupriest and Noynaert, 2022 and 2024) that the team anticipated. The early loss of ROP in hard rock is typically characterized by a 30%-50% reduction within the first 30-50 m (94-164 ft) of drilling, followed by an eventual steady-state ROP that is 50%-70% of the initial performance.

This trend was documented in the FORGE project, along with the investigation into the root causes (Dupriest and Noynaert 2022 and 2024). By pulling bits early, before performance indicated a failure, the FORGE team was able to see the cutters had developed small wear flats before failure (Dupriest and Noynaert 2022). While the current GVL-1 drilling team ran the bits to the more traditional economic pull point, where more severe damage had occurred, several bits were pulled due to non-ROP reasons. These bits, along with surviving cutters on other bits, clearly indicate the presence of similar wear flats (Fig. 5).

Figure 5: Wear flats are created rapidly, causing ROP to start high and begin to decline. Then, they reach a state where they grow slowly, and ROP is at a near equilibrium. Once the wear flat grows into the stud, the cutter is likely to experience thermal mechanical failure.

The most important guidance from FORGE and other hard rock projects the authors have participated in is to leverage the correlation between the loss of ROP and the development of wear flats. These wear flats appear to come from simple cutter-rock wear, not from dysfunction.

When considering wear in terms of the sliding distance needed to create it, the primary goal of the real-time response in the limiter redesign process is to increase the depth of cut per revolution, thereby achieving more well footage before the wear flat appears from sliding a certain distance. Fig. 6 shows this concept, which is a core topic of the physics-based limiter redesign training. It is illustrated with a spring or a slinky, where increased depth of cut stretches the slinky and extends both the early period of high ROP and the overall run length before thermal mechanical failure or other dysfunctions end the run. Consequently, the term “stretching out the slinky” became part of the drilling team’s lexicon.

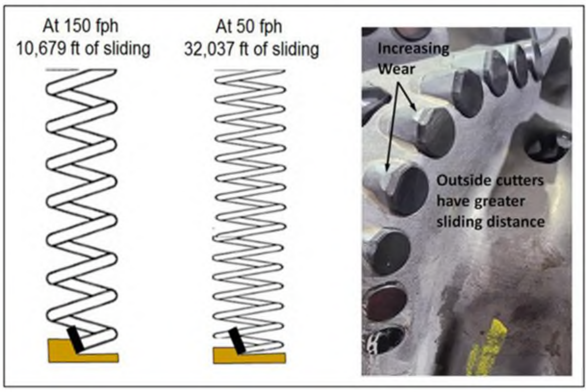


Figure 6: Wear flats from a drill bit pulled after the initial decline in hard rock drilling in FORGE. Since wear flats develop from sliding distance, increasing WOB enables the bit to drill more at a higher ROP and extend the overall run length. (Figure from Dupriest and Noynaert 2022).

4. CORE SAMPLES

To mitigate uncertainty in the Switzerland project, three core samples were collected for laboratory drillability studies. As shown in Fig. 7, the cores came from three different boreholes and are distinct lithologies:

- Monzonite (referred to as Basel-1) was extracted at a depth of 4,900 m (16,076 ft).
- Metapelite (Kaisten) was extracted at 1,000 m (3,609 ft).
- Granite (Schafisheim) was extracted at 1,600 m (5,249 ft).

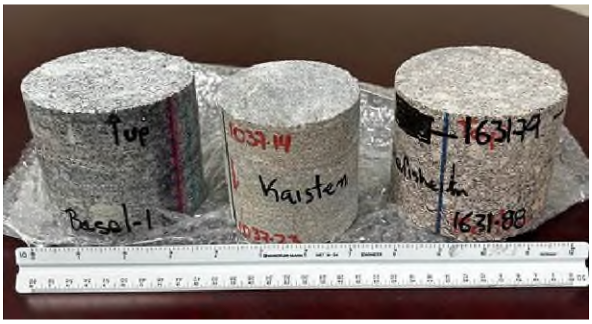


Figure 7: Field cores left to right – Monzonite (Basel-1), Metapelite (Kaisten), and Granite (Schafisheim).

Monzonite is an intrusive igneous rock formed from magma, composed primarily of plagioclase and alkali feldspar, with possible inclusions of biotite, hornblende, orthopyroxene, quartz, nepheline, and olivine. Metapelite refers to metamorphosed clay-rich sedimentary rocks such as mudstone or shale, known for a wide range of mineral assemblages and microstructures at metamorphic facies. Granite typically consists of quartz, feldspar, and plagioclase, with a coarse-crystalline texture.

At the time of testing, the unconfined compressive strength (UCS) of the field cores was uncertain. However, clear differences were observed in their grain structures and bulk densities (Figs. 8-10).

Figure 8: Grain structure view of Monzonite, Metapelite, and Granite.

Figure 9: Grain structure view of Metapelite and Granite.

Figure 10: Grain structure view of Granite.

The Basel core closely resembled typical laboratory-tested granite samples, featuring a black-and-white coloration. The Kaisten core exhibited visible surface porosity and internal fissures, with finer grains that appeared somewhat sedimentary. Meanwhile, the Schafisheim core had a grain structure like Basel’s but differed in color.

The goal was to design a polycrystalline diamond compact (PDC) bit suitable for the Haute-Sorne geothermal drilling application. Understanding how PDC cutters shear hard rock is increasingly important as more PDC bits are used in geothermal drilling.

Laboratory tests were designed to replicate downhole mechanical conditions, excluding thermal effects.

In line with the physics-based drilling approach, single-cutter shearing mechanics and cuttings generation were used as foundational elements of bit design. A series of single-cutter tests were performed using various placement parameters such as back rake, side rake, depth of cut, and rotational speed. These tests captured force data that reflect rock behavior during shearing, influenced by properties such as internal friction angle and microstructure. The most efficient set of placement parameters is then leveraged into the bit design. The optimal bit designs are then evaluated in the laboratory drilling rig.

In these tests, the cutter is made to shear at a constant depth of cut per revolution as illustrated in Fig 11. As the test progresses, the cutter's shear length and shear area increase steadily as it engages deeper into the rock, eventually reaching a steady state. Forces in the three orthogonal directions—axial, tangential, and lateral—are recorded at high frequency to capture the full cutting interaction for analysis.

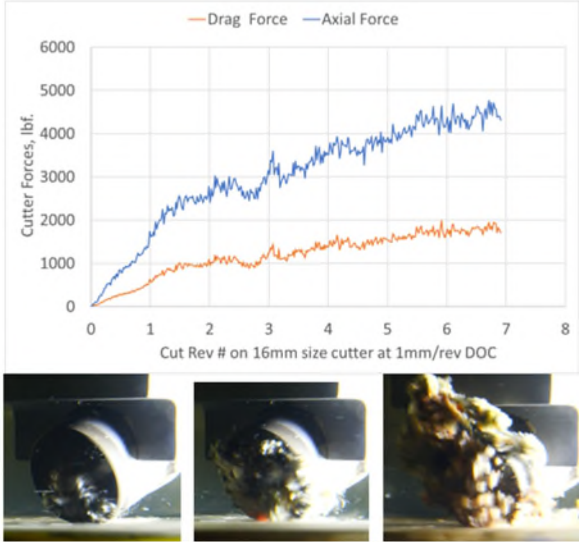


Fig.11: Still images from a video recording as PCD cutter shears granite rock at constant RPM and fixed depth of cut.

The three orthogonal forces provide critical insights into the rock-shearing process and serve as a foundation for understanding cutter behavior and optimizing bit design. Axial or vertical load is the force required for the cutter to penetrate the rock and achieve the desired depth of cut. The cumulative axial force generated by all cutters on the bit approximates the effective WOB, depending on cutter placement. Tangential or drag load is the force required to shear the rock at the established depth of cut. The combined tangential forces from all cutters contribute to the torque applied at the bit. Meanwhile, lateral or side load is an out-of-plane force on a cutter due to the placement configuration.

Sierra white granite (SWG) served as the baseline rock formation for comparison. With a UCS of 193 MPa and a density ranging from 2.64 to 2.75 g/cm³, SWG is a certified igneous rock composed mainly of quartz and feldspar. Single-cutter data from SWG served as a benchmark.

Subsequent tests on the three field core samples used the same 16-mm PDC cutter, subjected to a confining pressure of 3,000 psi. Testing was performed at 60 RPM, with depths of cut set at 0.5 mm/rev and 1.0 mm/rev.

Figures 12 and 13 present axial force comparisons between SWG and the three field cores at each depth of cut. The results indicate that the Basel-1 formation is harder rock than SWG, as it required 10-15% higher forces both axially and tangentially. Meanwhile, Kaisten and Schafisheim showed comparable performance to SWG.

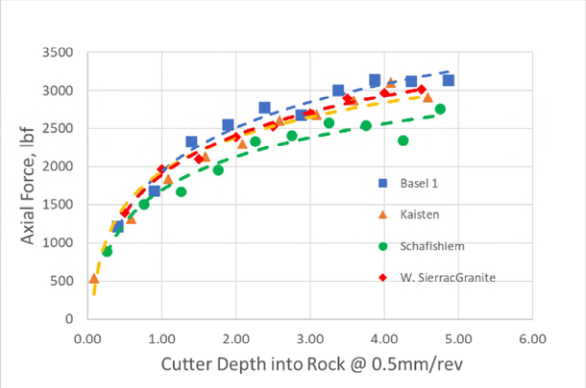


Figure 12: Cutter test results at 0.5 mm/rev depth of cut.

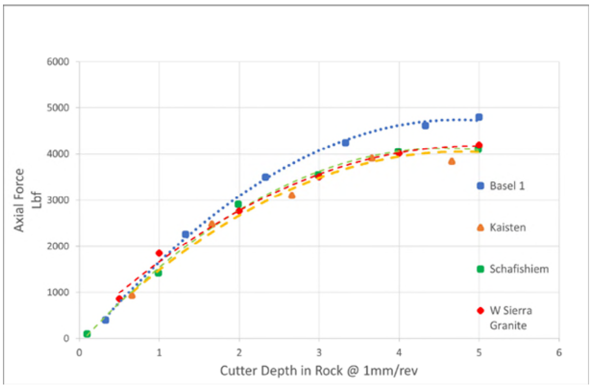


Figure 13: Cutter test results at 1 mm/rev depth of cut.

5. CHISEL SHAPED CUTTER VS. CONVENTIONAL ROUND CUTTER

Shaped cutter technology has been the new frontier in cutter technology advancements. Shape cutters and drill bit design collectively are improving drilling efficiencies in hard rock and geothermal applications. One such shape cutter is the chisel shape cutter. Detailed laboratory studies were conducted to compare the performances between that of a conventional round cutter and a chisel shaped cutter (Fig.14). Several design iterations were conducted to optimize the Chisel tip geometry along with the chamfers. It was clearly demonstrated through several analytical investigations (Fig. 15) that the chisel tip geometry would impart high failure stress on to hard rock formations in more significant manner than its round counterpart.

Pressurized single cutter tests also demonstrated that the chisel shaped cutter could cause fractures quicker and release the rock chips effectively. As a result of lesser shearing length, the chisel tip could benefit with lesser wear. Laboratory tests on wear analysis between the two were found to be interestingly similar and equal while drilling equal volume of hard rock formation. Fig. 16 shows the wear on the diamond tables of the round and chisel shaped cutter.

Fig. 14: Conventional Round cutter (Top) and Chisel shaped cutter (Bottom)

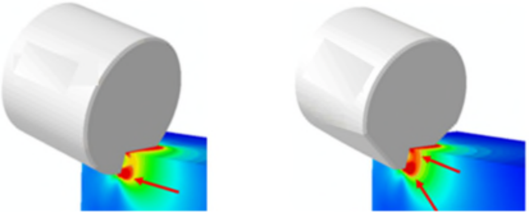


Fig.15: Engineering analysis demonstrates chisel shape cutter delivers higher stress into the rock formation.

Furthermore, full scale drilling tests demonstrated that the chisel shaped cutters had a better durability in drilling hard rock formations

Figure 17 shows pictures of chisel cutter maintaining its tip geometry while the round cutter had spalled while drilling the same formation under identical drilling conditions.

The reason primarily being the chisel tip imparts higher formation failure stress quicker than that of its round counterpart.

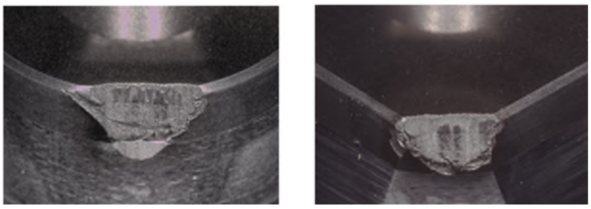


Fig.16: Round cutter(Left) and Chisel shape cutter (Right) with similar wear volume for identical lab wear test simulation.

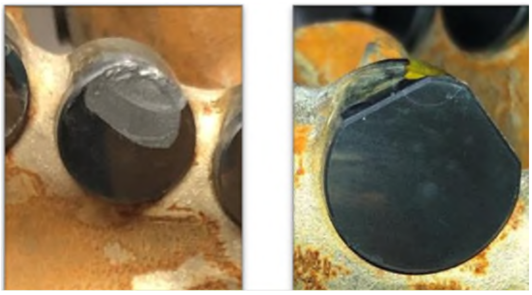


Fig. 17: Chisel shape cutter (Right) demonstrated better durability over round (Left) while drilling hard rock in lab tests

Figure 18 shows a situation where the bottomhole patterns generated by the chisel shape cutter are distinctly engaging with the rock formation, shown by the clear concentric grooves formed. This will mitigate bit dysfunctions by improving the stability of the cutting structure, reducing the onset of lateral vibrations.

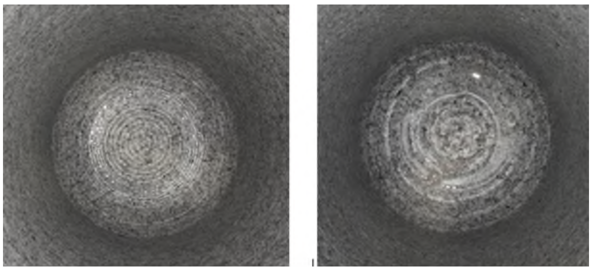


Fig.18: Bottomhole pattern with drill bit fitted with chisel shape cutters (Left) vs BOP with round cutters bit (Right)

These lab validated observations and results became the driving force to use the chisel shape cutter primarily in the drill bit designs for geothermal drilling for the FORGE project.

Because SWG served as the benchmark in the Utah FORGE project (UCS 35 ksi), its test data informed bit design and cutter selection. Based on this foundation, chisel-shaped cutters were selected for their performance under demanding conditions. The chisel-shaped cutter can withstand higher drilling forces and, when optimized, impart higher loads onto the rock formations. Cutter material was also chosen for resistance to thermal, mechanical, and abrasion failure modes.

Overall, the field core tests confirmed that these formations exhibit higher strength than the granite formations encountered in the Utah FORGE project. This validated previous decisions on cutter geometry and material, supporting optimized bit design that balances performance with reliability and minimizes the risk of premature bit failure.

6. DRILL BIT CONSIDERATIONS

To optimize drilling time and minimize the number of trips required to complete the 12¼-in. section, the selection of bit designs was carefully considered. Due to the complexity of the project, the plan also included testing various PDC cutter grades, depending on the observed performance of the bits and the dull mechanism. The ability to interchange cutters between different bit designs was seen as a key factor in finding the most effective solution by testing different bit options and minimizing turnaround time.

Since there were no recent offset wells in similar applications in this region, the goal was to evaluate different solutions to develop optimal drilling practices, BHA configurations, and bit designs for future wells.

Based on experience from the Utah FORGE project and local knowledge, four bit designs were selected for the GVL-1 well. All the bits had a matrix body to provide the required abrasion resistance for the expected formations. As shown in Fig. 19, the first design was an eight-bladed bit with 13-mm cutters, similar to a conservative design that had been initially field-proven at the Utah FORGE project. Three more aggressive bit designs were also selected, equipped with 16-mm cutters, to allow for a higher depth of cut (DOC) and potentially higher ROP, based on the most recent Utah FORGE well, FORGE 16B (78)-32.

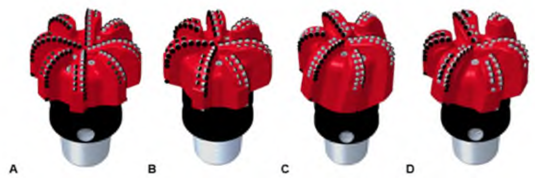


Fig.19: Dominant bit designs from left: (A) eight bladed, 13-mm chisel-shaped cutters with DOCC inserts; (B) seven-bladed, 16-mm six-bladed, 16-mm chisel-shaped cutters with DOCC inserts; and (D) six-bladed, 16-mm chisel-shaped cutters, secondary cutters.

Various additional design elements were tested to improve performance in hard rock drilling. Two six-bladed bit designs incorporated insert-style Depth of Cut Control (DOCC) elements positioned near the blade's face, close to the cone. These elements are strategically placed to contact the formation at a specific cutting depth, limiting the ROP and preventing excessive bit engagement and sudden torque increases. The secondary cutters were used in the eight-bladed, seven-bladed, and the final six-bladed designs.

All drilling BHAs used downhole motors as the primary driving and steering mechanism. Since the well was planned to be near-vertical, the motors' bend angles were intentionally limited to 0-1° to permit only minimal trajectory corrections. Within the applied range of drilling parameters, the straight motor BHA demonstrated an excessive building tendency. An adjustable kick off (AKO) of 0.8° proved sufficient to achieve the required trajectory adjustments. In select BHA configurations, roller reamers were strategically integrated into the assembly, positioned immediately above the mud motor.

7. LIMITERS

The limiters encountered while drilling the GVL-1 exploration well ranged from typical to more unusual. They are categorized as on or off-bottom, or bit or non-bit limiters. The primary metric used in physics-based limiter redesign for drilling is typically mechanical specific energy, or MSE, (Dupriest et al. 2022). However, other parameters, ranging from standard rig sensors to downhole vibration, were just as critical and monitored the drilling process in real time by all wellsite and office personnel.

7.1 Borehole Quality

Physics-based limiter redesign is often misunderstood as simply a means of drilling faster. In reality, it encompasses the entire process from rig release to rig release, including off-bottom performance factors such as borehole quality and formation integrity. Key limiters during this phase often include borehole instability, inadequate hole cleaning, lost circulation, and excessive torque and drag during trips.

In this case, the primary off-bottom, downhole limiter was a shale and schist interval below the assumed top of the basement. While drilling the intermediate interval, formation samples, drilling parameters, and offset well log correlation indicated that the crystalline rock had been reached. However, due to limited nearby offset wells, the team was unaware of a 450-m (1,476-ft) sedimentary interval situated below the misidentified crystalline top. This interval, having significantly lower strength than the expected crystalline formation, experienced severe breakout during drilling of the 12¼-in. hole.

Shaker surveillance, a crucial part of any drilling operation, was diligently conducted by the team. The team observed small, blocky cuttings and splinters at the shakers, indicating borehole instability. Although the mud weight was increased by nearly 1 lb/gal, further increases were constrained due to concerns over lost circulation and the high costs associated with maintaining mud volumes in this area. To mitigate these risks, the team implemented additional circulation before pulling out of hole (POOH) and provided specific guidance to drillers on navigating the problem zone. These measures successfully prevented major non-productive time (NPT), though some NPT did occur due to excessive reaming on each trip. Overall, these issues contributed to approximately 48 additional hours of rig time during drilling and casing operations.

More consequential, however, was the inability to obtain open-hole image logs. Despite acquiring adequate logging while drilling (LWD) logs, they were not ideal for the complex geophysical analyses intended. From a limiter redesign standpoint, the absence of wellbore image logs represented a significant loss of valuable data for future well redesign. Wellbore image logs are a valuable tool being increasingly used in the industry for assessing borehole quality, vibration-causing and caused patterns, and understanding drag issues (Fonseca et al. 2024). This is especially true in hard rock drilling (Dupriest and Noynaert 2022 and 2024).

7.2 Shaker Vibration

The application of physics-based limiter redesign workflows in drilling comprises all aspects of the operation. These can include regulatory frameworks, organizational challenges, and other factors not traditionally associated with physics-based approaches.

As part of the drilling team training, the concept of a "limiter" was discussed broadly, defined as anything that limits drilling progress, typically in terms of applying more WOB or increasing RPM. During the GVL-1 well, the team encountered several limiters. One unique non-bit limiter was shale shaker vibration.

Regulatory oversight and requirements were stringent, especially concerning seismic monitoring. Based on experience with enhanced geothermal systems (EGS) from the FORGE project, the operator had a full team of on-site seismologists. While no seismicity was observed due to subsurface activity, small vibrations were felt at a nearby farmhouse during drilling of the 17½-in. section. Investigation revealed that the shale shakers were operating at a resonant frequency with the local soil conditions. This effect was amplified by the rigid, high-specification concrete and asphalt pad, which was built to meet regulatory site construction standards.

Drawing from previous examples (Redman 1986), the only viable mitigation at the time was to reduce the shaker speed. As a result, the ROP was lowered to prevent overwhelming the less-effective shakers with high volumes of cuttings. As with any limiter, the response was closely monitored to validate the underlying physics and inform future mitigation strategies. In this case, the operator installed acoustic and seismic monitoring equipment in the farmhouse to track any further vibrations throughout the remainder of the operation.

Looking ahead, the redesign to eliminate this surface-based limiter may involve modifying the shaker mounting system or placing vibration-dampening mats beneath certain rig components.

8. PERFORMANCE ANALYSIS

At the beginning of the interval, the drilled formations were highly interbedded, consisting of gneiss and schist rocks, which presented challenges in establishing performance-oriented drilling practices. The cutting structure was more prone to impact-related damage due to the different properties of the rocks encountered. Additionally, in the highly interbedded formations, establishing effective cutting structure engagement and minimizing vibrations proved difficult. From 2,240 m (7,350 ft) MD, more uniform crystalline rocks were encountered. During the more homogeneous intervals, it was possible to test more aggressive bit designs to achieve a higher ROP and drill longer intervals with the same workload on the bit.

Bit A, the first 12¼-in. PDC bit, started in the schist/shale lithology and remained in this lower-strength rock for the first half of the run, and ROP remained relatively high. It should be noted that the initial decline in ROP at the formation transition is primarily due to sliding; however, surface vibrations, potentially caused by the transition into the gneiss, briefly limited the ROP as well. Although once the bit was drilling a majority of gneiss lithology, the effect of the hard rock is seen as ROP declines rapidly to a lower, steady-state value. This decline occurs despite maintaining or improving drilling parameters during the second half of the run.

As mentioned earlier, the crystalline basement analog core samples tested showed strengths exceeding those at FORGE. Therefore, the team anticipated the ROP decline and incorporated this understanding into training to help the drilling team recognize the phenomenon, distinguish it from bit damage, and emphasize the significance of maximizing early footage. Fig. 20 shows ROP as a function of measured depth. Bit B illustrates this concept. Step tests established the maximum WOB, which was limited in this case by surface vibrations.

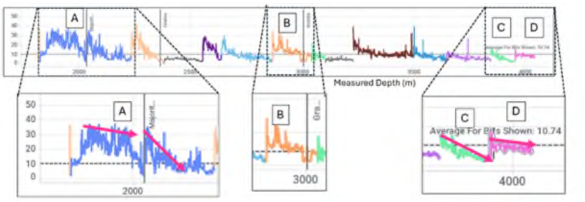


Fig.20: The PDC bits showed ROP decline behavior like that of other hard rock drilling projects. Each bit is shown in a different color (roller cones in gray are low and flat ROP), with the early decline in all but a few runs.

By reaching a higher WOB quickly, the team was able to drill further at the higher ROP and appeared to reach a higher steady-state ROP. Unfortunately, this run, as well as three other PDC runs in the 12¼-in. interval, experienced bit damage immediately following several slides. However, the value of the higher WOB and its resulting gains can still clearly be seen. Bit C is an example of the effect of reduced WOB, thereby decreasing the footage drilled at high ROP.

Bit C was run with a WOB 30-50% lower than the other PDC bits. The ROP started lower and declined just as fast to a lower steady-state value. More importantly, the MSE rose rapidly early in the run, indicating severe bit damage had occurred and the run was terminated, much shorter than expected. This occurred despite using the previously successful and more durable eight-bladed design, along with upgraded cutters recommended based on single-cutter testing.

As explained earlier, the goal is to "stretch the slinky or spring" out, meaning higher DOC and thus extend the amount of footage drilled before the sliding distance reaches the point where the small wear flats appear, and the ROP falls to the lower, steady-state value. Bits B and C are examples of these physics in action. Bit D is an example of the recommended bit redesign to combat the drop in ROP. Bit D is the six-bladed bit with secondary cutters instead of non-cutting inserts. This configuration creates a more aggressive bit at higher WOB.

Early WOB similar to other runs, low and being brought up over the first stand drilled, but the early ROP was lower than other PDC bits, indicating the design is initially less aggressive. However, offsetting the low initial ROP, the slope of the later ROP is clearly shallower than other bit runs, indicating the bit is establishing a higher steady-state ROP for the remainder of the run. Unfortunately, this bit design's full potential remains a question mark as it was pulled for TD after a short run, but it can be hypothesized that the higher steady-state ROP over a full bit run would yield good results. And, once the rig teams felt comfortable applying WOB quicker, early ROP would be expected to be better, further improving performance. Therefore, based on available data, it does appear to be a successful example of applying limiter redesign based on the physics of a particular limiter.

Meanwhile, one of the main challenges in this application was related to wellbore quality and BHA hanging. With high WOB applied, the BHA tended to encounter the formation and develop excessive wear on the positive displacement motor and stabilizer above. There was no direct correlation between the presence of a roller reamer tool and observed surface torque, wellbore quality, and the durability of the drilling bit or performance. After two runs with roller cone bits, it was observed that both PDC bits achieved a noticeably higher average ROP throughout their entire runs. Further trials will be necessary to overcome the challenges experienced in this application and develop optimal solutions for similar projects in the future. Based on the experience gained, it is recommended to incorporate borehole conditioning tools within the BHA to mitigate tight spots and prevent drillstring stalling.

The results showed that additional protection against impact-related damage to the primary cutting structure is critical for bit longevity and bottomhole quality (Figs. 21 & 22). All seven-bladed bits with only PDC cutters on secondary positions had developed severe wear to the shoulder cutters, progressing to the bit body. This type of wear disturbed the bottomhole pattern, leading to the following bit's inability to engage properly with the formation, resulting in cutter overload and premature failure, as well as excessive gauge wear.

Fig.21: Critical wear progression to the bit body after the integrity of the cutting structure is compromised.

Fig.22: Typical impact damage across the cutting structure. The run was terminated due to low ROP/ineffective cutter engagement.

Experience from this drilling application suggests the effectiveness of DOCC elements appears limited in hard, homogenous formations. The initial performance peak observed at the beginning of the drilling run is considered favorable, but there is no evident correlation between limiting it at the start of the run and subsequent consistent ROP stabilization. Moreover, the secondary cutters did not significantly enhance durability. Replacing these secondary cutters with impact-resistant inserts is recommended to improve overall bit performance and longevity.

The complex, multi-faceted approach taken in this project, including extensive bit testing and optimization, enabled the team to develop an understanding of the critical success factors for drilling in these challenging hard rock formations. Applying these learnings to future well designs and bit selection will be key to replicating and building upon the exceptional drilling performance achieved in the 12.¼-

in. section (Fig. 23).

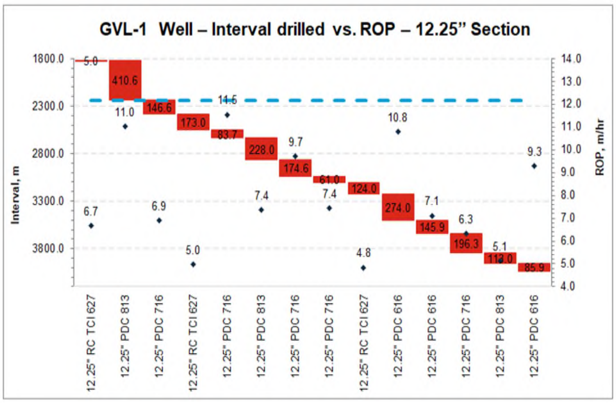


Fig.23: 12¼-in. section performance. Crystalline basement from 2,240 m MD.

GVL-1, the first borehole in the entire Jura Arc to reach the crystalline basement and provide information about the deep subsoil, reached TD 26 days ahead of authorization for expenditure (AFE), as shown in Fig. 24. The rig was released 16 days ahead of schedule.

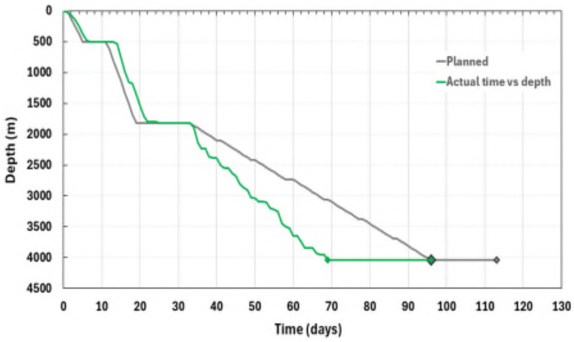


Fig.24: GVL-1 well depth/time planned vs. actual

9. CONCLUSIONS

The physics-based practices developed at Texas A&M University for the oil and gas industry have also proven effective in the geothermal industry. Their success at FORGE in Utah and the Geysers Field in California informed the Haute-Sorne project, where similar strategies were adopted. By building drilling team knowledge through training, reinforced with real-time monitoring and discussion, the team improved drilling efficiency through MSE surveillance and limiter redesign, reaching TD 26 days ahead of schedule.

Single-cutter tests for hard rock offer significant insights into identifying the optimal cutter grade and shape for use in hot, dry rock, which risks diminishing the cutting structure's lifespan due to high abrasion and thermal wear. Rapid iterations of drill bit designs, including variations in both body material and configuration, along with selecting cutter types based on dull grades between runs, prove valuable for enhancing ROP and reducing the likelihood of bit trips.

As with any formation, especially high-strength formations, it is critical to follow limiter redesign principles to work to maximize WOB and RPM continually. Step tests help identify limiters, enabling real-time response and engineering redesign that can improve performance more deterministically and more quickly than empirical methods.

Roller reamers assisted in minimizing vibration in many runs, as expected. However, they are only part of the overall drilling assembly. Redesigning BHAs through advanced high-frequency data collection and modeling is necessary to achieve truly quiet BHAs. Due to their minimal cutting ability, roller reamers cannot eliminate borehole patterns created by whirl-prone BHAs or drilling parameters.

All the tested bit designs showed varying degrees of impact-related damage to the cutting structure. Based on the lessons learned, cutter selection should focus on impact resistance to better withstand the harsh downhole conditions.

As seen in other hard rock projects, notably Utah FORGE, increased indentation depth, both through increasing WOB and bit aggressiveness, is critical early in a bit run. The development of small wear flats results in a rapid decline in ROP that is not proportional to the size of the wear flat. Therefore, for any hard rock drilling application, whether oil and gas or geothermal, adapting the bits to the rock type is one of the keys to maximizing efficiency. This also serves as a baseline to implement in offset wells in the campaign to minimize iteration work, added to new cutter types as technology evolves quickly. Aggressive cutting structures that incorporate additional mechanical safeguards, such as impact-resistance features, are desirable to enhance overall drilling performance and bit durability.

REFERENCES

Garcia A., El-Alfy A., Noynaert S., Centala P., Wojaczek D, Moldoveanu S., 2025. Limiter Redesign Workflow Yields Positive Results in Deep Geothermal Drilling in Switzerland, presented at 2025 SPE/IADC International Drilling Conference and Exhibition, Stavanger, Norway, SPE 223784-MS.

Dupriest F., Pastusek P., Lai S., Best B., Behounek M., Cook B., Cutts C., Collins J., Kanyab M., Moore D., Pulpan E., Jeske A., Wilson J., Sheets J., 2022. Standardization of Mechanical Specific Energy Equations and Nomenclature, accepted for presentation at IADC/SPE International Drilling Conference and Exhibition, Galveston, Texas, USA, SPE-208777-MS.

Dupriest F., 2006. Comprehensive Drill-Rate Management Process to Maximize Rate of Penetration, presented at SPE Annual Technical Conference and Exhibition, San Antonio, Texas, USA. SPE-102210-MS, https://doi.org/10.2118/102210-MS.

Dupriest, F. and Noynaert, S. 2022. Drilling Practices and Workflows for Geothermal Operations. Paper presented at the IADC/SPE International Drilling Conference and Exhibition, Galveston, Texas, USA, 8–10 March. SPE-208798-MS.

Dupriest, F. and Noynaert, S. 2024. Continued Advances in Performance in Geothermal Operations at FORGE Through Limiter-Redesign Drilling Practices. Presented at the SPE/IADC Drilling Conference. Galveston, Texas. SPE 217725-MS.

Mann, C.B., Dupriest, F.E., and Noynaert, S.F. 2016. Successful Design and Operational Practices to Mitigate Common Bit Damage Mechanisms in Hard Laminated Formations. Presented at the IADC/SPE Drilling Conference and Exhibition, Fort Worth, Texas. SPE-178848-MS, https://doi.org/10.2118/178848-MS.

Noynaert, S.F., El-Sayed, I., Hopkins, Z., Dupriest, F.E., 2020. The Reality of Mud Motor Performance: Actual Vs Expected Performance in Unconventional Formations. Presented at the SPE/IADC Drilling Conference. Galveston, Texas. SPE 199655-MS.

Rahmani, et al. 2021. Investigation of PDC Cutter Structural Integrity in Hard Rocks. SPE Drilling and Completions 36 (01):11-28. SPE paper 199598-PA.

Redman, P.J. 1986. Drilling Environmentally Sensitive Wells in Southern England. Presented at SPE European Petroleum Conference. London, UK. SPE 15899.

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