Innovative Conical Diamond Element Bit in Conjunction With Novel Drilling Practices Increases Performance in Hard-Rock Geothermal Applications, California

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\textbf{ABSTRACT}

The Geysers Geothermal field is an area of geothermal activity situated in the Mayacamas Mountains of northern California, about 75 miles north of San Francisco. The field, covering approximately 45 square miles, is the world’s largest geothermal reservoir. The Geysers was formed over 1 million years ago when molten magma from the Earth’s core was squeezed toward the surface, recrystallizing and fracturing the surrounding rocks. These fractures allowed for water seepage which, many years later, created a reservoir of steam and ultra-heated rock below the Earth’s surface. This heat is now harvested by drilling into the reservoir and unlocking the steam for electricity generation. The energy capacity is enough to power more than 725,000 homes in northern California.

The drilling environment in The Geysers reservoir can be harsh. Extreme heat and hard and abrasive volcanic rock make this area one of the most difficult to drill anywhere in the world. The lithology is characterized by mineral rich rock such as serpentinite, argillicious graywacke, greenstone, and felsite. These extremely hard rocks provide a multitude of challenges for drill bits. Typically bit runs are short in hours and footage because of dulling and subsequent loss of rate of penetration (ROP). Beyond the cost of the drill bits themselves, the rig time necessary to replace bits increases the time to drill a well. Depending on the depth, it can take up to 18 hours to trip drillpipe out of the hole and return to bottom to start drilling again. Rig rates vary over time and across different areas, but a general rig rate of around USD 15,000–25,000 per day is common for a US land rig. With ancillary costs included, a 30-day well can cost approximately USD 2,000,000.

In response to these challenges, a new rock-removal system has been designed. The system implements conical diamond elements (CDE) to work in unison with polycrystalline diamond compact (PDC) cutters. These CDEs help to mitigate the breakage of the PDC cutters, resulting in greater durability than a conventional PDC fixed cutter bit and a higher ROP than roller cone (RC) bits. This, coupled with new drilling practices, has brought a new era of performance to the world of hard-rock drilling. Traditional drilling parameters have been overhauled to maximize the potential of CDE bits. Utilizing CDE bits over the course of 3 wells, one operator in The Geysers has seen a footage increase of up to 29\% and ROP increase of up to 44\% on comparable wells. This represents a sizable reduction in the number of days needed to complete a well. On just three bit test runs utilizing a CDE bit, one operator reduced drilling time by approximately 30 hours, representing a potential rig savings of USD 90,000.

\textbf{Introduction}

Geyser wells, similar to other hard rock applications, are typically drilled using RC bits (Brittenham 1982). RC bits utilize three rolling cones with inserts made of tungsten carbide that are used to crush the rock. In most classic sedimentary basin applications, the use of RC bits has steadily been phased out by the use of fixed-cutter bits, generally known as poly-
crystalline diamond (PDC) bits. PDC bits show an improvement in the rate of penetration (ROP) and are generally more reliable as there are no moving pieces to lose down hole. Although PDC bits have proliferated most applications in the oil and gas industry, their use in geothermal and hard-rock drilling has been largely unsuccessful due to the harsh drilling environments. PDC cutters are at a greater risk of brittle failure such as chipping and breaking in hard, nonhomogeneous formations and can thermally degrade if there is too much heat generation (Durrand 2010).

Operators in The Geysers drill a variety of hole sizes, but 12.25 inch followed by 8.5 inch diameter hole sizes are the most commonly used intermediate and bottomhole sizes in the field. These are the hottest and hardest intervals because the heat and formation strength typically increase with well depth. The bottomhole 8.5 inch is entirely or partially drilled using air as the circulating fluid. For the purpose of this study, all of the bits were tested and compared with runs using mud as the drilling fluid, which is the standard intermediate interval practice. Using 2014 and 2015 averages for an operator in The Geysers, the average run length of a 12.25 inch bit was 537 ft, and an 8.5 inch bit average was 439 ft. Operators in the field typically need to drill between 5,000-ft and 8,000-ft 12.25 inch and 8.5 inch holes to reach the necessary depths. Using these averages, a typical well in the field will require up to 18 drill bits.

To effectively reduce the drilling costs, the performance gains must be twofold—maintaining a high ROP to reduce overall well time and increase footage to reduce the number of round trips for bit changes. A new rock removal system, which combines CDEs and PDCs, has been designed to achieve these high performance goals.

**PDC Cutter Dulling Mechanics in The Geysers Hard Rock**

PDC bits work by dragging sharp diamond cutting elements across the bottom of the hole. As the cutters penetrate the formation, they create cuttings that are removed from the hole similar to a drill bit used for drilling wood. This method of rock removal in soft to medium-hard formations is typically very efficient, which leads to good ROP. In harder formations, the cutters can struggle to penetrate the formation, creating frictional heat that can lead to premature cutter wear (Zhan, 2014). Additionally, heterogeneity in the formation can be troublesome to the PDC cutters because the rotational impact when going from soft to hard formation can produce enough energy to break or chip the cutters. RC bits, in contrast, use the weight of the drillstring to help push its teeth into the formation, crushing and fracturing it. This rock removal type, although less efficient in softer formation, is typically more durable in heterogeneous formations and can be quite efficient if the formation fails in a brittle manner.

The specific lithology of the rocks in The Geysers exhibits both high compressive strength and heterogeneity. While a medium-hard formation could be described as having an unconfined compressive strength (UCS) of between 15,000 psi to 20,000 psi, formations in The Geysers can have a UCS as high as 60,000 psi. This would typically lead to a PDC cutter unable to have an effective depth of cut and skim across the formation. The result would be heat generation, which can degrade the diamond elements and break them down (Figure 1).

The heterogeneity of the formation can be described as a hard to soft transition that a cutter could achieve drilling foot by foot, or even within a single revolution. As the bit hits a harder streak, the rotation of the drillstring is slowed as the energy is dissipated through the cutters. If the energy taken by the cutters exceeds their fracture strength, the cutter will chip or break. This leads to a significant loss of ROP, as the once-sharp element has lost its sharp edge.

**Conical Diamond Elements**

German et al. (2015) explained how a CDE’s unique conical geometry can improve performance over a traditional PDC cutter (Figure 2). CDE elements have 25% more wear resistance, twice the impact strength, and twice the diamond thickness (Figure 3).

The addition of CDEs to a PDC bit cutting structure can also have a positive effect on the vibration characteristics of the bit. CDEs operate in a manner similar to PDC cutters, as they are fixed to the bit and are dragged across the hole bottom. But where PDC cutters action can be described as shearing, the CDE plows the formation (Figure 4). This difference in cutting method is what gives the CDE a unique ability to bridge the gap between PDC bit and RC bit in harder, heterogeneous applications.
Implementation of CDEs

To best utilize the CDEs superior impact and wear resistance, it’s necessary to understand how bits commonly dull. As a result of the heterogeneity of the Geysers formation, impact is a likely first mode of PDC cutter damage. Impact damage itself is a result of the PDC cutter absorbing an impact force that is greater than the yield strength of the cutter. This can be as small as micro cracks in the surface of the cutter, and progress all the way to a completely broken cutter. Impact damage is typically seen toward the outer radius of the bit. This is logical, as the cutters farthest from the center of the bit are moving at the greatest tangential velocity (Figure 5). To mitigate the impact on these cutters, CDEs were placed behind the cutters starting approximately halfway along the radius of the bit, from the nose to the shoulder. In this position, the CDEs protect the PDC cutters from impact damage.

Wear is the second cause of PDC dulling. As the PDC cutters drag across the hole bottom, heat is generated at the cutter tip. CDEs, however, employ a plowing-type cutting action on the rock. Using their concentrated point loading, the CDE is able to more easily penetrate hard formations. As the CDE penetrates the rock, it fractures and weakens the rock for the coming PDC cutter. This combination of the CDE and PDC cutters can be very efficient in formations that are not traditionally drillable using PDCs.

Performance of CDE bits Compared With RC Bits

Operator A in The Geysers drilled test wells with both traditional RC bits and a CDE bit in 8.5 inch hole size. The RC bits were characterized by the IADC classification method as 527X and 517X (McGehee 1992). These are commonly run bits in The Geysers that typically have good performance. Figure 6 shows the two offset wells. Well 1 was drilled with one of each type of 527X and 517X RC bits. Due to hole problems, the same well was drilled twice. The average footage between the two bits was 1,475 ft drilled at an ROP of 24 ft/h. Well 2 was drilled with the CDE test bit, which drilled 1,898 ft at 24 ft/h. This represents a 29% increase in footage at the same ROP as baseline bits. The CDE bit went in at a depth 500 ft deeper than the RC bits, which would typically mean that

![Figure 3. CDE performance compared with PDC.](image3)

![Figure 4. Finite-element analysis (FEA) simulation of formation stress when penetrated with PDC (left) and CDE (right).](image4)

![Figure 5. Implementation of CDE cutters on a PDC bit.](image5)

![Figure 6. 8.5 inch bit performance.](image6)
it drilled harder and hotter formation. All of the bits were pulled for non-bit-related issues, so the general performance is best judged by the dull rating. The 517X bit was left in hole, which means the dull cannot be judged. The 527X bit drilled 1,558 ft and was graded 3-4-WT, which is similar to the CDE test bit rating of 3-4-BT. For a similar dull rating, the CDE bit increased footage drilled with a similar ROP to the baseline RC type bits.

Further testing of CDE bits was performed with Operator A in 12.25 inch hole in a near-surface application. The CDE bit drilled 960 ft in Well 6 compared with offset wells of RC IADC type 547X bits that drilled 510 ft and 804 ft (Well 4 and Well 5). This represents an average increase of 46% in footage, with both groups achieving an average ROP of 26 ft/h. The bit on Well 4 had a worse dull grading than the CDE while drilling 450 ft less formation and at an ROP 44% less than the CDE bit. This is more relevant performance than the bit that drilled on Well 5, as that bit went in at 211 ft. The bit on Well 5 avoided much of the hardest surface formation, a 300 ft section of siliceous graywacke that starts near surface. Below the hard graywacke is more homogenous greenstone, which typically imparts less damage on the bits than the graywacke above (Figure 7).

Well 7 represents a 12.25 inch bit comparison on the same well as RC type 437X was run 226 ft and pulled for hole problems (HP). Upon surface inspection, the dull was too severe to run again (3-4), and a CDE bit was run into the hole. This bit drilled 721 ft to the desired depth, and the dull was a much better grade of 2-2 while drilling approximately 500 more feet. The 437X bit exhibited better ROP by approximately 27%, which indicates that the bit could perform better in a faster, softer application. As a result of the additional footage drilled by the CDE bit, the operator was able to save at least one bit run compared with the 437X bit seen in Figure 8.

Utilizing New Parameters

As Mohamed et al. (2009) highlighted, typical hard rock drilling is typically achieved by utilizing RC bits with high weight on bit (WOB). Due to the cutting action differences between RC bits and CDE bits, a new range of parameters (WOB and bit RPM) were developed to maximize bit life and performance. This change was driven by rig-level experimentation during drilloff tests. Parameters were varied and the effect on ROP was observed. Figure 9 shows the differentiation between the two types of bits and the parameters used. In the 8.5 inch hole size, RPM was increased substantially compared with the median 8.5 inch run. In the 12.25 inch hole size, the RPM was already high for both bit types, but the WOB shows a slight drop on the CDE bit.
Conclusion

The implementation of CDEs in The Geysers Geothermal field in California has shown significant potential to reduce the amount of bits and subsequent bit trips while drilling geothermal wells. Additionally, with using newly developed parameters, there is the potential to increase ROP for each given bit run as a result of the unique drilling mechanism of CDE bits. The inherent properties and strategic placement of these new elements has enabled the use of PDC cutters in an application that was previously only successfully drilled with RC bits. CDE bits do not suffer the typical early dulling caused by impact and wear-related damage. CDE bits have been shown to significantly reduce the rig time needed to drill a typical well.

References


