

PDC Bits Outperform Conventional Bit in Geothermal Drilling Project

**David Raymond, Steven Knudsen and Doug Blankenship
Sandia National Laboratories¹, Albuquerque NM
Steve Bjornstad /USN Geothermal Program Office, China Lake, CA
Joel Barbour / Barbour Well, Inc.
Aaron Schen / NOV Downhole**

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Abstract

Geothermal drilling is hampered by the challenges of hard rock, fractured formations, and high temperatures. This drilling difficulty has traditionally been a point of distinction between geothermal and oil and gas applications yet recently this difference is less pronounced as the oil and gas industry targets more challenging formations for sustained production. This synergy can benefit the geothermal industry as technology developed for oil and gas, backed by significant research and testing, can be adapted for use in geothermal drilling. The work described herein demonstrates the use of mature oil and gas drilling technologies on an actual geothermal well construction project. The principal objective is to develop and demonstrate Enhanced Geothermal Systems (EGS) drilling solutions based upon mature, proven rock penetration systems that have been used in the oil and gas industries to penetrate hard rock formations.

Polycrystalline diamond compact (PDC) bits are routinely used in the oil and gas industry for drilling medium to hard rock but have not been adopted for geothermal drilling, largely due to past reliability issues and higher purchase costs. The Sandia Geothermal Research Department has recently completed a field demonstration of the applicability of advanced synthetic diamond drill bits for production geothermal drilling. Two commercially-available PDC bits were tested in a geothermal drilling program in the Chocolate Mountains in

Southern California. These bits drilled the granitic formations with significantly better Rate of Penetration (ROP) and bit life than the roller cone bit they are compared with. Drilling records and bit performance data along with associated drilling cost savings are presented herein. The drilling trials have demonstrated PDC bit drilling technology has matured for applicability and improvements to geothermal drilling. This will be especially beneficial for development of Enhanced Geothermal Systems whereby resources can be accessed anywhere within the continental US by drilling to deep, hot resources in hard, basement rock formations.

Background

Sandia has had a long standing role in the development of PDC bit technology that has contributed to catalyzing the application of synthetic diamond technology for oil and gas drilling. However, a number of barriers have resulted in a lack of interest within the geothermal drilling industry; these include: 1) the sheer lack of geothermal wells drilled annually, 2) the absence of the drilling service industry from directly supporting geothermal well construction, and 3) poor performance of PDC bits in field trials during their infancy. Risk aversion has slowed the adaptation of advanced methods in the geothermal drilling industry.

The work undertaken in this project is intended to reduce the risk borne by the geothermal driller/operator in attempting new drilling

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technologies by bearing the testing resource burden within the framework of a grant-funded project as opposed to the risk of private investment. The US Department of Energy bears the cost of demonstrating these technologies and offers them to the drilling contractor for companion testing in a geothermal exploration and/or production well construction project for in situ evaluation.

Another barrier within geothermal drilling is that the drilling products developed are largely intended for the larger oil and gas and minerals drilling industries. This standard product line is subsequently offered to the geothermal drilling industry without specific regard for the application. This project engages service companies collaboratively with the problems faced by the geothermal drilling industry that forges participation and develops fit-for-purpose solutions specifically for the geothermal drilling industry.

Drilling Project Description

Sandia worked with the US Navy (USN) to accomplish the subject demonstration on a geophysical test hole sponsored by the US Navy Geothermal Program Office (GPO), whose mission is to explore for, develop and manage geothermal resources on Department of Defense (DoD) lands. The historic lead-time for the discovery and development of geothermal resources in the United States is too long – 7 to 10 years or more – to be responsive to Presidential and DoD mandates for the implementation of military installation renewable energy requirements. The GPO has adopted an aggressive exploration philosophy aimed at identifying and assisting in the development of geothermal energy resources on military installations.

CMAGR is a military air and ground training range situated along the eastern margin of the Salton Sea in Southern California. The range is managed by the Marine Corps Air Station, Yuma, AZ. The US Navy Geothermal Program Office began a geothermal energy assessment and exploration activities in 2008 at the request of the Commandant, United States Marine Corps. As a component of its evaluation of the geothermal energy potential, the GPO proposed to drill 1 or 2 deep geophysical test holes to further investigate the temperature field and potential hydrothermal alteration in the Camp Billy Machen/Hot Mineral Spa region. The siting (targeting) for these holes is based on a variety of geological and geophysical data combined with the results of shallow (500-ft) temperature gradient

drilling conducted from January to March 2010. The shallow drilling revealed areas with high near-surface temperature gradients which appear to be associated with buried granitic basement structures. The geologic and geophysical data collected from the resulting holes was compiled and analyzed to provide necessary insight into potential geothermal resources. Sandia and NOV Downhole were invited to participate in demonstrating PDC bits in this environment.

Cooperative work between the USN GPO and Sandia was covered by a Memorandum of Understanding between the Department of Defense and the Department of Energy addressing collaborative development of renewable energy resources. The USN GPO drilling contractor, Barbour Well, agreed to collaborate with Sandia in evaluating the subject drilling technologies during drilling of the geophysical test hole. Sandia, Prime Core, and the Barbour Well mud logging company, Prospect Geotech, fielded instrumentation on the Barbour rig to allow monitoring of drill rig parameters during the drilling process. Sandia worked with bit manufacturer, NOV Downhole (Reed Hycalog), to recommend commercially available bits for use during the subject well construction. NOV Downhole provided the drill bits, readily available from their commercial product line, and also provided knowledgeable personnel on-site to counsel the drilling contractor during the production drilling runs. The Sandia/NOV Downhole team coordinated with the USN GPO and Barbour Well throughout the round-the-clock well construction process to monitor bit performance and recommend preferred implementation methodologies for the drill bits.

Location

The test hole site, 17-8, is located in the northwestern portion of the Chocolate Mountains Aerial Gunnery Range, approximately 13 miles northwest of Niland, Ca. The GPS coordinates for the hole are N 33° 24' 02" W 115° 38' 39" with a surface elevation of 184 feet above sea level. A map of the area is shown in Figure 1.

The Navy Geothermal Program Office (was responsible for all permitting activities. The final permits to drill were granted on 31 October 2011. Pad and road construction began 7 November 2011.

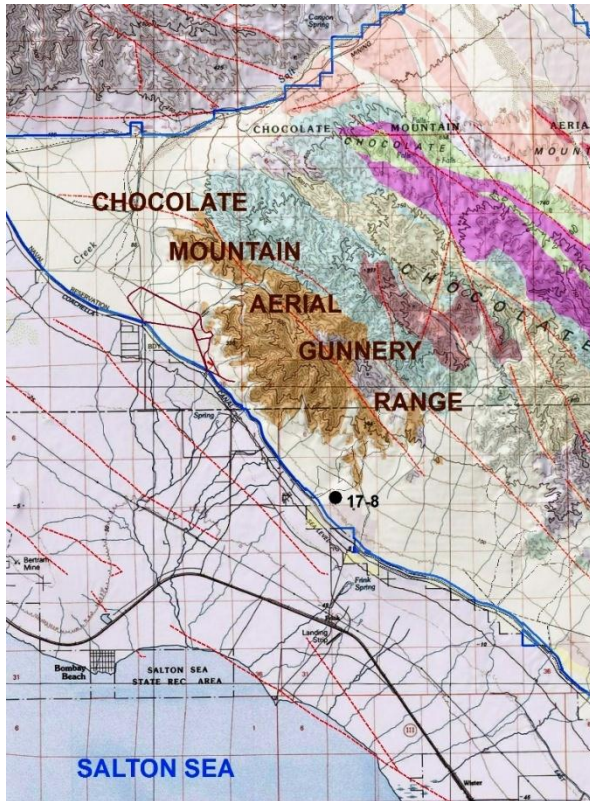


Figure 1. Geophysical Test Hole 17-8, northwest Chocolate Mountains, California.

Rig

The rig used to drill the Chocolate Mountain deep test hole was Barbour Rig 77 (Figure 2). The rig has a double block system with separate blocks for tripping and drilling. The mast is rated for 200,000 pounds static load, and handles a single 30 foot joint of drill pipe. The rotary table is capable of several speed/torque ranges. The PDC bits covered herein were drilled in 5th and 6th gear. This provided a maximum torque of 8761 ft-lbs and a maximum rotary speed of 84 RPM in 5th gear and maximum torque of 6415 ft-lbs with maximum rotary speed of 114 RPM in 6th gear. The maximum torque of the rig became a limiting factor to ROP particularly with one of the PDC bits. A specifications sheet for Rig 77 is included in Figure 3. The kelly bushing (KB) for this drilling operation was 15 feet above ground level. All depth measurements are reported referenced to the KB.



Figure 2. Barbour Rig 77

Barbour Rig 77 Specifications

Pulling Capacity: 200,000 lb

Drawworks: Taylor RT 5000 Driven by (1) C15 CAT 500 HP Diesel Engine.

Mast: Taylor RT 5000 Square set Derrick rated @ 200,000LBS Static Hook Load, Height 70 feet.

Substructure: Height 13.6 feet with 15 foot K.B elevation.

Mud Pump #1: Gardner Denver PZ7 Triplex Pump Powered by (1) Series 60 Detroit 600 HP Tier 3 Engine. Centrifugal Charge Pump.

Mud Pump #2: Gardner Denver PZ7 Triplex Pump Powered by (1) Series 60 Detroit 600 HP Tier 3 Engine. Centrifugal Charge Pump.

Rotary Table: DSM Hydraulically adjustable 18

Swivel & Drilling Block: McKisick 6 Line 100 Ton Swivel PG 60 Western Rubber.

Tripping Block: McKisick 6 Line 100 Ton

Generators: (1) Magnum 235 KW, (1) Magnum 185 KW (when needed), generator trailer.

Mud System: (2)-240 Barrel, 3-Compartment Mud Tank, (1)-5x6x11 Centrifugal Mixing Pump, (1)-5x6x11 Centrifugal Desilting Pump. (Second 220 bbl. Mud Tank by request)

Fuel Storage: (2) 2000 Gallon Fuel Tanks.

Auxiliary Equipment: Survey Machine with 5000 feet of e-line, Pipe Wrangler, 10,000 lbs Multifunction Loader (forklift, front loader and jib boom)

Figure 3. Rig 77 specifications.

Instrumentation

There were three separate instrumentation systems that were used during drilling. One instrumentation system was provided by Prospect Geotech of Albuquerque, NM. Prospect is a commercial mud logging company that provides mud logging services to the oil, gas and geothermal drilling industry. Their drilling instrumentation system is built around the popular National instrument CompactRIO platform. This system allows a number of instrument interfaces as well as wireless connectivity. The system provided the parameters listed in Table 1 at 8 Hz. A wireless receiver was used to get these parameters into the Sandia data acquisition system.

Table 1. Prospect Provided Data

Parameter	Units
Temperature in	°F
Temperature out	°F
RPM	RPM
Hook Load	pounds
Head Height	feet
Standpipe Pressure	psi

A second set of data was acquired by a National Instruments NiDAC system which was co-located with the Sandia data acquisition system. The second set of acquired data provided surface rig acceleration data and rig hydraulic drive system pressure data from which the rig torque was calculated. The parameters acquired by this system are listed in Table 2.

Table 2. Sandia Acquired Data

Parameter	Units
Z Acceleration-1	g
Z Acceleration-2	g
Torque	ft-lbs

The torque values were calculated at 8 Hz and the acceleration data was taken at 512 Hz allowing the use of an FFT to resolve frequencies out to 255 Hz. One accelerometer was mounted on each side of the mast to sense the axial acceleration induced on the mast by the drilling operation. The accelerometers used were Wilcoxon 726 50g units which were mounted on blocks which allow the use of radiator clamps to firmly couple the accelerometers to the test object. A NI 9234 acquisition module was selected which has a hardware antialiasing filter built in as well as a sampling method that oversamples to help eliminate aliasing problems. Once the data was

acquired from the module at 2048 Hz the data passed through a low pass IIR Butterworth 16th order filter with a 3dB point at 184 Hz and finally the data was decimated by a factor of four.

Several calculated data values are derived from the raw data stream. Weight On Bit (WOB) was derived by measuring the hook load and calculating from the tally sheet the drill string weight. WOB is an important parameter as it is one of the values that can be controlled by the driller. Rate Of Penetration (ROP) is calculated from the head height and time. This is the most important parameter in judging the performance of bits. Some care must be taken in the calculation of ROP as the head height signal can be quite noisy. In this particular system, an IIR low pass filter with a 3 dB point of 0.3 Hz was used. This filter was implemented in the LabView software. Depth of cut is calculated from ROP and RPM, and tracks the amount of material removed for each revolution of the bit. A secondary value which is calculated is bit specific energy, a value that can be compared to the compressive strength of the rock to judge among other things the dulling of the bit.

Once the data has been acquired the data from both acquisition systems is assembled into a software frame which allows time synchronization. The LabView based software that was used was a variant of the Diagnostics While Drilling software which was developed by PrimeCore Inc. for the Sandia Geothermal Research Department (Finger, et al 2002). Modifications were made by PrimeCore to adapt the software to this particular task. The software provides a large number of user configurable graphic presentations in a number of classes as shown in Table 3.

All of these graphics display classes are user configurable and can be placed by the user in the display area. This allows the user to custom configure a display area that has the parameters of interest where it is most advantageous to observe the drilling operation. This display system was used in the Chocolate Mountain drilling test with three 23 inch display screens. A Dell T3500 computer provided both the acquisition and display capability. The operational setup is shown in Figure 4.

Table 3. Graphics Classes

Class	Explanation
Chart	Plots time vs. parameter data
Stacked Chart	Plots time vs. up to 8 parameters on one chart
XY Graph	Plotting two parameters against each other; also used for depth vs. parameter charts
FFT Graph	Plots frequency vs. amplitude of the FFT of a parameter. Usually used for accelerometer data
Bar Display	Used to plot a simple indicator for real time use; Used for standpipe pressure or temperature
Intensity Chart	Plots parameter vs. parameter with color and or fading to show time progression
Waterfall Chart	Used to plot FFT data over a long period of time. Can use color to plot additional parameter

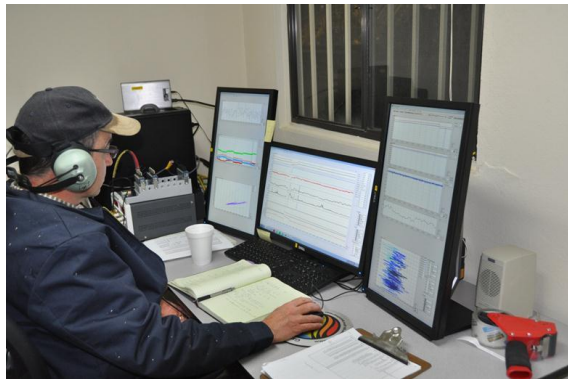


Figure 4. Data acquisition operational configuration.

The third data system was an NOV Downhole provided instrumentation sub capable of supporting two memorizing lateral acceleration and temperature measuring instruments, commonly referred to as plugs. This system is called Black Box™ system, which is commercially available from NOV Downhole. A photo of the system with its sub is shown in Figure 5. The Black Box™ plugs can be programmed to record data at two rates, a slow rate intended to sample data over the duration of the bit run and a fast rate which provides periodic snapshots. The Black Box™ slow sample rate was a sample every 2.56 seconds and the fast rate was set to 400 samples per second for 10 seconds. Further controls in the Black Box™ plug programming allow the user to set a delay before the recording begins and the timing between fast sample periods.

Sandia/NOV set both plugs for a 2.5 hour delay (for tripping in) and the fast samples were triggered every 5 minutes. Because there are two plugs in the system, the fast samples were staggered so that by combining the two plug data sets a fast sample was available every 2.5 minutes. NOV has developed proprietary software that allows the slow sampled data to be processed to yield a number of outputs upon recovery of the plugs. The data set selected from the processed slow data was time, RPM, RMS lateral acceleration, maximum lateral acceleration, centripetal acceleration and temperature. The processed RPM can be compared with surface RPM data to locate RPM events.

Table 4. Black Box™ Processed Data

Parameter	Units
RMS Lateral Acceleration	g
Max Lateral Acceleration	g
Centripetal Acceleration	g
RPM	RPM
Temperature	°F



Figure 5. Black Box™ plug and sub.

Drilling Program

Geology

The prospect area is located along the far eastern margin of the Salton Trough where a thick section of Quaternary alluvium slopes gently westward from the Chocolate Mountains. Away from the mountainside, the alluvium overlies Lake Cahuilla and associated late-Holocene/Pleistocene sediments. The mountains themselves are composed primarily of Tertiary intrusive, hypabyssal rocks - multiple parallel dikes of porphyritic quartz latite composition injected in fine-grained

porphyritic monzogranite of Tertiary age. The abundance and regularity of the dikes gives the appearance of well-layered rock. Isolated occurrences of Tertiary volcanics (rhyodacitic to rhyolitic plug domes, lava flows) are present as well. Underlying these Tertiary units is a Precambrian igneous and metamorphic rock complex (also mapped as the Chuckwalla Complex) of pelitic gneiss, amphibolite, laminated granitic gneiss, augen gneiss. (Powell, R.E., 1994).

Due to the complexity of surface outcrops in the prospect area, it was difficult to estimate what geologic formations the test hole was likely to encounter with any certainty. Three 500-foot deep temperature gradient test holes, in conjunction with the surface mapping, formed the basis for our knowledge of the near surface in this area. Hole TGH-9 intersected Quaternary and older alluvial slope wash, volcanic-dominated, to TD of 500 feet. Below that, we estimated intersecting some assemblage of the Tertiary rocks. This proved to be the case.

Clearly defining complex igneous petrology from drill cuttings during drilling is not easy; however the on-site geologists generally agreed that a bedrock assemblage dominated by granite porphyry, with lesser amounts of andesite and leucogranite was sufficiently correct for our needs, is generally very consistent with the mapping of Powell, and meets the drilling matrix requirements of this drill bit test project. A detailed petrographic analysis is under way at the University of Utah's Energy and Geoscience Institute.

Drilling Summary

A 13-3/8 conductor was set to 115 feet KB and cemented in place prior to the commencement of drilling. Final preparations were begun during the afternoon and evening of Nov 27 2011. The hole was spudded with an HTC type GX-C1V 12- 1/4 inch mill tooth tri-cone bit in the early morning hours of November 28. Drilling continued throughout the day and the hole was advanced to 647 feet by the end of the day. On the 29th drilling continued with the HTC bit to a depth of 734 feet. At 734 feet the HTC bit was run out of the hole and replaced with a Smith type GF-S15 roller cone tungsten carbide insert bit. The hole was then advanced to 844 feet by the end of the day on the 29th. On the 30th the hole was advanced to 911 feet at which time the Smith bit was run out of the hole. A Security type S84F bit was run into the hole and drilling continued to 916 feet by the end of the day.

Drilling on 1 December 2011 commenced at 916 feet with the Security bit and the casing point at 1225 feet was reached shortly before the end of the day. The 2nd and 3rd of December were spent logging the hole and running and cementing 9-5/8 inch 40 #/ft K55 casing to 1220 feet in the 12-1/4 inch hole. The BOP for the drilling of the lower portion of the hole was put in place and tested on the 4th of December. On the 5th of December the hole was reamed from that depth to 1245 feet and drilling commenced at that point to 1345 feet with an HTC GT-09 roller cone bit.

The HTC bit was pulled from the hole and the Sandia/NOV DRS813M-B21 eight blade PDC bit (here in referred to as bit 1) was run into the hole and the hole was advanced to 1472 feet by the end of the day. On December 6th the Sandia/NOV bit drilled from 1472 to 1918 feet. On the 7th the bit advanced the hole to 2070 feet and was pulled from the hole. The second Sandia/NOV bit, a type DSR713M-B21 seven blade PDC bit (referred to as bit 2), was run in the hole and advanced to 2194 feet by the end of the day. The 8th of December the hole was advanced with bit 2 to 2518 feet. On the 9th of December drilling continued with the second Sandia/NOV bit to 2643 feet.

In the early afternoon the bit was pulled from the hole and a Security type XSD30D roller cone bit (referred to as bit 3) was run in the hole and drilled from 2643 to 2647 feet by the end of the day. The 10th of December the Security bit advanced the hole to 2856 feet by the end of the day. On the 11th of December the Security bit continued drilling to 2929 feet at about 0830 hours. The string was then pulled from the hole and it was discovered that the bit, the near bit stabilizer, a drill collar and a second stabilizer had sheared off and had been left in the hole. Fishing commenced at 2000 hours and was ongoing at the end of the day. The fish was recovered in the early morning hours of the 14th of December. The HTC type GT09 bit was re-run (i.e., it was used before Bit 1) in the hole and the hole was advanced to 3007 feet by the end of the day. In the early morning hours of the 15th of December the HTC bit drilled the final footage to TD of 3020 feet, reaching TD at 0300 hours. Logging commenced by 1200 hours and was still in progress at the end of the day. On the 16th the 4-1/2 inch casing was run and the well head was attached. The 17th was the final day of drilling activity with the rig being rigged down.

Bit 1

As mentioned in the drilling summary the first Sandia/NOV bit was an 8-1/2 inch type DRS813M-B21 PDC bit. This bit was a last minute substitution as the team had originally brought 8-3/4 inch bits and discovered that they would not fit in the 9-5/8 inch casing. This bit is referred to as bit 1 or 1A. Bit 1 was a truly commercial bit that fortunately was in stock at the NOV warehouse in Bakersfield, California. This bit, in new condition, is shown in Figure 6. It was an eight blade, eight nozzle PDC bit. It is equipped with arrestors (aka Torque Control Components or TCCs) that prevent too large a depth of cut. The arrestors serve to protect the cutting structure from damage due to excessive WOB, but the arrestors also limit the ROP by their design. The Bottom Hole Assembly (BHA) consisted of the bit, a data acquisition sub, a bit sub, the near bit stabilizer, one drill collar, the intermediate stabilizer, another drill collar, the upper stabilizer and 14 drill collars. This configuration provided 41,159 pounds of weight in air for the bit to drill efficiently and is similar to conventional BHAs used in the drilling of geothermal holes in the area. Reaming began at a depth of 1337.7 feet. The bit drilled from 1345 to 2070.1 a total of 725 feet. The average ROP for bit 1 was 26.45 feet/hour (ft/hr) with a minimum of 16.8 ft/hr and a maximum of 38.2 ft/hr. This is a substantial improvement over conventional roller cone bits. The stand by stand data is shown in Table 5.

The bit after drilling is shown in Figure 7. Bit 1 was examined carefully after it was pulled from the hole and found to be still capable of drilling further with only slight cutter damage.

Bit 2

Bit 2 was an NOV type RH DSR713M-B21 PDC bit. This bit was a seven blade design without any arrestors and thus was a more aggressive bit. This bit had four user selected nozzles and three fixed nozzles. Drilling commenced at 2070 feet (shows as 2073 after tally adjustment in some records) where bit 1 had been pulled from the hole and continued to 2643 feet. Bit 2 drilled a total of 573 feet in granitic rock similar to that drilled by bit 1. The BHA was modified from the bit 1 BHA partially in order to try to limit the deviation of the hole. The BHA consisted of the bit, a data acquisition sub, a drill bit sub and 1 drill collar. The first stabilizer was then put in line and a second drill collar. The final stabilizer was inserted at his point and 14 drill collars to complete the BHA. Bit 2, in

new condition, is shown in Figure 10. Very shortly after drilling commenced with bit 2, it was noted that in order to get good performance out of the bit, the rig had to be run very near the torque stall point and this took considerable attention by the driller to maintain performance. Bit 2 averaged 20 ft/hr ROP over its run with a maximum of 28.9 ft/hr and a minimum of 11.2 ft/hr. Bit 2 was pulled from the hole on the afternoon of December 9th after the ROP began to drop. Stand by stand data for bit 2 is shown in Table 6.

The condition of bit 2 after it was pulled from the hole is shown in Figure 11. Careful inspection of the photo shows that three cutters on the inside two rows of the bit are missing. It is of course conjecture, but one probable cause is excessive dynamic/impact loading caused by running the bit very near the torque stall point of the rig, and having to restart the bit from frequent torque stalls and drill-offs. The aggressive nature of bit 2 resulted in a bit-preferred operating condition with a tendency to drill fast yet this operating condition exceeded available rig torque and resulted in frequent rotary table stalls; alternatively, the driller would pull the bit off bottom when it torqued-up to avoid impending stalls.

Bit 3

Bit 3 was used immediately after Bit 2 and is used herein for performance comparisons since it was used to drill the same formation. It was a type XDS30D roller cone insert bit manufactured by Security. A picture of the bit before going into the hole is shown in Figure 14. Bit 3 started drilling from 2643 feet, where bit 2 had been pulled from the hole. The team observed and recorded only 3 stands of data from bit 3 for comparison. Bit 3 averaged 10.7 ft/hr with a maximum of 15 ft/hr and a minimum of 7.3 ft/hr. This is lower than the minimum ROP seen with bit 1 or 2. The BHA for bit 3 was similar to that used with bit 2 with the removal of the data acquisition sub. Bit 3 drilled to 2929 feet where it sheared off as a result of a drill collar failure. Bit 3 was fished from the hole after drilling 283 feet and another bit was used to drill the final footage. The stand by stand data for the bit 3 stands that were monitored is shown in Table 7.



Figure 6. Bit 1 before drilling.



Figure 7. Bit 1 after removal at 2070 ft.

Table 5. Bit 1 Stand by Stand Data

Start Depth	Stop Depth	ROP	Total Depth
1337.7	1369.4	30.7	31.7
1369.4	1401.4	24.0	63.7
1401.4	1433.2	26.9	95.5
1433.2	1465	22.7	127.3
1465	1496.8	19.1	159.1
1496.8	1528.3	25.7	190.6
1528.3	1560.4	21.2	222.7
1560.4	1592.2	24.5	254.5
1592.2	1624	30.3	286.3
1624	1656	26.7	318.3
1656	1687.9	24.8	350.2
1687.9	1719.7	25.8	382
1719.7	1751.7	27.4	414
1751.7	1783.5	31.4	445.8
1783.5	1815.5	23.9	477.8
1815.5	1847.4	27.4	509.7
1847.4	1879.2	38.2	541.5
1879.2	1911.1	25.5	573.4
1911.1	1942.8	33.4	605.1
1942.8	1974.7	30.9	637
1974.7	2006.5	30.2	668.8
2006.5	2038.2	16.9	700.5
2038.2	2070.1	20.8	732.4
Average		26.5	
MIN		16.9	
MAX		38.2	

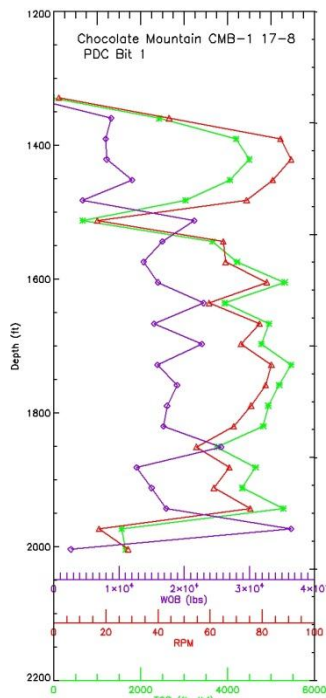


Figure 8. Bit 1 surface measurement of WOB , RPM, and Torque .

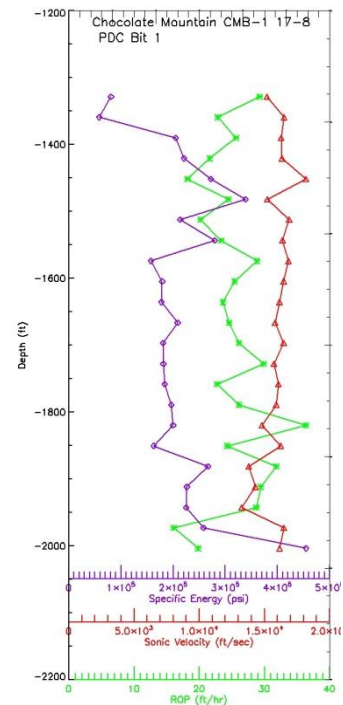


Figure 9. Comparisons of specific energy , sonic velocity and ROP for the Bit 1 drilling interval.



Figure 10. Bit 2 before running in hole.



Figure 11. Bit 2 after being pulled at 2634 ft.

Table 6. Bit 2 Stand by Stand Data

Start Depth	Stop Depth	ROP	Total Drilled
2073	2105	21.4	32
2105	2137	24.6	64
2137	2165	25.6	92
2165	2194	28.9	121
2194	2223	25.5	150
2223	2251.5	24.4	178.5
2251.5	2279.9	23.7	206.9
2279.9	2308.3	23.0	235.3
2308.3	2336.4	28.6	263.4
2336.4	2365.2	25.4	292.2
2365.2	2393.8	16.4	320.8
2393.8	2422.4	15.1	349.4
2422.4	2454.4	18.1	381.4
2454.4	2486.3	19.2	413.3
2486.3	2518.3	17.4	445.3
2518.3	2550.1	12.8	477.1
2550.1	2581.9	11.2	508.9
2581.9	2613.8	13.3	540.8
2613.8	2645.8	12.4	572.8
Average		20.4	
MIN		11.2	
MAX		28.9	

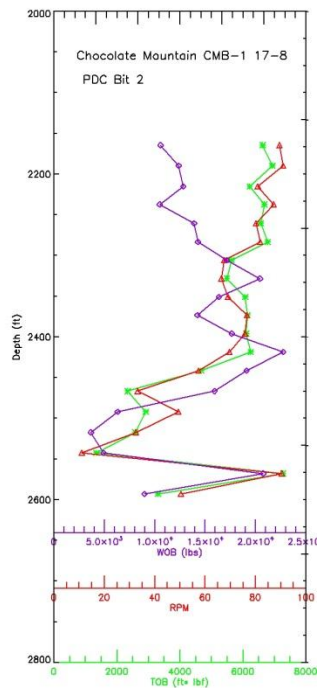


Figure 12. Bit 2 surface measurements of WOB , RPM , and Torque .

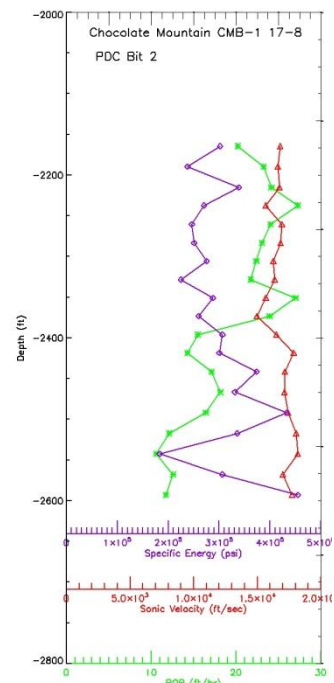


Figure 13. Comparisons of specific energy , sonic velocity and ROP for the Bit 2 drilling interval.



Figure 14. Bit 3 before going into the hole.

Table 7. Bit 3 Stand by Stand Data

Start Depth	Stop Depth	ROP	Total Footage Drilled
2643	2674.9	7.3	31.9
2674.9	2706.9	9.9	63.9
2706.9	2738.8	15.0	95.8
Average		10.7	
MIN		7.3	
MAX		15.0	

Logging

The logging suite was the same in both the upper and lower sections. Schlumberger Well Services ran an array induction with caliper, gamma ray, spontaneous potential, temperature, borehole compensated sonic and ultrasonic borehole imager logs in the upper portion of the well prior to the 9-5/8 inch casing being run. This set of logs was run on December 2nd. The same suite of logs was run on the 15th of December in the lower section of the hole after reaching TD.

An equilibrated temperature gradient log was run 29 March 2012 by Southwest Exploration Services to a depth of 3003 feet, bgl.

Data Analysis

The sonic velocity from the log of the lower section of the hole is compared to measurements of the ROP and specific energy for bit 1 and 2 in figures 9 and 13 respectively. The comparison of ROP and sonic velocity is as one would expect, as the sonic velocity goes up implying harder rock the ROP is decreased. Comparison of figures 15 and 16 shows a higher peak RMS lateral acceleration in figure 15 in several areas particularly in the early part of the run. One possible explanation of this is that the TCC of the bit limited the Depth Of Cut (DOC) to such a degree that proper engagement of the formation for optimal stabilization was not achieved. In general higher levels of vibration are expected for higher

ROPs and larger DOCs. However, sometimes limiting the DOC can result in higher RMS Vibration.

Figures 17 and 18 show the correlated surface and downhole RPM for bits 1 and 2; the downhole RPM is estimated from the centripetal acceleration. (This is not a precise measure of RPM but is well correlated to downhole torsional stability and stick slip; note baseline drift accumulates in bit 2 response). Torsional and lateral vibration are clearly evident in the downhole measurements.

Drilling Cost Comparisons

The rock reduction component of drilling costs for this drilling program can be computed and compared to consider the cost savings that can be realized due to PDC bits replacing roller cone bits on typical geothermal drilling projects. NOV has quoted the PDC bits run in this trial are available to the geothermal drilling industry at a lease rate of \$4 per foot with a \$14,500 minimum charge (i.e., the minimum charge applies for footages up to 3625 ft) with no repair charges provided the PDC bit body is not damaged. However, if the PDC bit body matrix is damaged, then the bit return is denoted Damaged Beyond Repair (DBR) and the cost of the bit increases to a percentage of list price; NOV has quoted \$46,888 per bit for the PDC bits used in this drilling program.

By contrast, the roller cone, bit 3, was a re-run (manufacturer’s refurbishment) and was purchased at a fixed price of \$3200. Using the Barbour Rig 77 rate and a round-trip tripping rate of 1000 ft/hr, drilling costs are computed and summarized in Table 8, using the formulations in the appendix. Several cases can be considered to compare the rock reduction component of drilling costs for PDC and roller cone bits:

- Case A – PDC Bit 1 drilled the 725 ft interval from 1345’ to 2070’ at a rate of \$45/ft at an interval cost of \$33k.
- Case B – If the roller cone, Bit 3, drilled the interval described in Case A, a total of two bits would be required based upon actual ROP performance and bit life observed on-site for roller cone bits (i.e., approximately 10 ft/hr and 400 ft, respectively), which anecdotally is comparable to industry-wide performance of roller cones for geothermal drilling. This results in an interval cost of \$72.40/ft with an interval cost of \$52k.

- Case C – PDC Bit 2 was damaged beyond repair, due to frequent drill-offs, during the course of drilling from 2070 to 2645 ft. Accordingly, the DBR cost was incurred producing a footage rate of \$115/ft at an interval cost of \$65k.
- Case D – If the rig had greater torque capability, PDC Bit 2 would not have been damaged beyond repair, resulting in a total interval rate of \$59/ft and an interval cost of \$33k.
- Case E – If the roller cone, bit 3, drilled the bit 2 interval at typical industry rates, the cost would have been \$77/ft at an interval cost of \$44k.

Furthermore if adequate rig torque were available that was matched to the capabilities of the PDC Bit 2, further costs savings could have been realized due to the additional penetration rate capability of this bit as the preferred penetration rate of the bit was not achievable. Further savings can be realized in the future with the development of fit-for-purpose PDC bit designs for geothermal drilling solutions.

For this project, the Bit 1 interval was drilled at a cost savings of \$19k (Case A vs. B). Due to Bit 2 not being well-matched to rig capabilities, the bit 2 interval was more expensive than if it had been drilled by a roller cone (Case C vs. E.) Yet with adequate matching of rig torque to bit requirements, the bit 2 interval could have been drilled with \$11k of cost savings (Case D vs. E.)

Table 8. Rock Reduction Component of Drilling Costs.

Case	Bit Type	Bit	Scenario	Bit Cost, BC [\$]	ROP [ft/hr]	Footage Drilled, L [ft]	Initial Depth, ID [ft]	Drilling Time, DT [hr]	Trip Time [hr]	Cost Per Foot [\$ /ft]	Interval cost [\$k]
A	PDC	Bit 1	Actual performance	\$15,000.00	26.5	725	1345	27.4	2.1	\$ 45	\$32,780
B	Roller Cone	Bit 3	if Bit 3 drilled the Bit 1 interval	\$ 3,200.00	10	400	1345	40.0	1.7	\$ 71	\$52,507
				\$ 3,200.00	10	325	1745	32.5	2.1	\$ 74	
C	PDC	Bit 2	DBR	\$46,888.00	20.4	566	2070	27.7	2.6	\$ 115	\$65,243
D	PDC	Bit 2	Adequate rig torque - no DBR	\$15,000.00	20.4	566	2070	27.7	2.6	\$ 59	\$33,355
E	Roller Cone	Bit 3	if Bit 3 drilled the Bit 2 interval	\$ 3,200.00	10	400	2070	40.0	2.5	\$ 72	\$43,681
				\$ 3,200.00	10	166	2470	16.6	2.6	\$ 89	

Conclusions

From the data presented herein it can be concluded that commercial-off-the-shelf PDC bits are capable of drilling geothermal wellbores at ROPs well above that experienced with roller cone bits and further that these PDC bits have demonstrated longer lifetimes than roller cones in this geothermal drilling environment. The use of bits with impact arrestors (Torque Control Components) should be considered, but it should be possible to design a bit, BHA, and drilling program that would maximize ROP without TCC in the bit. Using PDC bits successfully requires that the parameters of the rig be well matched to the needs of the bit with respect to torque and RPM. Further the use of advanced automatic drilling hardware is necessary if optimum performance is to be achieved.

The project team is quite encouraged by the performance of the off-the-shelf bits in this environment and the next phase of this project is to develop and test new bits that are optimized to the geothermal drilling environment.

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Appendix

Drilling Cost per Foot is calculated using (Lapeyrouse):

$$CPF = (BC + RR(DT + TT))/L$$

where

CPF = Cost Per Foot, [\$/ft]

BC = Bit Cost, [\$]

RR = Rig Rate, [\$/hr]

DT = Drilling Time, [hr]

TT = Trip Time, [hr]

L = Footage Drilled, [ft]

Using the performance parameters for ROP and bit life, the corresponding drilling time is computed as

$$DT = L / ROP$$

and

$$TT = (ID + L)/TR$$

where ID is the initial depth, [ft],

and TR is the round-trip trip rate [ft/hr].

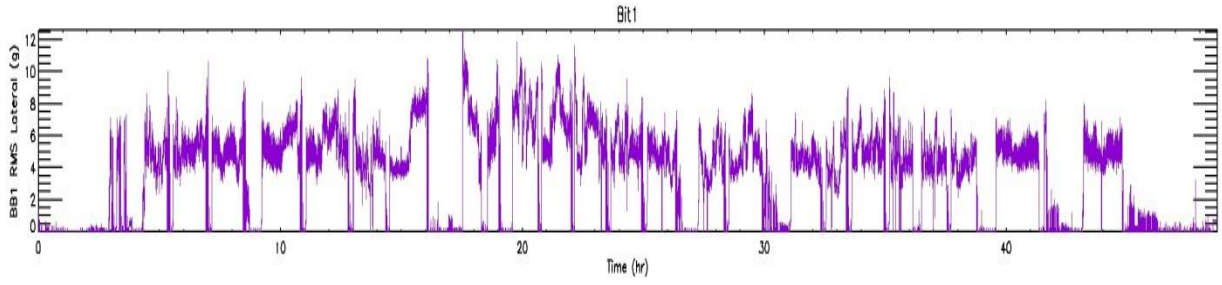


Figure 15. Bit 1 RMS Lateral Acceleration (BB#762) throughout run.

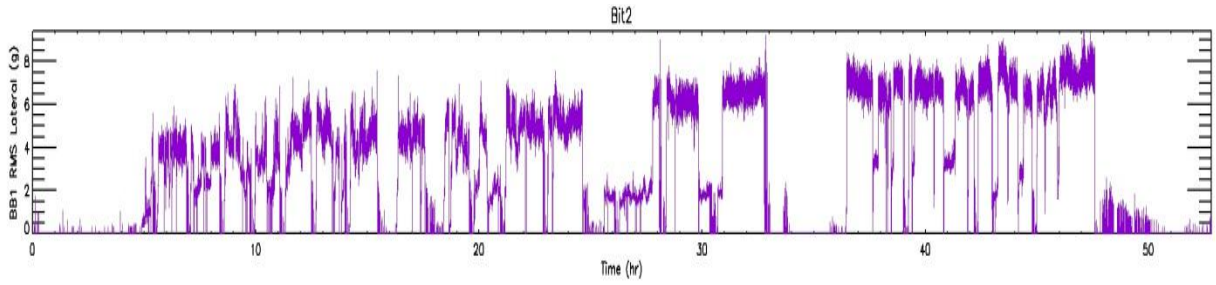


Figure 16. Bit 2 RMS Lateral Acceleration (BB#744) throughout run.

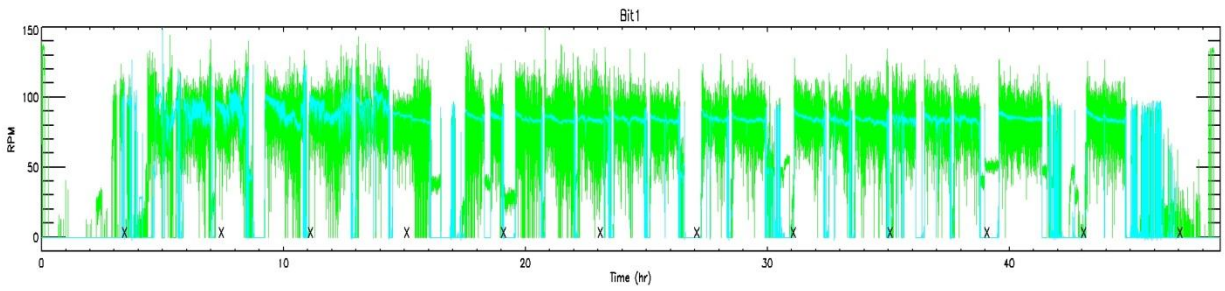


Figure 17. Comparisons of uphole (blue) and downhole (green) rotary speed measurements (per BB #762) for Bit 1.

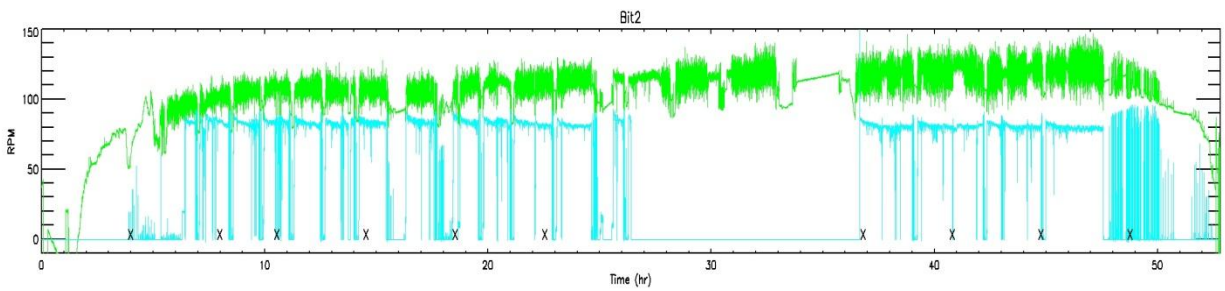


Figure 18. Comparisons of uphole (blue) and downhole (green) rotary speed measurements (per BB #744) for Bit 2.