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Analysis of Drilling Performance Using PDC Bits, Fallon FORGE Well 21-31

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ABSTRACT

FORGE well 21-31 was drilled and completed to a total depth of 8,139 ft from 5 February to 31 March 2018. Specifying the surface location, drilling, and testing of the 21-31 deep exploration well was a primary activity of Fallon FORGE Phase 2B. While the primary objective for drilling the well was to assess that subsurface conditions of the Fallon FORGE site, drilling the well offered opportunities to test the performance of drilling technology in the geothermal conditions of the Fallon geothermal resource, which included comparative analysis of bit performance for the polycrystalline diamond compact (‘PDC’) bits used to drill the 21-31 well versus the tri-cone bits used to drill the nearby Fallon 82-36 well.

PDC bits are routinely used by the oil and gas industry for drilling medium to hard rock but continue to see limited application in the geothermal industry, largely due to previous reliability issues and higher purchase costs. Design improvements have led to reliability improvements and, as evidenced by the case study of Well 21-31’s drilling performance, when correctly applied (with adequate attention given to bit selection and drilling parameters), PDC bits can present a drill-time reduction advantage that can offset their higher purchase cost. Specific steps that may be taken during planning and execution of well drilling to further improve and realize the time and cost benefit that PDC bits can provide are described herein.

1. INTRODUCTION

FORGE well 21-31 was drilled and completed to a total depth of 8,139 ft from 5 February to 31 March 2018. Specifying the surface location, drilling, and testing of the 21-31 deep exploration well was a primary activity of Fallon FORGE Phase 2B. Figure 1 shows the geographical location of the well. The objective of drilling the 21-31 well was to evaluate and confirm permeability characteristics, the presence and characteristics of the crystalline basement rock, and the requisite temperatures required for the FORGE project. These objectives and the exploration results of well 21-31 are described in more detail in a forthcoming paper by Kraal *et al.* (in prep).

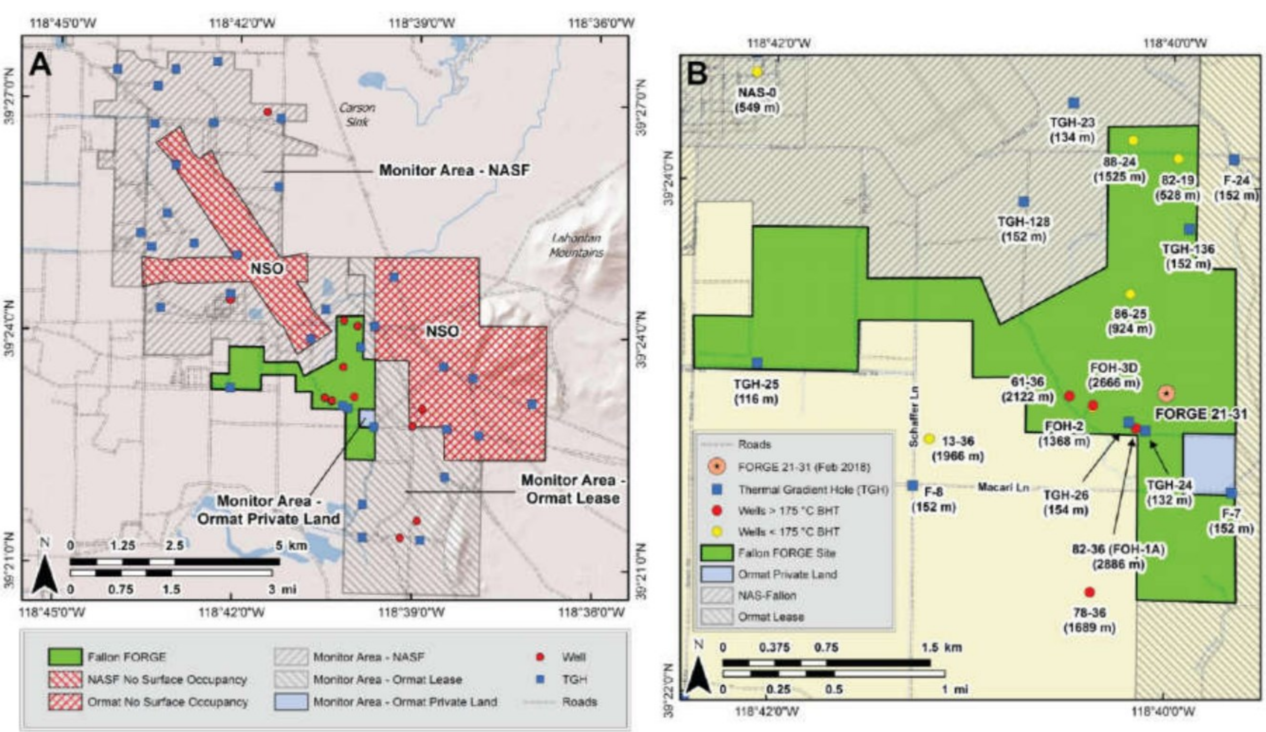

Figure 1: Map of the Fallon FORGE site and Location of Well 21-31. Modified from Sandia (2018).

A secondary objective of the 21-31 well was testing the performance of drilling technology in the geothermal conditions of the Fallon geothermal resource. Review and summary of drilling performance is the topic of this paper, which includes:

- An analysis of days-versus-depth for 21-31 and a comparison to off-set well 82-36, which is also located within the Fallon project area.
- A summary of drilling results for each section (including a record of bits and the bottom-hole assemblies ('BHAs')) used during the drilling process.
- Comparison of bit performance (e.g., rate-of-penetration ('ROP'), mechanical specific energy ('MSE' (i.e., the energy required to remove a unit volume of rock)), wear, and footage cost) for the different polycrystalline diamond compact ('PDC') bits used to drill the 21-31 well versus the tri-cone bits used to drill the nearby 82-36 well.

All depths in this report are referenced to the rig floor (KB), 22 ft above ground level. The well was drilled by Ormat Nevada Inc. ("Ormat") on behalf of the Fallon FORGE team. The well is located at Section 30, T18N, R30E in Churchill County, Nevada.

Drilling was conducted using Rig 6 from Paul Graham Drilling, Inc. from Rio Vista, California. Rig 6 is a 1,000 HP conventional land rig, with a box-on-box substructure and a double derrick that is hydraulically raised, and cable scoped. The rig is rated for a maximum depth of 10,500 ft with 4-1/2-in drill pipe. It has two Gardner Denver PZ-9, 1,000 HP triplex pumps and a total active drilling fluid capacity of 400 barrels.

Drilling engineering and supervision were conducted by Ormat. Well site geology and mud logging were provided by Horizon Well Logging (HWL). Directional equipment services were provided by Scientific Drilling, Inc. (SDI). Cementing services were provided by Resource Cementing (Rio Vista, California). Mud engineering and supplies were provided by Sinclair Well Products. All drill bits used in drilling well 21-31 were PDC bits (or PDC hybrid bits), primarily manufactured by National Oilwell Varco (NOV) (one bit was manufactured by Security) and supplied by San Joaquin Bit Service.

Well 21-31 was spudded on 5 February 2018 at 3:00 AM, and the rig was released at 8:30 AM on 31 March 2018, after a total of 55 days. The total active time spent was 862.5 hours. A detailed analysis of the time by activity (including non-productive time) is presented in Table 1. The Rimbase drilling monitoring program was used for summary and analysis of well 21-31 data described herein.

Operations Time Analysis — GEOTHERMEX, INC.
Well ID: FORGE 21-31 — Well Name: FORGE 21-31
Sect: 30 Town: 18N Rng: 30E County: Churchill State: NV

P. Graham Rig 6	Total Hrs	% of Total
BOPOPS		
BOP Nipple Up	48.00	5.6
Other BOP Operations	0.50	0.1
BOP Testing	29.33	3.4
Total	**77.83**	**9.0**
CASING		
Running Casing	33.00	3.8
Total	**33.00**	**3.8**
CEMENT		
Primary Cement Operations	24.02	2.8
Waiting On Cement	21.50	2.5
Total	**45.52**	**5.3**
DRILL		
Circulate/Condition Mud	53.57	6.2
Cement Squeeze	15.00	1.7
Drill Cement	5.75	0.7
Drilling Ahead w/ Connections	2.18	0.3
Drilling - Rotating	339.28	39.3
Reaming/Underreaming	3.22	0.4
Running Survey Tools	1.00	0.1
Total	**420.00**	**48.7**
EVALUATE		
Leak Off Test	6.00	0.7
Wireline Logging	12.25	1.4
Testing Operations, DST etc	39.00	4.5
Total	**57.25**	**6.6**
OTHER		
Slip and cut drilling line	5.50	0.6
Other Activity	2.25	0.3
Rig Service	10.00	1.2
Welding Operations	4.00	0.5
Total	**21.75**	**2.5**
PROBLM		
Rig Repairs	12.33	1.4
Waiting on Equipment	23.98	2.8
Waiting on Orders	2.25	0.3
Waiting on Personnel	3.00	0.3
Total	**41.57**	**4.8**
TRIP		
BHA Operations	42.75	5.0
LDTOOL	3.50	0.4

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Operations Time Analysis — GEOTHERMEX, INC.
Well ID: FORGE 21-31 — Well Name: FORGE 21-31
Sect: 30 Town: 18N Rng: 30E County: Churchill State: NV

P. Graham Rig 6	Total Hrs	% of Total
Run In Hole	0.92	0.1
Tripping in	59.83	6.9
Tripping Out	51.08	5.9
Total	**158.08**	**18.3**
DRILL		
Make Up Bottom Hole Assembly	0.50	0.1
Total	**0.50**	**0.1**
OTHER		
Stand by	7.00	0.8
Total	**7.00**	**0.8**
Total Elapsed Time for Well	**862.50**	
Total Non-Productive Time for Well	**52.82**	**6.1**
Total Productive Time for Well	**809.68**	**93.9**

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Table 2: Well 21-31 Operational Time Analysis

The well was spudded from the bottom of the 20-in conductor pipe, which had been cemented at a depth of 130 ft (KB). The well was drilled in three sections: 17-1/2-in from 130 ft to 910 ft; 12-1/4-in from 910 ft to 6,058 ft; and 8-1/2-in from 6,058 to 8,100 ft. A total of 9 BHAs and 9 drilling bits (including 1 re-run) were used in the drilling operation (see Tables 2 – 3 for details of BHAs and drilling bits used).

BHA Summary Report
Well ID: FORGE 21-31

GEOTHERMEX, INC.
Well Name: FORGE 21-31
Sect: 30 Town: 18N Rng: 30E County: Churchill State: NV

										Weight in Air (lbs)				Buoyed Weight (lbs)					
No	Date/Time In	Depth In	Date/Time Out	Depth Out	Drilling Hrs	RPM	WOB Avg/Max	BHA Len	Drillstring Len	BHA	Drillstring	Above Jars	Below Jars	BHA	Drillstring	Above Jars	Below Jars	HWt in BHA	Mud Wt
1	02-Feb-18	130	07-Mar-18	910	10.48	187	700/2,000	354.53	354.53	45,256	45,256	13,092	28,075	38,961	38,961	11,271	24,170	Yes	9.10
	Items: BIT, BS, MMTR, SSTAB, NMPC, NMDC, MWD, HYBRID, NMDC, S.S., DC, JARS, DC, X-O, DC									**Comments:** BHA 1 USED WITH BIT 1									
2	07-Feb-18	910	12-Feb-18	910	29.00	50	5,000/10,000	895.97	895.97	62,941	62,941	41,345	17,506	54,282	54,282	35,657	15,098	Yes	9.00
	Items: BIT, MMTR, DC, JARS, DC, XO, DC, HWDP									**Comments:** BHA 2 USED WITH MILLED TOOTH BIT 2, FOR DRILLING CEMENT INSIDE THE SHOE TRACK									
3	12-Feb-18	910	15-Feb-18	3,406	53.32	295	4,800/15,000	970.11	970.11	72,978	72,978	41,345	27,543	62,939	62,939	35,657	23,754	Yes	9.00
	Items: BIT, MMTR, SSTAB, NMPC, NMDC, MWD, HYBRID, NMPC, SHKSUB, DC, JARS, DC, XO, DC, HWDP									**Comments:** BHA 3 USED WITH PDC BIT 3									
4	15-Feb-18	3,406	20-Feb-18	4,380	72.63	190	19,600/25,000	974.82	974.82	73,506	73,506	41,345	28,071	63,169	63,169	35,531	24,123	Yes	9.20
	Items: BIT, MMTR, SSTAB, NMPC, NMDC, FLOW, NMPC, NMPC, SHKSUB, DC, JARS, DC, XO, DC, DC									**Comments:** BHA 4 USED WITH PDC BIT 4									
5	20-Feb-18	4,380	02-Mar-18	6,058	66.50	184	17,300/20,000	974.96	974.96	74,052	74,052	41,345	28,129	63,186	63,186	35,278	24,002	Yes	9.60
	Items: BIT, MMTR, SSTAB, NMPC, NMDC, FLOW, NMPC, NMPC, SHKSUB, DC, JARS, DC, XO, DC, HWDP									**Comments:** BHA 5 USED WITH BIT 3 (RE-RUN)									
6	02-Mar-18	6,058	06-Mar-18	6,562	19.25	194	13,500/15,000	882.88	882.88	51,332	51,332	33,883	14,596	44,662	44,662	29,481	12,700	Yes	8.50
	Items: BIT, RR, PONYDC, RR, XO, MMTR, RR, NMPC, NMDC, NMXO, FLOW, NMPC, NMPC, SHKSUB, DC, JARS, DC, HWDP									**Comments:** BHA 6 USED WITH PDC BIT 6									
7	06-Mar-18	6,562	08-Mar-18	6,894	26.03	204	20,600/35,000	882.67	882.67	51,409	51,409	33,883	14,673					Yes	
	Items: BIT, RR, PC, RR, XO, MMTR, RR, NMPC, NMDC, NMXO, FLOW, NMPC, NMPC, SHKSUB, DC, JARS, DC, HWDP									**Comments:** BHA 7 USED WITH BIT 7									
8	08-Mar-18	6,894	10-Mar-18	7,561	32.42	199	14,000/18,000	882.94	882.94	51,578	51,578	33,883	14,842					Yes	
	Items: BIT, RR, PONYDC, RR, XO, MMTR, RR, NMPC, NMDC, NMXO, FLOW, NMPC, NMPC, SHKSUB, DC, JARS, DC, HWDP									**Comments:** BHA 8 USED WITH PDC BIT 8									
9	10-Mar-18	7,561	13-Mar-18	8,100	22.97	208	20,800/30,000	882.99	882.99	51,516	51,516	33,883	14,780					Yes	
	Items: BIT, RR, PONYDC, RR, XO, MMTR, RR, NMPC, NMDC, NMXO, FLOW, NMPC, NMPC, SHKSUB, DC, JARS, DC, HWDP									**Comments:** BHA 9 USED WITH PDC BIT 9									

Table 2: Well 21-31 BHA Summary Report

Bit Summary Report
Well ID FORGE 21-31

GEOTHERMEX, INC.
Well Name: FORGE 21-31
Sect: 30 Town: 18N Rng: 30E County: Churchill State: NV

	Run														Depth (ft)		Hole		ROP	WOB		Flow													
No	No	Diam	Manuf.	Model	Serial No	Nozzles - 1/32 in							TFA	Date/Time In	In	Out	Made (ft)	Hrs	(ft/hr)	AVG (lbf)	RPM	(gal/m)	MWt	Major	Loc	Brg	Grading			Gge	Oth	Pull	Cost ($)	Cost ($)/ft	Notes
Well I FORGE 21-31																																			Well Name: FORGE 21-31
1	1	17.500	NOV	TFX519S	E118718	14	14	14	14	14			0.752	02-Feb-18 03:30	130	910	780	10.5	74.4	700	146	754	9.10	1	1	NO	A		X	1	NO	TD	$36,000.00	$46.15	
2	1	12.250	SEC	R24AMP	K71752	16	16	16					0.589	10-Feb-18 08:00	910	910	0	0.0	0.0	0	0	0	9.00										$16,875.00	-	Milled tooth
3	1	12.250	NOV	SKH716D	E152286	16	16	16	16	16	16	16	1.374	12-Feb-18 01:30	910	3406	2496	53.3	46.8	4800	108	750	9.20	2	1	CT	N		X	1	NO	BHA	$29,875.00	See re-run	
4	1	12.250	NOV	E716	A206781	16	16	16	16	16	16	16	1.374	15-Feb-18 16:15	3406	4382	976	72.6	13.4	19600	166	720	9.20	1	1	PN	A		X	1	NO	BHA	$29,875.00	$30.61	
5	2	12.250	NOV	SKH716D	E152286	15	15	15	15	15	15	15	1.208	20-Feb-18 12:00	4382	6058	1676	66.5	25.2	17300	161	706	9.60	2	1	CT	A		X	1	NO	TD	Re-Run	$7.16	Bit re-run
6	1	8.500	NOV	E716	A188388	15	15	15	15	15	15	15	1.208	02-Mar-18 15:30	6058	6562	504	19.3	26.2	13500	190	550	8.50	2	1	CT	N		X	1	NO	HP	$19,500.00	$38.69	
7	1	8.500	NOV	E716	A187387	15	15	15	15	15	15	15	1.208	06-Mar-18 22:00	6562	6894	332	26.0	12.8	20600	179	598	8.50	3	2	WT	A		X	1	NO	BHA	$19,650.00	$59.19	
8	1	8.500	NOV	FT76	A247357	16	16	16	12	12	12		0.920	08-Mar-18 19:00	6894	7561	667	32.4	20.6	14000	195	590	8.50	2	1	CT	N		X	1	WT	BHA	$45,150.00	$67.69	
9	1	8.500	NOV	FT76	A247356	16	16	16	12	12	12		0.920	10-Mar-18 19:30	7561	8100	539	23.0	23.5	20800	208	600	8.50	2	2	CT	N		X	1	WT	TD	$45,150.00	$83.77	

Table 3: Well 21-31 BHA Summary Report

The well was drilled vertically from surface with directional control and was actively steered to the depth of the last casing string. Directional drilling continued with a motor in the open hole where a very small angle (3 degrees) was developed in the SW direction from 7,000 ft to TD (8,100 ft). The maximum horizontal well departure at 8,100 ft from its surface location was 81 ft. A borehole schematic is provided on Figure 2.

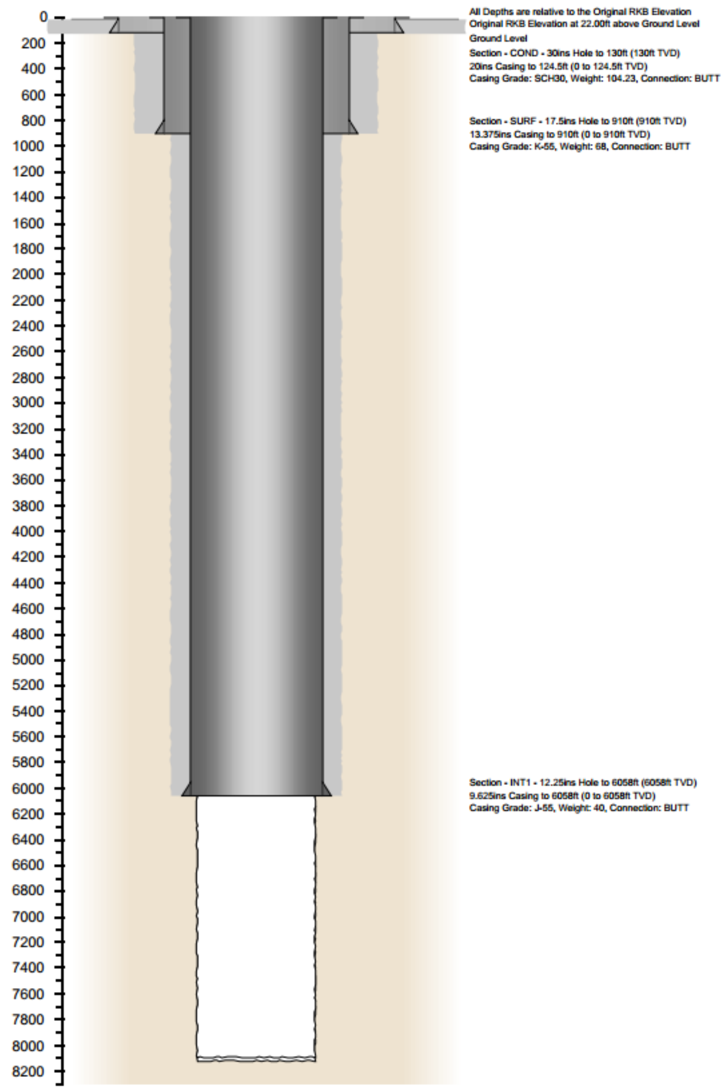


Figure 2: Well 21-31 Borehole Schematic

An 8-1/2-in coring bit and a 40-ft core barrel were used to core the interval from 8,100 ft to 8,139 ft, recovering less than one foot of core.

A series of geophysical logs was run in the open hole, including Schlumberger's Triple Combo, sonic and caliper logs from 300 to 6,062 ft; dipole sonic, FMI and external temperature from 6,055 to 8,109 ft; and Triple Combo (MT-LEH-STGC-QILE-QCNT-HLDT-QAIT) from 5,970 ft to 8,139 ft. Analysis of wireline geophysical logging are summarized in Kraal *et al.* (in prep) and Perdana *et al.* (2020). Sidewall cores (1-1/2-in x 3-in and 1 x 2-in) were then cut at multiple depths, ranging from 8,075 through 6,435 ft, retrieving a total of 45 sidewall core samples.

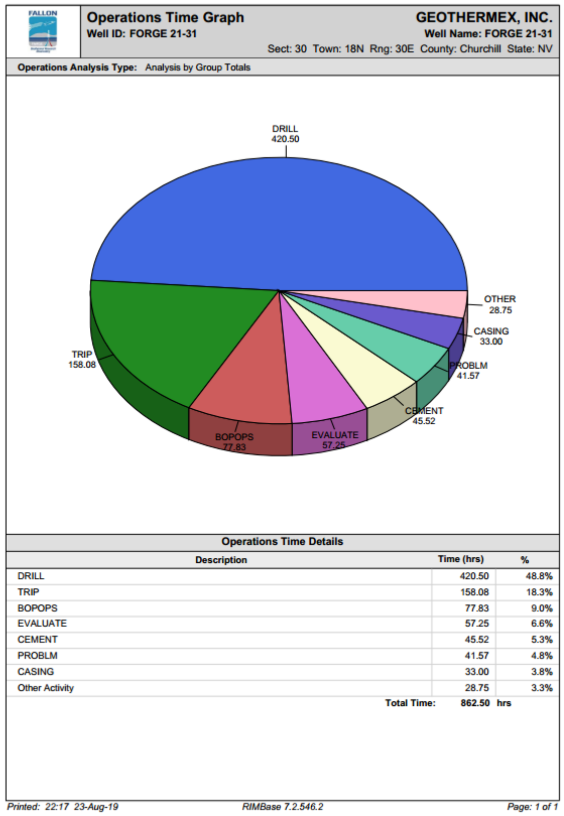
Well testing by injection took place on two different occasions: 4 March and 13-15 March 2018. These testing activities are described in more detail within Kraal *et al.* (in prep).

As completed, well 21-31 conforms very closely to its intended program. Provided below is a discussion of the results obtained from the various PDC bits used to drill the well intervals. Also described below is a comparison of the drilling results of well 21-31 with nearby well 82-36, located in the Fallon project area (Figure 1). The 82-36 wellhead is approximately 2,000 ft south-west from the location of 21-31.

2. DRILLING SUMMARY

The construction of the drilling pad for well 21-31 began on 13 January 2018. A 20-in conductor pipe was set using a small rat-hole digger rig and cemented at an approximate depth of 110 ft below surface level (132 ft KB). Paul Graham's Rig 6 was moved to the 21-31 wellsite between 25 January and 4 February 2018 and drilling commenced on 5 February 2018.

A summary of time spent in drilling the well, separated by category (including non-productive time), is presented on a graph on Figure 3.



Description	Time (hrs)	%
DRILL	420.50	48.8%
TRIP	158.08	18.3%
BOPOPS	77.83	9.0%
EVALUATE	57.25	6.6%
CEMENT	45.52	5.3%
PROBLM	41.57	4.8%
CASING	33.00	3.8%
Other Activity	28.75	3.3%
Total Time:	862.50	hrs

Figure 3: Well 21-31 Operations Time Graph

The first stage of the well (17-1/2-in) was drilled from the bottom of the conductor pipe during February 5 and 6. The 13-3/8-in, K-55, 68 lb/ft, buttress-threaded casing was set at the depth of 910 ft. This stage was drilled with a single 17-1/2-in PDC bit (Bit #1), which drilled a total of 780 ft in 10.5 hours, corresponding to a rate of penetration (ROP) of approximately 74.4 ft per hour (ft/h). No circulation losses or formation problems were reported for this interval. Table 3 summarizes bit details including model, nozzle arrangement, date/time in, footage drilled, hours, ROP, bit cost, cost/ft, etc. for each bit used to drill 21-31.

The 13-3/8-in casing was cemented by pumping 223 barrels of Therma-Lite, 13 pounds per gallon (lbm/gal) lead slurry, followed by 51 barrels of Therma-Tail, 15 ppg tail cement slurry. An approximate volume of 80 barrels of cement slurry returned to surface and no top jobs were needed.

After drilling out the casing shoe, a casing shoe integrity test failed when pressured to a formation fracture gradient of 0.61 psi/ft. The section below the shoe was squeezed and cement was allowed to set, after which it passed a casing shoe integrity test of 0.57 psi/ft.

Drilling of the 12-1/4-in hole continued between 12 and 24 February 2018, from 910 ft to 6,058 ft using BHA's 2 – 5 (Table 2). A total of 3 PDC bits (with the 3rd bit being a re-run of the 1st) were used to drill 5,148 ft in approximately 192 drilling hours, with an average ROP of 28.5 ft/h. Individual bits and their associated drilling parameters and performance (on average) were as follows:

- Bit #3: ROP (46.8 ft/h); depth in/out (910/3,406 ft); hours (53.2); WOB avg (4,800 lbf); RPM (108); flow (750 gal/min). For this bit, the WOB and MSE are considered relatively low (Figure 4).

- Bit #4: ROP (13.4 ft/h); depth in/out (3,406/4,382 ft); hours (72.6); WOB avg (19,600 lbf); RPM (166); flow (720 gal/min). For this bit, ROP was relatively low, while WOB, RPM, MSE, and torque were high. The ROP of Bit #4 is noted to have been caused by a missing nozzle that was not installed by the drilling team prior to tripping the bit into the well.

- Bit #5: ROP (25.2 ft/h); depth in/out (4,382/6,058 ft); hours (66.5); WOB avg (17,300 lbf); RPM (161); flow (706 gal/min). This bit (a re-run of Bit #3) showed improved ROP (compared to Bit #4), with similar if somewhat higher WOB, similar RPM and torque, and significantly lower MSE.

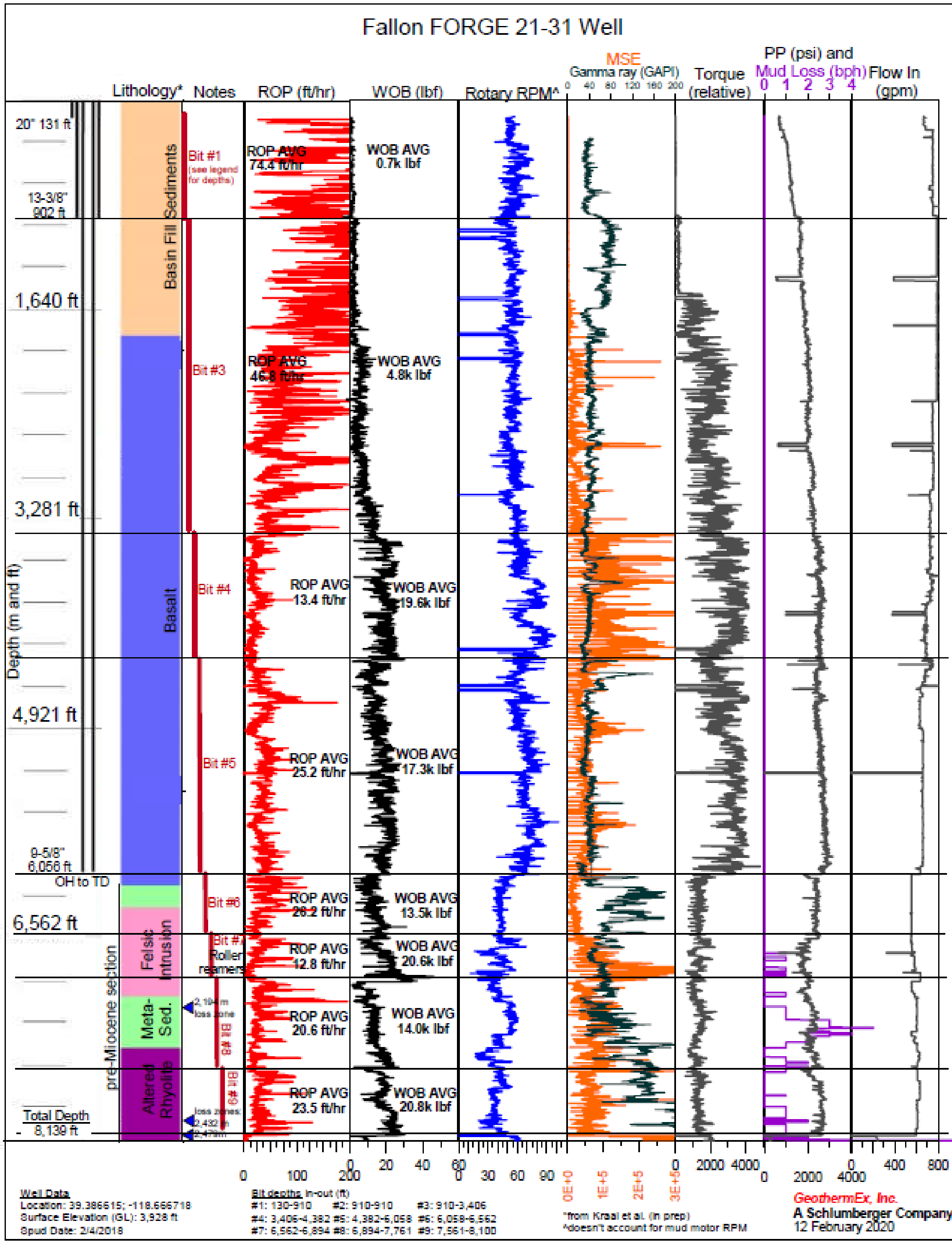


Figure 4: Well Construction, Geology, and Drilling Parameters for the Fallon FORGE 21-31 Well

Bit #3 performed appreciably better than Bit #4, and a bit trip was made specifically to inspect Bit #4 and then to replace it with a re-run of Bit #3. The re-run Bit #3 (referred to as Bit #5 above and on Table 3) did not achieve the same ROP as its first run but again outperformed Bit #4. Cumulatively, Bits #3 and #5 achieved a notable $7.16/ft of drilled hole (i.e., bit cost/total footage drilled), which is significantly better than Bit #4's $30.61/ft. The individual cost and the cost/ft determined for each bit are provided on Table 3. We note that footage costs are interesting to evaluate, but may not be particularly meaningful for well 21-31 because the bits were not run to the end of their useful life, as is often done when drilling conventional wells. For well 82-36, 12-1/4-in tricone bit cost was not available, which would allow a comparison of whether PDC bits were more profitable than the tricone bits in the Fallon conditions.

On 25 February geophysical logs were run in the 12-1/4-in open wellbore with a Platform Express Quad Combo (density, neutron porosity, resistivity, and Sonic Scanner (e.g., compressional shear, Stoneley slownesses, and waveform)) from 300 to 6,062 ft. These logs are summarized in Kraal *et al.* (in prep) and Perdana *et al.* (2020).

The 9-5/8-in, J-55, 40 lb/ft, buttress-threaded casing was set at the depth of 6,058 ft and was cemented by pumping 635 barrels of Therma-Lite HT, 13.5 ppg lead slurry, followed by 41 barrels of Therma-Tail, 15 ppg tail cement slurry. Partial cement returns were experienced while pumping the lead cement, and total losses occurred while pumping the tail cement portion. A decision was made to flush the annular space with water and pump 94 barrels of 13.5 ppg Therma-Lite HT cement slurry through the annulus, followed by squeezing 20 barrels of 13.5 ppg RC-Therma-Lite HT cement slurry and holding the pressure for one hour. The results of this second operation were successful, as the operation sealed the annulus sufficiently to surface, allowing drilling to continue.

Drilling continued between 3 and 12 March 2018 with 8-1/2-in Bits #6 through #9 from 6,058 ft to 8,100 ft. A total of 4 PDC bits were used to drill this 2,042 ft interval in approximately 101 drilling hours, with an average ROP of 20.7 ft/h. A polymer mud was used to drill this section of the well with elevated mud temperatures, measured by the MWD tools to be in the range of 160 – 230°F. Individual bits and their associated drilling parameters (on average) were:

- Bit #6: ROP (26.2 ft/h); depth in/out (6,058/6,562 ft); hours (19.3); WOB avg (13,500 lbf); RPM (190); flow (550 gal/min). This bit provided the best ROP in the pre-Miocene metamorphic, plutonic and altered-volcanic section (encountered below approximately 5,500 ft) and had notably low MSE compared to later bit runs (Figure 4).
- Bit #7: ROP (12.8 ft/h); depth in/out (6,562/6,894 ft); hours (26.0); WOB avg (20,600 lbf); RPM (179); flow (598 gal/min). This bit provided higher than average ROP to start, but due to mechanical issues (described below) it then declined during the bit run. The MSE increase during the bit run may have been reflective of the mechanical issues that affected this bit run.
- Bit #8: ROP (20.6 ft/h); depth in/out (6,894/7,561 ft); hours (32.4); WOB avg (14,000 lbf); RPM (195); flow (590 gal/min). This bit had lower ROP than Bit #6, though lower WOB was used. The relatively high MSE is notable and is likely reflective of drilling dysfunctions attributable to the reduced WOB (likely bit whirl).
- Bit #9: ROP (23.5 ft/h); depth in/out (7,561/8,100 ft); hours (23.0); WOB avg (20,800 lbf); RPM (208); flow (600 gal/min). Compared to Bit #6, this bit had the second highest ROP and second lowest MSE, and was drilled with minor losses.

Overall, Bits #6, #8, and #9 performed comparably for ROP while being used to drill similar footage.

Bit #7 started with higher than average ROP but its performance declined in the deeper part of its run (this is noted on Figures 4 and 5 as a decline in ROP with depth), possibly due to declining motor performance as motor failure was the reason for the trip at the end of this run.

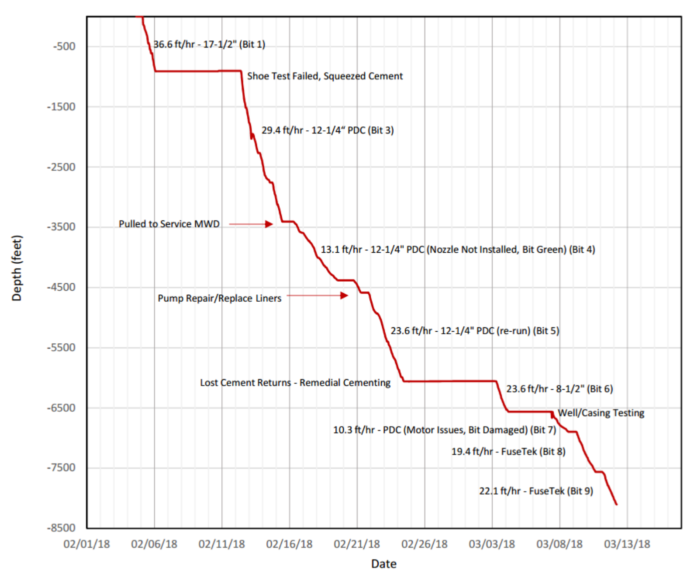


Figure 5. Rotary Drilling Days vs. Depth Performance of Well 21-31 (with annotation). Refer to Table 3 for details on (Bit #).

On closer inspection of the Bit #7 run, when this bit was pulled out and inspected because the string pressured up (and ROP reduced), it was noted to have rubber inside from the motor. While the bit was not at the end of its useful life it did have the most wear of all bits run in this hole. It was replaced with a new bit while the BHA was out of the hole to reduce the need for future trips. Regarding the rubber pieces that were found inside the bit, the problem may have been caused by excessive torque in the mud motor and the higher mud temperatures. Both factors may have played a role in the stator degradation.

After reaching a depth of 8,100 ft, there was a series of attempts to conduct formation permeability testing on selected intervals of the open hole section of the well. A summary of permeability testing activities and results is provided in Kraal *et al.* (in prep).

On 19 March, a coring operation was conducted to drill and recover a solid core from the formation between 8,100 and 8,139 ft (the well's TD). About a foot of cored formation was retrieved. The core barrel was re-run to bottom on 23 March in an attempt to collect the unretrieved core without success, and the core barrel was then laid down.

Geophysical logs were run on 20 March (Dipole Sonic, FMI, External Temperature) and 24 March (Triple Combo: MT-LEH-STGC-QILE-QCNT-HLDT-QAIT and Temperature-Pressure) from 6,080 to 8,140 ft. During the up-run, the logging tool became stuck and had to be retrieved with a fishing overshot operation. These logs are summarized in Kraal *et al.* (in prep) and Perdana *et al.* (2020).

Between 25-27 March, sidewall coring operations took place in the interval between 8,075 and 6,435 ft. A total of 45 samples were recovered (16 samples were 1-1/2 x 3-in and 29 were 1 x 2-in).

Equipment was rigged down between 28-31 March, and the rig was released at 8:30 AM on 31 March 2018.

3. DRILLING BIT ANALYSIS

It is difficult in any drilling situation to conduct a comparative bit analysis, because specific and accurate formation and rig data for the well is typically not available. The differences in geologic environments, combined with the driller's application of WOB, RPM, and pump rate, plus the choice of the most appropriate nozzle combination, and even the bit brand and IADC type, make it very hard to make a direct comparison.

For the specific case of well 21-31 there were significant differences in the number of hours and the footage drilled by the larger diameter bits used in the upper hole compared with the smaller diameter bits, as shown in Table 3 and Figure 4. In general, the larger bits showed higher ROP and longer hole sections and were notably more efficient (achieved better cost-per-foot-drilled) than the smaller bits, which were used to drill shorter intervals with lower ROP, while noting the smaller bits used to drill 21-31 were not run to the end of their useful life. The relative short drilled intervals of the smaller bits are compounded by the longer tripping time required to pull them out of the hole, yielding a larger cost per foot of hole.

The MSE of each bit run is characterized in the section above. Because the measurement of drilling torque was relative (i.e., the measurement was determined using an idler on the kelly bushing chain drive and is therefore unitless), MSE was also relative. A discussion of the means by which MSE may be determined is provided in a paper by Dupriest and Koederitz (2005). Analysis of relative MSE during drilling, and modification of drilling parameters (including WOB, RPM, torque, and PP) to reduce MSE, proved useful at guiding operations toward greater drilling efficiency and ROP improvements during the drilling of 21-31. Consideration must be given to changes in geologic conditions that may influence MSE. For example, the lowest relative MSE recorded for 21-31 was for the Bit #6 run (6,058-6,562 ft; Figure 4), which corresponded with a lithology change from altered-basalt to quartzite and a felsic intrusion (with the quartzite and felsic intrusion showing an associated gamma ray increase at the point when MSE decreased).

Ormat provided data for nearby well 82-36 (drilled in March of 2008) within the same region of the Carson Sink and in similar geologic formations. This well was drilled to the depth of 9,500 ft and completed in 12-1/4-in diameter, using only tricone bits instead of PDC bits as in well 21-31. The general comparison we can make of the performance of the 12-1/4-in bits used in both wells to drill pre-Miocene metamorphic and/or altered igneous rock shows that the ROP drilled by the PDC bit on 21-31 (over a section of 608 ft) was better than the ROP of the tricone bits used in 82-36 (over a section of 3,750 ft), illustrated on Figure 6. For 82-36, 12-1/4-in section ROP ranged from 8.3 – 12.8 ft/h (average of 10.5 ft/h), compared to an average of 35.4 ft/h for Bit #5 of 21-31. The 12-1/4-in section of 82-36 was drilled utilizing the Verti-Trak system from Baker Hughes, which is considered a fast and efficient directional controlled system. Without the Verti-Trak, the 82-36 ROP would almost certainly have been lower.

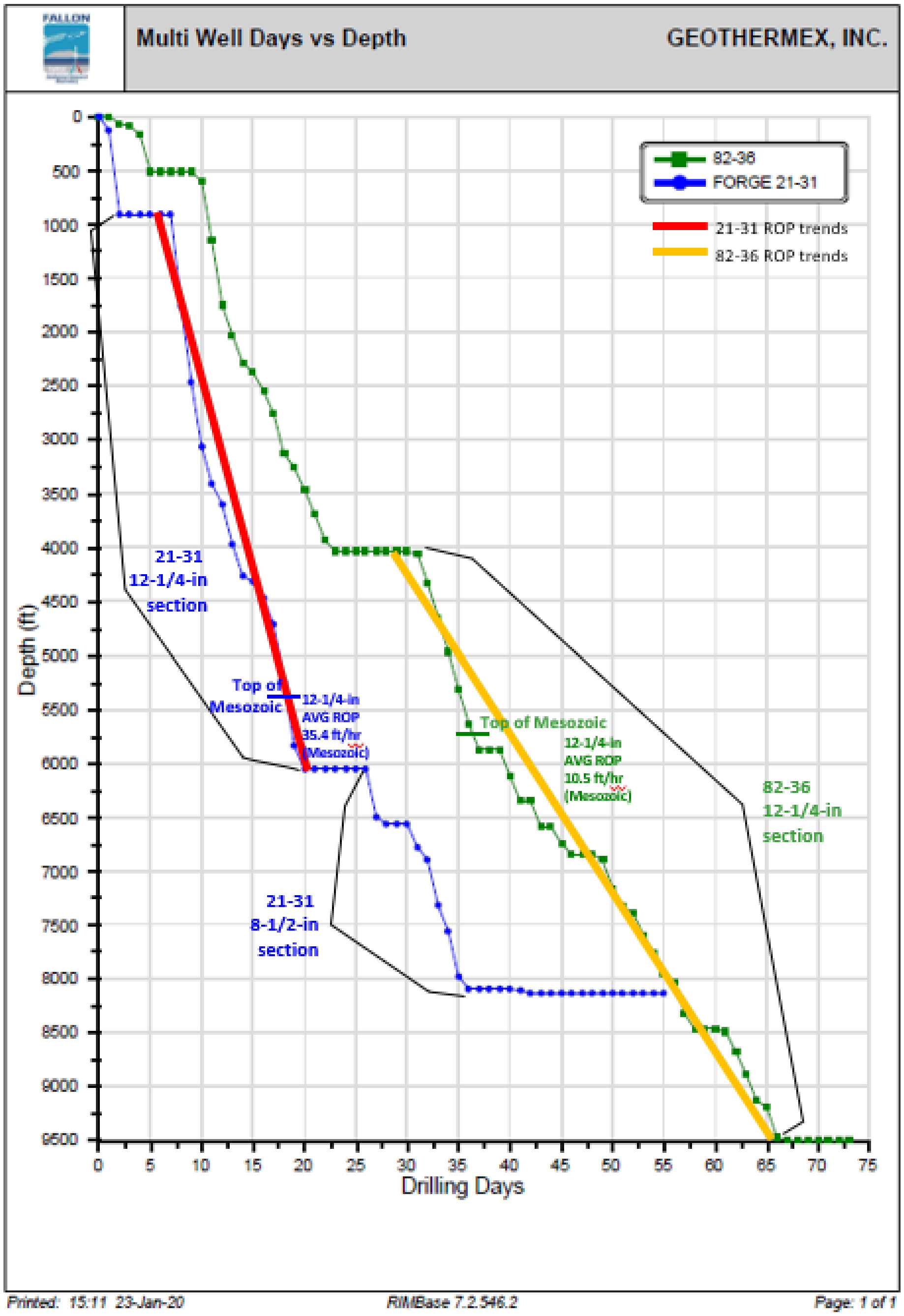


Figure 6. Well 21-31 and Well 82-36 Days vs. Depth Plots and Average Well Section ROPs

A closer comparison of ROP with the geologic section of 82-36 may allow for more insight in this ROP assessment (i.e., ROP is greater in the shallower part of the hole and lower in the deeper part where pre-Miocene lithologies are present; this is also the case with 21-31).

For a well of similar design to 82-36, without considering the number of trips, and by applying the average ROP achieved for the PDC bits from 21-31 (35.4 ft/h) and the tricone bits from 82-36 (10.5 ft/h), the 12-1/4-in the pre-Miocene section (5,750 – 9,500 ft) could be drilled in 106 hours and 357 hours, respectively. This represents a time improvement of 10.5 days with PDC bits (that may be translated as drilling time), again irrespective of bit trips. We can infer in crystalline basement rock that tricone bits last 500-600 ft on average (as represented by the 12-1/4-in section of 82-36) and that PDC bits may last roughly 1-3 times as long (as represented by 12-1/4-in and 8-1/2-in bits for 21-31, noting that many of these bits were not damaged beyond repair). This indicates that 7-8 tricone bits would be required to drill the section while 3-8 PDC bits would be required for the same section. With PDCs acquired for a price that is twice that of tricone bits (assuming PDC bits cost an average of USD 32,000 (Table 3)), this results in a potential cost savings (by use of fewer PDC bits) of USD 16,000 (assuming 3 PDC bits to 7 tricone bits) to a potential additional cost of USD 128,000 (assuming 8 PDC bits and 8 tricone bits). In the case of bit cost savings by using fewer PDC bits, this presents an obvious advantage. In the case of USD

128,000 in additional costs for these bits, this reduces but does not eliminate the savings from drilling time improvements by using PDC bits, provided they are used to drill consistently at higher ROP. Raymond *et al.* (2012) provides a more detailed evaluation of PDC bit performance and costs compared to tricone bits from drilling Test Hole 17-8, Chocolate Mountains, California.

It is noteworthy that the cost for PDC bits can vary depending on whether the bit's body was repairable or if it was instead damaged beyond repair, based on inspection after the bit is retrieved from the hole. Although difficult to predict, if the PDC bits can be retrieved in a repairable condition, their cost per foot will drop significantly, reducing the cost differential between PDC and tricone bits.

Per standard wear charts, none of the bits run in well 21-31 were worn to their maximum capacity, on a scale from 0-8; the most damaged one (Bit #7) is indicated to have been a "3". Therefore, it is possible the bits could have drilled more than (possibly double or triple) the 500-600 ft on average noted above, though possibly with reduced ROP because of bit-face wear.

Figure 5 shows the days vs. depth plot provided by Sandia with notations on drilling activities and bit ROP performance; it is comparable to 21-31 on Figure 6, which presents a days vs. depth plot for both wells. Comparing the slope of the two curves for the 12-1/4-in section between 900 and 4,000 ft, we can clearly observe that the ROP of the PDC bits used in well 21-31 was significantly higher than that of the tricone bits in well 82-36.

4. CONCLUSIONS

FORGE well 21-31 was drilled and completed to a total depth of 8,139 ft from 5 February to 31 March 2018. Specifying the surface location, drilling, and testing of the 21-31 deep exploration well was a primary activity of Fallon FORGE Phase 2B. The objective of drilling the 21-31 well was to evaluate and confirm permeability characteristics, the presence and characteristics of the crystalline basement rock, and the requisite temperatures required for the FORGE project. A secondary objective was testing the performance of drilling technology in the geothermal conditions of the Fallon geothermal resource, specifically, to assess the different polycrystalline diamond compact ('PDC') bits used to drill the 21-31 well versus the tricone bits used to drill the nearby Fallon 82-36 well.

It is difficult in any drilling situation to conduct a comparative bit analysis, because specific and accurate formation and rig data for the well is typically not available. The differences in geologic environments, combined with the driller's application of WOB, RPM, and pump rate, plus the choice of the most appropriate nozzle combination, and even the bit brand and IADC type, make it very hard to make a direct comparison.

Analysis of relative MSE during drilling, and modification of drilling parameters (including WOB, RPM, torque, and PP) to reduce MSE, proved useful at guiding operations toward ROP improvements during the drilling of 21-31. In particular, where MSE was high, ROP was low. MSE can and should be used to identify bit and BHA performance issues. Consideration must also be given to changes in geologic conditions that may influence MSE.

Results of wells 21-31 are compared to nearby well 82-36 drilled in 2008 within the same region of the Carson Sink and in similar geologic formations. Comparing the slope of the two curves for the 12-1/4-in section between 900 and 4,000 ft, we can clearly observe that the ROP of the PDC bits used in well 21-31 was significantly higher than that of the tricone bits in well 82-36.

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