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Analysis of Rig Parameter Data Using Drilling Process Modeling Constraints

Volume 1: Summary of Utah FORGE Wells 16A(78)-32, 56-32, 78B-32 and 16B(78)-32

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ABSTRACT

Drill rig parameter measurements are routinely used during deep well construction to monitor and guide drilling conditions for improved performance and reduced costs. While insightful into the drilling process, these measurements are of reduced value without a standard to aid in data evaluation and decision making. In the main body of this work (Volume 1), a method is demonstrated whereby rock reduction model constraints are used to interpret drilling response parameters; the method could be applied in real-time to improve decision-making in the field and to further discern technology performance during post-drilling evaluations. Drilling parameters are evaluated using laboratory-validated rock reduction models for predicting the phenomenological response of drag bits (Detournay and Defourny, 1992) in computational algorithms. The method presented has applicability to development of advanced analytics on future geothermal wells using real-time electronic data recording for improved performance and reduced drilling costs. A drilling cost model is also used to show the tradeoff between rate of penetration and bit life and the influence on interval drilling costs.

Details of the bit specifications and performance are cataloged in an independent volume, documented under separate cover, for each of the four wells, and include Volume 2: Utah FORGE 16A(78)-32; Volume 3: Utah FORGE 56-32; Volume 4: Utah FORGE 78B-32 and Volume 5: Utah FORGE 16B(78)-32.

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EXECUTIVE SUMMARY

The United States Department of Energy has sponsored development of geothermal well construction at the Utah Frontier Observatory for Research in Geothermal Energy (FORGE). Drill rig parameter data were acquired by drilling contractor Frontier Drilling and evaluated for four wells: 1) Utah FORGE 16A(78)-32, a directional injection well with vertical depth to a kick-off point at 5892 ft and a 65 degree tangent to a measured depth of 10987 ft and, 2) Utah FORGE 56-32, a vertical monitoring well to a depth of 9145 ft, 3) Utah FORGE 78B-32, a vertical well drilled to a depth of 9500 ft, and 4) Utah FORGE 16B(78)-32, a directional production well drilled vertically to a kick-off point at 5269 ft, and a 65 degree tangent to a measured depth of 10947 ft. Sandia National Labs has accessed, cataloged, evaluated and recorded drill bit performance information used on the four Utah FORGE wells herein.

The subject drilling program has resulted in a large database of bit performance and durability records for drilling hot, hard rock characteristic of geothermal reservoirs. The majority of the Utah FORGE wells were drilled almost exclusively with Polycrystalline Diamond Compact (PDC) drill bits. The characteristic features of PDC bits and cutters are accordingly reviewed. While synthetic diamond cutter materials and bit design methodologies have improved over time, the recent success of these types of bits in hard rock formations may also be attributed to monitoring of drilling system response parameters using electronic data recorders on the surface rig for preferential performance and bit health monitoring.

Drill rig parameter measurements are routinely used during deep well construction to monitor and guide drilling conditions for improved performance and reduced costs. While insightful into the drilling process, these measurements are of reduced value without a standard to aid in data evaluation and decision making. In the main body of this work (Volume 1), a method is demonstrated whereby rock reduction model constraints are used to interpret drilling response parameters; the method could be applied in real-time to improve decision-making in the field and to further discern technology performance during post-drilling evaluations. Drilling parameters are evaluated using laboratory-validated rock reduction models for predicting the phenomenological response of drag bits (Detournay and Defourny, 1992) in computational algorithms. The method presented has applicability to development of advanced analytics on future geothermal wells using real-time electronic data recording for improved performance and reduced drilling costs.

Bit program and performance summaries are tabulated and presented for each well. These summaries include bit manufacturer model references, drilling system penetration rates, and overall bit lives. Representative drilling parameter data are evaluated to illustrate parameter use to monitor bit response, wear, and cutting structure damage. These bits failed by both normal wear and tear and drilling dynamic dysfunctions resulting in chipped and worn cutters, cutter shear and ring outs. Nevertheless, exemplar bit penetration rates easily exceeded 100 ft/hr and produced several 100 feet of hole construction. The tradeoff between rate of penetration and bit life is addressed with a drilling cost model using representative drilling cost parameters.

Details of the bit specifications and performance are cataloged in an independent volume, documented under separate cover, for each of the four wells, and include Volume 2: Utah FORGE 16A(78)-32; Volume 3: Utah FORGE 56-32; Volume 4: Utah FORGE 78B-32 and Volume 5: Utah FORGE 16B(78)-32. Bottom hole assembly information and daily drilling reports are also included.

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
BHA	Bottom Hole Assembly
DOE	Department of Energy
EDR	Electronic Data Recording
FORGE	Frontier Observatory for Research in Geothermal Energy
GTO	Geothermal Technology Office
ROP	Rate of Penetration
WOB	Weight on Bit

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1. BACKGROUND AND INTRODUCTION

Geothermal drilling is difficult as the rock is hot, hard, and often fractured. Wellbore construction costs have historically dominated the cost of geothermal energy development and have been an impediment to widespread development of geothermal energy. Technology improvements are needed to enable improved access and reduced drilling costs.

One technology improvement that can be applied to geothermal wellbore construction is the use of polycrystalline diamond compact (PDC) drill bits. Research and development on PDC drill bits has been sponsored by the United States Department of Energy for years resulting in improved diamond formulations, bonding techniques, bit designs, and hardening features that comprise the state of the art in the drilling industry. The oil and gas industry has benefited widely from these developments as the bits are routinely used to drill the majority of oil and gas wells worldwide. While the geothermal industry has benefited from incidental use of PDC bits for geothermal drilling, recent use of PDC bits at the DOE-sponsored Utah FORGE site has resulted in significant data for evaluation to address the efficacy of PDC bits for geothermal drilling.

1.1. Utah FORGE

The DOE-sponsored program, Utah Frontier Observatory for Research in Geothermal Energy (FORGE) was implemented to foster the development and demonstration of technologies supporting commercial applications of geothermal energy. The site is located near Milford, Utah (Moore, 2019). US DOE sponsorship of the FORGE activities de-risks developing technology for accessing deep geothermal reserves on a broad scale. One of the primary obstacles to commercial geothermal development is high drilling costs. The FORGE campaign applies state-of-the-art drilling technology to demonstrate well construction and completion activities on a utility scale. Multiple wells are planned over the life of the FORGE program. Well 16A(78)-32 was a directional well; 56-32 was drilled as a vertical monitoring well; 78B-32, was a vertical well; and 16B(78)-32, was a directional well. These four wells were drilled with the top-drive, triple shown in Figure 1-1.

Figure 1-1. Frontier Rig 16 used to drill wells 16A(78)-32, 56-32, 78B-32 and 16B(78)-32.

1.2. Sandia Role

With a long legacy of programmatic research pertaining to the development of synthetic diamond drill bit technology, Sandia is participating with DOE/EERE/GTO and the Utah FORGE drilling program to provide evaluations of the rock reduction technologies used at Utah FORGE. Although not expressly involved in the day-to-day decisions associated with the drilling program, the Sandia team has accessed electronic data recording services to review drilling system performance. This effort has primarily been focused on monitoring and evaluation of multiple parameters to identify areas where improved productivity and cost savings can be realized via improved drilling performance. Drilling response parameters have been compared to rock reduction model constraints that have been proven in the laboratory to identify possible performance enhancement areas.

The methods used have been exercised in a post-processing manner. To provide the greatest benefit to the drilling process, a method is needed to enable the intuitive interpretation of response parameters and is amenable to implementation in computational algorithms for real-time evaluation. A method is demonstrated whereby drilling response parameters may be interpreted for improved drilling performance. This analysis is not an exhaustive assessment but rather an overview of representative bit performance that demonstrates the application of the approach using rock reduction constraints. Drilling data from the Utah FORGE site have been used for the analyses.

2. DRILLING TECHNOLOGIES EVALUATION

Well construction is an arduous process that requires multiple parties, capabilities and knowledge for success. Drilling hardware is an engineered system with many subsystems and components that constrain its response. Operating conditions and process parameters determine the performance of the overall system. Similarly, personnel and logistics supporting the operation influence decisions that determine overall outcomes. With such a broad range of activities, a drilling technologies evaluation must comprise a technical approach focused on specific areas of the well construction process to evaluate potential areas of improvement.

2.1. Technical Approach

The technical approach to this work is focused upon an objective evaluation of drilling technologies via review of performance indicators. A well construction plan typically involves an overall specification of objectives and/or requirements. This plan will specify the site selection and an overall drilling plan that will specify the profile of the well to be drilled including hole diameters, depths, and the casing program to be emplaced. This specification gives rise to determination of the drilling system configuration that will be used to construct the well. Specific hardware is configured, including the appropriate rig, drillstring, bottom hole assembly (BHA), bit program, and other components within each corresponding BHA. Many of these configurations and parameters can change throughout the well construction process depending upon the drilling conditions encountered including the bit design, drilling fluids, and operating conditions. As the well is drilled, the input operating conditions are monitored, and the drilling system will generate response data including rate of penetration, bit life, and overall drilling system performance that is cataloged in daily drilling reports and electronic data recording systems. This data is available for review to evaluate performance and constraints on the overall drilling process giving rise to assessments that result in recommendations for improvements to the overall drilling process. This process is summarized in Figure 2-1.

While multiple areas of the well construction process can be evaluated, the focus of the work described herein is on rock/bit interaction. This includes the drill bit and its interaction with the formation and its influence from the balance of the overall drilling system configuration. The Utah FORGE wells addressed herein were constructed almost exclusively with Polycrystalline Diamond Compact (PDC) drill bits. This effort has generated more performance and response data for PDC drill bits in hard rock formations than has been heretofore available to the DOE/EERE/GTO geothermal well construction research and development community. The characteristic features of state-of-the-art bits used in this drilling campaign are summarized below followed by a cursory explanation of drilling system parameters that can additionally be considered when evaluating their performance. The technical approach to evaluating drill bit response includes a consideration of the following key areas: 1) Bit Specification, 2) Drilling System Configuration, 3) Drilling System Response, and 4) Drilling Process Evaluations. Each of these are described in greater detail in the following subsections.

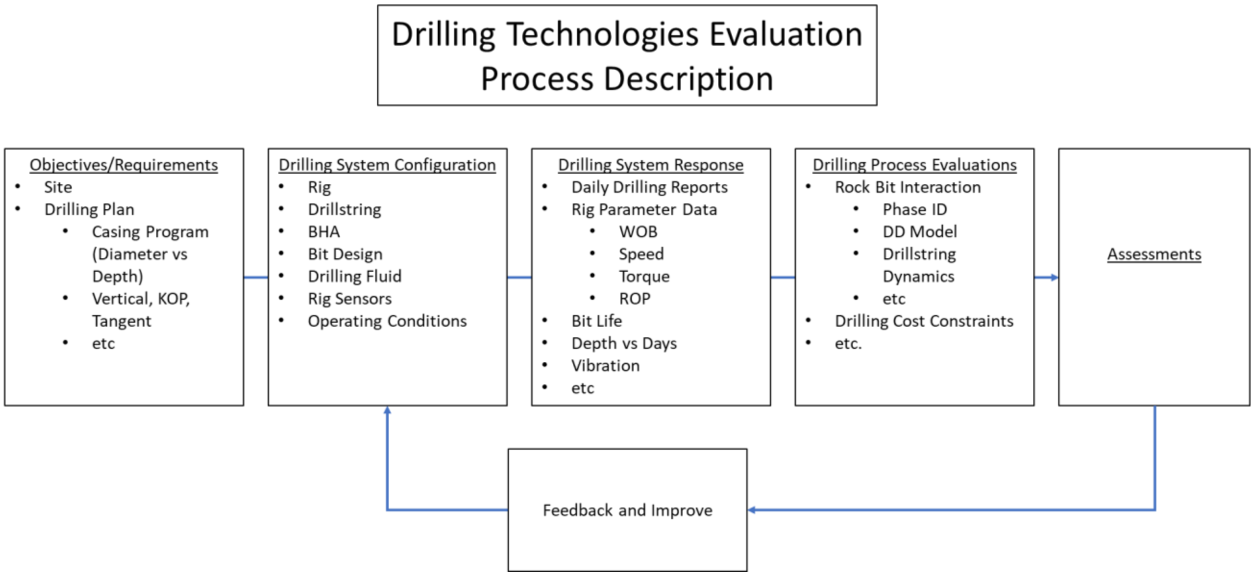


Figure 2-1. Technical Approach to Drilling Technology Evaluations

2.2. PDC Bit Feature Review

PDC bits vary widely in their design features depending upon overall drilling objectives, the formation to be drilled and the anticipated response. With the current focus on rock/bit interaction, the prevailing features governing the interaction of fixed-cutter bits with a formation must be readily identified. These include both cutter and bit features. Major features are identified in representative drag bits in Figure 2-2.

2.2.1. PDC Cutter Specification

The PDC cutters that comprise a drill bit can have a wide range of geometric and diamond material properties and are specified for each bit depending upon the application. The properties of diamond tables have gone through multiple generations of continuous improvement. Characteristic features include:

- Cutter geometry: Most PDC cutters are round but other shapes, e.g., chisel shaped cutters have been used. A PDC cutter generally consists of a leading edge synthetic diamond table that is bonded to a tungsten carbide disc substrate. The tungsten carbide disc is brazed on to the bit body to form the bit cutting structure.

- Diamond table thickness: The diamond table thickness on cutters can be as large as 2 mm (~0.080 inch). Thicker diamond tables allow for a more resistant cutter but can be at the expense of cutter impact resistance.

- Diamond table chamfer: A chamfer on the leading edge of the diamond can make cutters less likely to chip but can also reduce the stress concentrations at the rock interface. Cutter chamfers act like cutter wear flats and can reduce the penetration rate response so optimal chamfer dimensions are pursued within the diamond manufacturing researchers.

- Processing conditions: PDC manufacturers have proprietary processing conditions that are used to sinter diamond from graphite powder into cutters. These proprietary formulations vary among manufacturers and contribute to the performance of the individual cutters.

- Grain size & Distribution: The size and distribution of graphite used in processing conditions affects the wear rate and impact performance of the cutters.
- Polycrystalline diamond (PCD) vs Thermally-Stable Polycrystalline diamond (TSP): Bit designers have the choice between conventional PCD and TSP cutters. TSP cutters are traditional PCD cutters with the cobalt binder leached from the leading edge of the cutter. Thermal heating of the leading edge of the cutter during cutting can cause differential thermal expansion within the diamond matrix that can lead to spallation and chipping. TSP cutters are able to endure higher cutting temperatures by virtue of this modification. These modifications can be at the expense of other performance features so the choice of TSP over PDC cutters is at the discretion of the bit designer.

2.2.2. PDC Bit Specification

Fixed cutter drag bits are designed to present a cutting structure to the rock interface that is appropriate for the formation to be drilled and the desired performance. Likewise each drill bit is specified for the application. Major features include:

- Material (matrix vs steel): the material the bit is constructed of is an important consideration as it prescribes the design of the bit cutting structure. Most bits are fabricated from sintered tungsten carbide that allow the orientation of each of the cutters comprising the cutting structure to be preferentially oriented. Matrix bits are sintered using sand castings.
- Blade Count: blade count is one of the dominant features in bit specification as the number of bit blades largely determines the overall cutter count.
- Cutter count: overall cutter density comprising the cutting structure and can vary from a light-set to heavy-set bit, a measure of the diamond cutters distributed across the bit face.
- Cutter geometry:
    - Cutter Geometry is a variable in bit design. This includes the cutter diameter. Some bits use larger cutters on the nose of the bit and smaller cutters distributed toward the gage.
    - Cutting structure design can also include variable cutter geometries distributed across the face of the bit. While circular cutters are conventional, dimensional cutters are being introduced including chisel shaped cutters and cutters with protrusions on the leading face.
    - Cutter chamfer: The leading edge of the cutter can also be chamfered to reduce the likelihood of edge chipping when the bit first engages the formation.
- Cutting Structure Design Features: Multiple features comprise a bit specification and can include:
    - Cutter back-rake: the inclination of a cutter with respect to cutting direction
    - Cutter side-rake: the rotation of a cutter with respect to cutting direction
    - Torque control components: on the bit face to limit depth of cut
    - Impact arrestors: typically located on the outer radii to guard against whirl and lateral vibration

- Back up cutters/multi rows: redundant cutters distributed on a given blade (see seven blade bit in photo below)

- Bit Nozzle Hydraulics: the size, number and distribution of the nozzles will influence bit performance as drilling fluid is directed at the cutting structure blades to lubricate the rock/cutter interface and provide cutter cooling to promote enhanced cutter life.

Figure 2-2. Drag Bit Design Feature Description. Eight blade bit (left) with Torque Control Components and Impact arrestors and Seven Blade bit (right) with Backup cutters (Ref: Raymond et al, GRC 2012.)

2.3. Drilling System Description

The drilling system supporting advancing a PDC drill bit is important in understanding its overall response. Some major features include the following:

- Rig properties: The power available at the rig is an important parameter to ensure adequate torque is available downhole as drag cutter bits are inherently more torque sensitive than their roller cone counterparts. The Utah FORGE Frontier Rig 16 incorporates a hydraulic top drive.

- BHA properties: The Bottom Hole Assembly is designed to support the drilling objectives.

- Downhole Motor Properties: The motor must be appropriate for the flowrate and pressure delivery to develop adequate downhole torque.

- Drilling depth: As the drilling depth increases, the drill string naturally becomes more compliant due to the increased length.

- Stabilizers: Stabilizers are introduced to the BHA to mitigate lateral vibration within the wellbore.

- Other parameters in the overall drilling system can be important in evaluation of well construction performance.

2.4. Drilling System Response

Multiple data sources are used to monitor the drilling system response of each of the drill bits in the Utah FORGE bit program. These include:

1. Daily Drilling Reports were received via email distribution and logged within a database.
2. Rig parameter data is used to support the drilling technology evaluations. Electronic Data Recording (EDR) services were used to access rig parameter data. Nabors RigCloud service was used on 16A(78)-32 and Pason US DataHub was used on 56-32, 78B-32 and 16B(78)-32. Measured data typically include weight on bit (WOB), top drive speed and torque, flow rate in, differential pressure, and penetration rate. Bottom hole assembly (BHA) specifications were tracked and downhole motor parameter data were updated to correctly interpret bit rotary speed and torque. Drilling inflow was monitored to predict downhole rotation rates based upon the positive displacement motors in the BHA; differential pressure measurements were used to predict corresponding downhole torques. Drilling data were collected and cataloged for each bit run in a master database. Drilling parameter data were captured from the EDR systems using a fidelity of one data point per foot for the initial evaluations; higher resolutions are available for detailed evaluations. Higher data rates of one (1) sample per second were used later in the data evaluation program on wells 56-32 and 16B(78)-32. Representative drilling parameter data plots are generated for each bit run as shown in Figure 2-3. The figure exemplifies how difficult it can be to discern overall drilling response from primary drilling parameters; an improved method is needed to aid in determining overall bit performance.

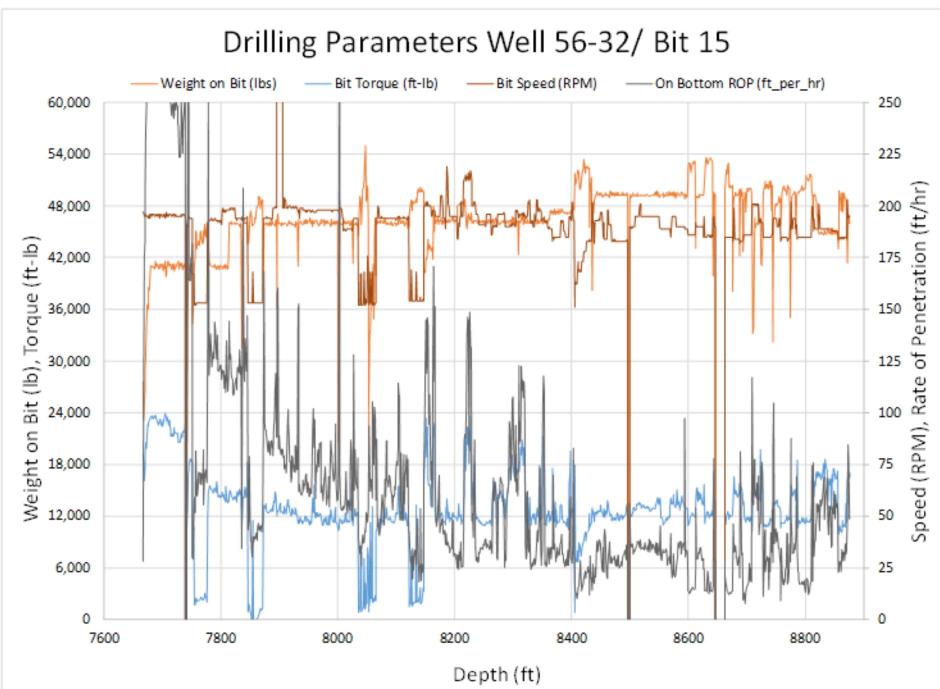


Figure 2-3. Plot of typical Drilling Parameter Data from Well 56-32/Bit 15.

3. Bit run information includes start/stop records for a particular bit. The drilling parameters may be varied during an individual bit run to discern optimal performance such as WOB step tests and rotary speed test tests. Other bit run information may include photographic

records before and after drilling. Bit Dull Grading reports are sometimes included in the daily drilling reports.

4. Other information such as lithology reports, directional surveys, hardware performance evaluations and others are collected for insight into data observations in the EDR evaluations.

2.5. Drilling Process Evaluations (Data Management and Evaluation)

Sandia project personnel devised a data management system to catalog the data documenting the system configuration and the accompanying drilling system response. The technical approach to developing recommendations for improvements to drill bit technology include evaluations of the data sources in the context of objective, physics-based evaluations. Essential elements include:

- Database: A Master Bit Record for each Utah FORGE well that documents each bit within the program.
- EDR Records and Charts of individual bit response
- Constraint Model: A drilling process model used to evaluate the EDR drilling data to discern overall bit performance. This constraint model is presented in the following section and is used as a primary basis for the bit evaluations reported herein.
- MATLAB Script: An EDR data processing script for standardization of bit performance reporting across all Utah FORGE wells.
- Drilling Cost Evaluations: Evaluation of drilling performance parameters to determine the influence on overall drilling costs for the bit interval drilled.

3. DRILLING PROCESS MODELING

3.1. Constraint Model

A rock reduction model is used to conduct advanced analytics on the drilling parameter data. The method is based on original laboratory cutter force measurements made at Sandia by Glowka and formulated into a formal phenomenological model by Detournay et.al. Glowka (Sandia) measured individual PDC cutter rock cutting forces as a function of depth of cut and rock type using an instrumented linear mill (Glowka, 1987). Detournay and Defourny (Detournay and Defourny, 1992) used the Glowka cutter data as the basis for a phenomenological model for the drilling action of PDC bits. The model has been validated by Sandia using laboratory (Raymond, 2001) and field data (Raymond, 2012) and is used herein as a valid representation of a constraint on the rock-bit interaction.

The Detournay and Defourny model, hereafter referred to as the DD model, assumes the rock-cutter interaction at their interface consists of two processes, cutting and friction. Cutting is characterized by intrinsic specific energy (ε) and a cutting force ratio (ζ) and friction by the coefficient (μ). Measured as specific energy [psi], ε is a measure of the energy necessary to cut a volume of rock and depends on rock strength, on-bottom and local pore pressure, and weakly on the back-rake angle of the cutters. A unitless measure, ζ represents the ratio of vertical (F_n) to horizontal (F_s) cutter forces for a sharp cutter, i.e., in the absence of friction. Also unitless, μ is the friction coefficient at the cutter wear-flat/rock interface. At the individual cutter level, the forces can be resolved for a sharp cutter as shown in Figure 3-1(a) and a blunt cutter shown in Figure 3-1(b).

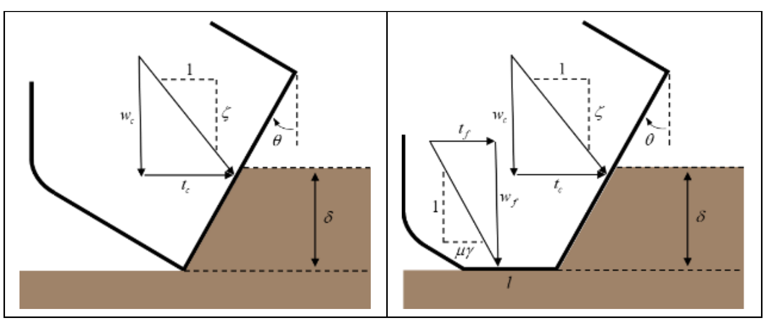


Figure 3-1. Force balance per Detournay and Defourny, 1992: (a) sharp cutter, (b) blunt cutter. Note that forces attributable to cutting and frictional processes are denoted with superscripts *c* (i.e., *F*^{c}) and *f* (i.e., *F*^{f}), respectively.

In the DD model for a cutter (Detournay and Defourny, 1992), the specific energy E is defined as

$$E = \frac{F_s}{A} \tag{1}$$

and the drilling strength, S

$$S = \frac{F_n}{A} \tag{2}$$

where for a sharp cutter

$$E = \varepsilon \qquad\qquad S = \zeta\varepsilon \tag{3}$$

and for a blunt cutter

$$E = E_0 + \mu S \tag{4}$$

with

$$E_0 = (1 - \mu\zeta)\varepsilon \tag{5}$$

The single cutter force data measured at Sandia (Glowka, 1987) is used to derive E & S based upon the measured penetrating (F_n) and drag (F_s) forces and the frontal areas (A) corresponding to the depth of cut and cutter diameter. Fitting the Sandia data to the DD model results in the E-S diagram for a cutter shown in Figure 3-2. The worn cutter data points conform to a trendline in accordance with equation 4. The points approach a minimum value of specific energy at high depth of cut converging to the limiting value corresponding to a sharp cutter for which (S, E) = $(\zeta\varepsilon, \varepsilon)$; the data in the figure show convergence to a level approximating the unconfined compressive strength of Sierra White Granite (~28,000 psi). The DD model refers to this limiting minimum value as the cutting locus for sharp cutters. The cutting locus has a slope of $1/\zeta$, where ζ is the ratio of vertical to horizontal cutter forces in the absence of friction (i.e., pure cutting). The cutting locus, characterized by ζ, falls within a range of values of 0.7 – 0.9 for several sedimentary rock types (Detournay and Defourny, 1992). Glowka's data predicts an average value ζ of 1.1 (Raymond, 2001) for Sierra White Granite for depths of cut up to 0.06 inches (0.15 cm).

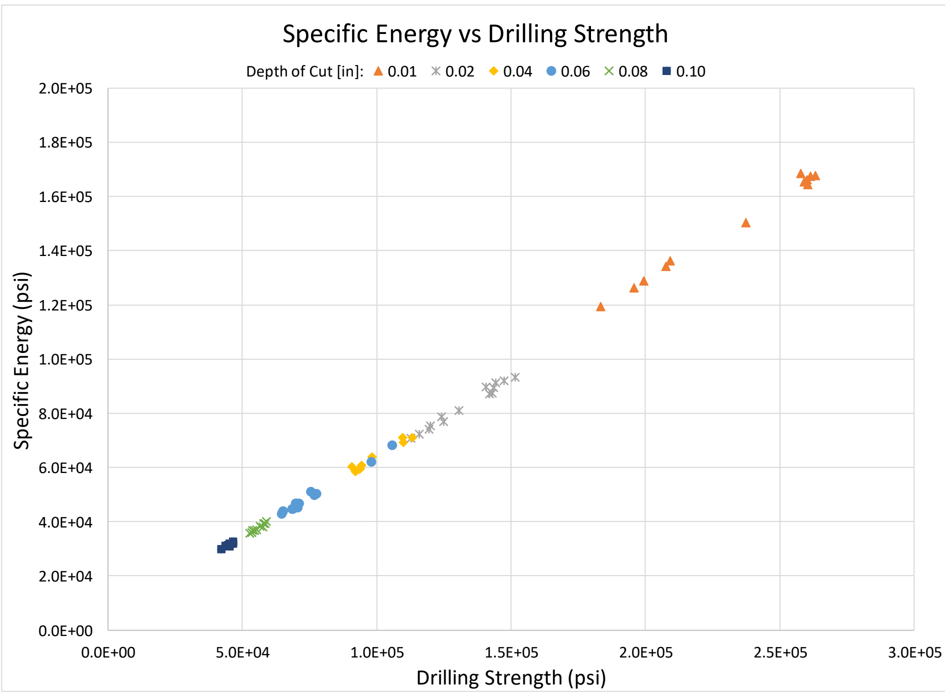


Figure 3-2. E-S diagram for a worn cutter in Sierra White Granite using data for Cutter F from Glowka, 1987.

For a full drill bit, the DD model yields,

$$\frac{2T}{r} = (1 - \mu\gamma\zeta)\varepsilon\delta r + \mu\gamma W \tag{6}$$

where T is the torque, W is the weight on bit, r is the bit radius, γ the unitless bit constant, and δ the depth of cut per revolution. Full derivation of this expression is given in Detournay and Defourny, 1992. Through γ, the full bit response can be expressed in the same manner as an individual cutter in terms of E and S.

This expression represents a constraint on the response of a PDC bit based upon the assumption of cutting and frictional processes. As with a cutter, the response can be expressed in terms of the specific energy and drilling strength. The specific energy represents the rotational energy component of the overall mechanical specific energy and corresponds to the work done by torque to drill a unit volume of rock:

$$E = \frac{2T}{r^2\delta} \tag{7}$$

and the drilling strength, S

$$S = \frac{W}{r\delta} \tag{8}$$

dividing equation (6) by rδ results in

$$E = E_0 + \mu\gamma S \tag{9}$$

where

$$E_0 = (1 - \beta)\varepsilon \tag{10}$$

and

$$\beta = \gamma\mu\zeta \tag{11}$$

The interpretation of the DD model is shown in Figure 3-3. The E-S diagram for a bit is similar to the one for a cutter except the slope of the friction line is replaced by the product $\mu\gamma$, where the constant, γ, embodies the influence of the bit design on its mechanical response. The E-S diagram depicted in Figure 3-3 is used for both a sharp single cutter (dotted cutting locus) and a full bit (solid friction line).

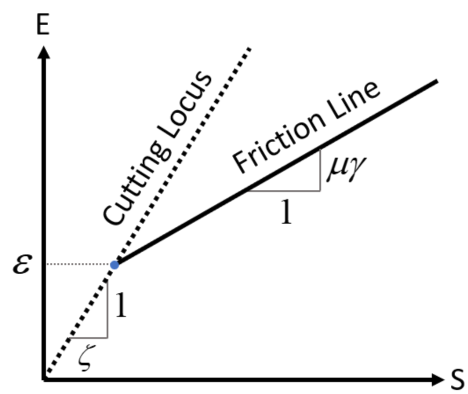


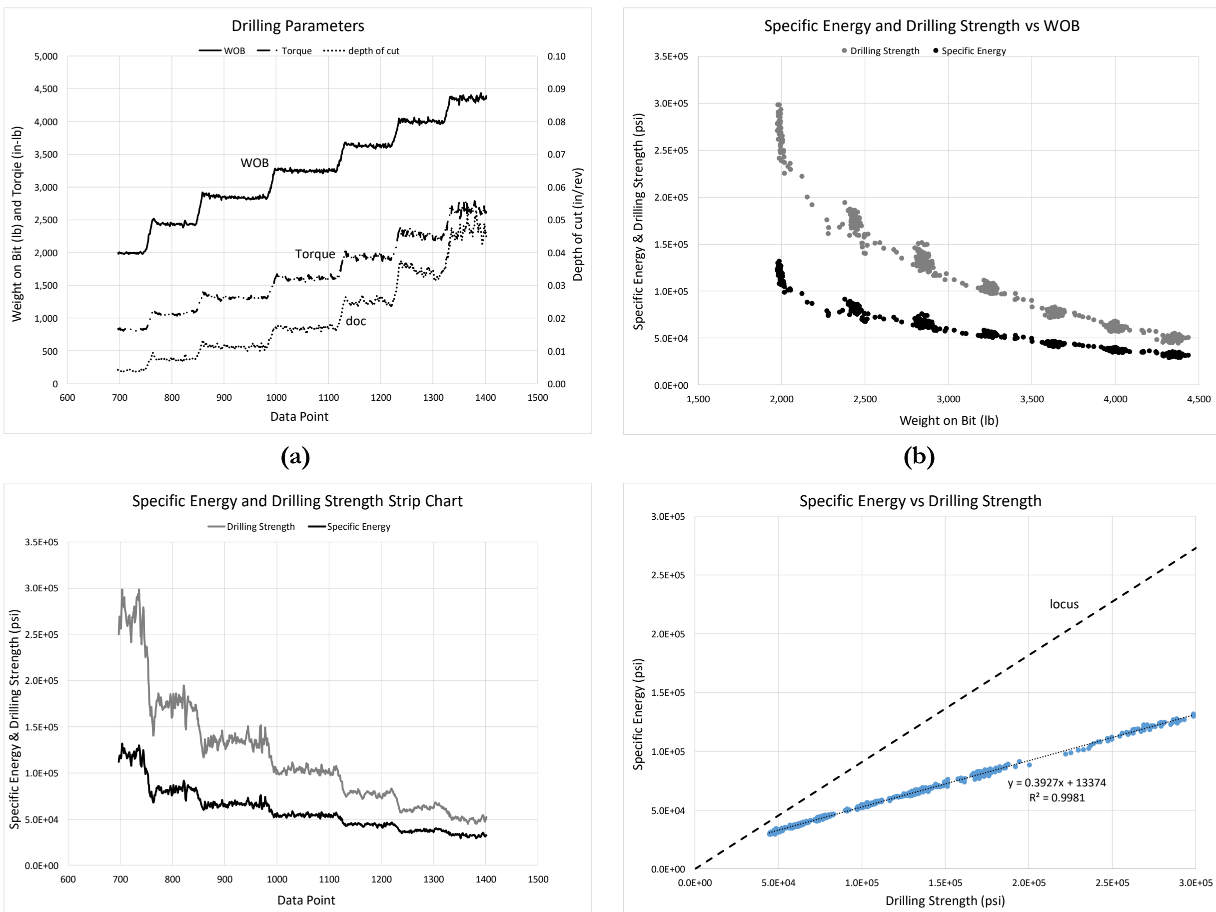
Figure 3-3. Specific Energy vs Drilling Strength Diagram.

3.2. Laboratory Validation

Sandia has validated the DD model using laboratory data for a five-bladed NOV bit (Figure 3-4(a) & (b)) in the Sandia Hard Rock Drilling Facility (Figure 3-4(c)). Drilling parameter data for the five-bladed NOV bit is presented in Figure 3-5(a). Figure 3-5(b) & Figure 3-5(c) show specific energy and drilling strength parameters versus WOB and data point, respectively. Figure 3-5(d) is a response plot of specific energy versus drilling strength for the NOV PDC bit response shown in Figure 3-5(a). Also plotted in Figure 3-5(d) is the locus of cutting points for a cutter in Sierra White Granite. With increasing weight on bit, the response of the bit approaches the cutting locus with a nominal value of ζ =1.1 for Sierra White Granite.

(a) (b) (c)

Figure 3-4. Laboratory validation of rock reduction constraint model: (a) Face view of NOV 3¾" diameter, five blade bit (b) Profile of NOV 3¾" diameter, five blade bit and (c) Sandia Hard Rock Drilling Facility.



(a) (b)

(c) (d)

Figure 3-5. NOV 3¾" diameter, five-blade bit testing in Sandia Hard Rock Drilling Facility: (a) Drilling parameters, (b) E& S vs WOB, (c) E& S strip chart, and (d) ES plane.

3.3. Field Implementation

Application of the DD model is readily applied as an objective guide in the response of a PDC bit using EDR data in the field. The primary surface measurements of weight on bit and torque are readily available. Depth of cut per revolution is readily determined from the ratio of rate of penetration and bit rpm. The downhole torque on bit and bit rpm are adjusted from surface measured parameters by the contributions of a downhole motor, if included. Motor speeds are generally linearly proportional with flowrate (assuming no leakage); likewise, motor torque contributions are linearly proportional to differential pressure (assuming no leakage). EDR data often include surface rotary speed and torque and the motor contributions as independent channels. These measurements can be verified within the EDR to ensure correct interpretation.

Although readily implemented, field EDR data can challenge the immediate interpretation of the DD model due to the following phenomena that contribute to variations in the observe response:

3.3.1. Cutter Phase Variations

The drilling response of the drill bit must be in the correct regime. The DD model identifies three distinct cutting phases including phase 1 - scratching, phase 2 - cutting, and phase 3 -foundering. In phase 1 the cutters and bit are not fully engaging the formation preceding the onset of cutting. At the other extreme corresponding to phase 3, excessive WOB can result in bit foundering where excessive thrust is acting upon the cutters resulting in a disproportional increase in ROP with increasing WOB; this can result in excessive friction on the cutters and rock interface. The preferred response is in the phase 2 region where penetration rate is proportional to applied WOB. The phase 2 region is typified by reasonable specific energy measurements that rival the compressive strength of the rock although adequate WOB must be applied to reduce the specific energy to minimum values.

3.3.2. Drilling Vibrations

The presence of downhole vibrations can cause the bit response to diverge from the preferred phase 2 region resulting in very high specific energy values as the bit response moves in and out of the cut. Downhole vibrations can include axial bit bounce, torsional vibrations, stick/slip, lateral vibration and whirl – all of which can cause variations in the applied load (WOB) and motion (RPM) and the corresponding reaction (torque) and response (rate of penetration). Variations in these parameters will likewise manifest as variations in the drilling strength and specific energy used in the DD model. While a deviation from the preferred stable drilling response, the variation in these surface-measured parameters provide insight into the potential dysfunctions encountered downhole.

3.3.3. Lithology Variations

Lithology variations comprise the geologic column. The response of the drilling system to changes in geology are captured in EDR measurements. Variations in specific energy measurements must often be inferred by considering the variation in the parameters comprising the bit response due to geologic changes.

3.3.4. Depth Variations

Since the objective of drilling is to increase wellbore depth, variations in response can be expected in the EDR record with depth including, for example, the increased flexibility of the drillstring contributing to the variation of modes of vibration with depth. Temperature and pressure variations can also be expected with increasing depth which affect drilling system performance and response.

3.3.5. Measurement Scatter

The variations of the individual measurements acquired by the EDR system can additionally contribute to variations in the model response. These can be in the sensitivity of the individual sensors or the data acquisition system itself. These measurements are often not systematically zeroed to allow absolute measurements to be made.

3.3.6. Relative vs Absolute Response

While a drilling process model provides insight into the overall drilling system response, it can be limited by the relative response of the fundamental measurements in lieu of a preferred absolute measurement value. Nevertheless, the drilling process model constraint provides insight into the response of the system even though the absolute response may be difficult to discern from the available measurements.

3.3.7. Other System Variations

Other system variations can be expected since drilling is a time-intensive process allowing hardware reliability, personnel assignments, and weather variations, to name a few, to contribute to variability in the measurements.

4. UTAH FORGE WELL SUMMARIES

4.1. FORGE WELL 16A(78)-32

4.1.1. Well Program

Utah FORGE Well 16A(78)-32 was drilled vertically to a kick-off point at 5892 ft, the curve was built at 5°/100 ft MD and a 65°tangent was drilled at an azimuth of 105° to a measured depth of 10955 ft. An additional 32 feet were used to capture core, advancing the hole to a measured depth of 10,987 at TD. The well profile is shown in Figure 4-1.

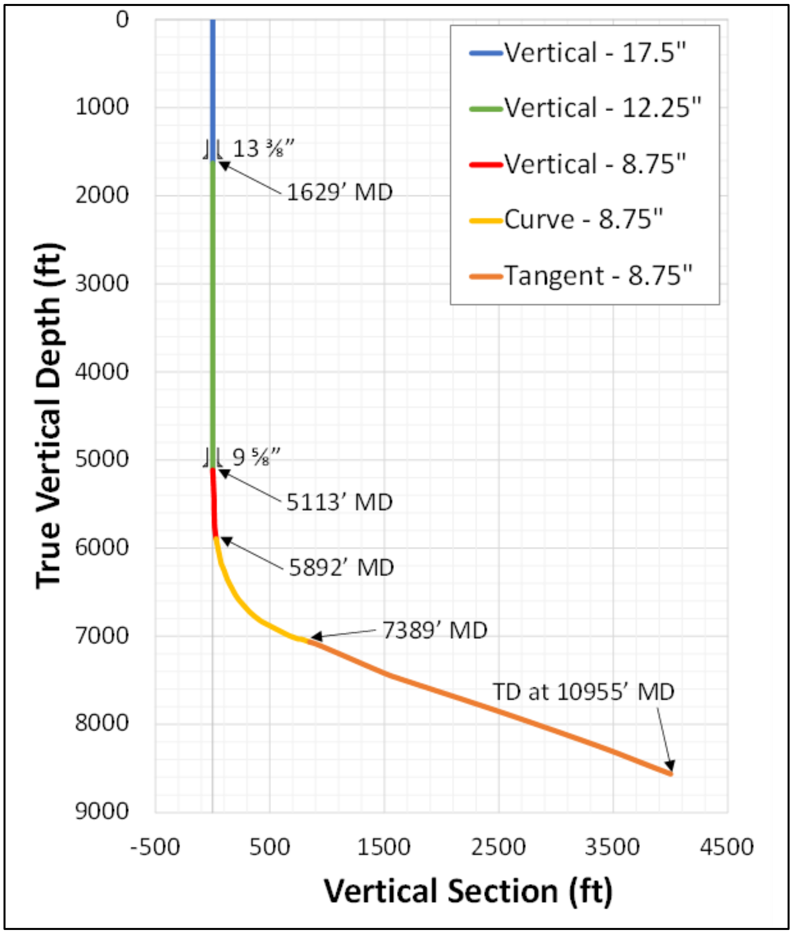


Figure 4-1. Utah FORGE Well 16A(78)-32 Profile.

4.1.2. Bit Program & Performance Summary

The bit program and resulting performance experienced on FORGE 16A(78)-32 are shown in Table 4-1 and Figure 4-2.

Table 4-1. FORGE Well 16A(78)-32 Bit Summary

Bit Run No.	Manufacturer	Type	Serial No.	BHA	Bit Dia. (in)	Depth Start (ft)	Depth End (ft)	Total Footage (ft)	Time on Bottom (hrs)	Net ROP (ft/hr)
1	NOV ReedHycalog	TKC76-C5 PDC	A275580	Surface BHA	17.50	28.0	1629.0	1601.0	21.5	74.5
2	NOV ReedHycalog	TKC66-R1 PDC	E266453	2	12.25	-	-	-	3.0	-
3	Smith	GF 15BODJPS TRI-CONE	RK6139	3	12.25	1629.0	1644.0	-	0.5	-
4	NOV ReedHycalog	TKC66-R1 PDC	E266453	4	12.25	1644.0	4552.0	2908.0	61.5	47.3
5	Smith	MDSi616	JM 7398	5	12.25	4552.0	4964.0	412.0	55.0	7.5
6	Smith	Z713S	JP4755	6	12.25	4964.0	5113.0	149.0	16.5	9.0
7	Smith	Z713S	JD4755	-	12.25	5113.0	5113.0	0.0	-	0.0
8	Smith	XS616	JV2705	9	8.75	5113.0	5345.0	232.0	17.5	13.3
9	Ulterra	U616M PDC	54132	10	8.75	5345.0	5469.0	124.0	9.0	13.8
10	CCI - Canamera 713	Core	462-06	11	8.75	5469.0	5495.0	26.0	0.0	0.0
10	CCI - Canamera 713	Core	462-06	12	8.75	5495.0	5504.0	9.0	0.0	0.0
11	NOV ReedHycalog	TKC66-P3 PDC	A271699	14	8.75	5504.0	5846.0	342.0	43.5	7.9
12	nine blade core bit	Core	Core	15	8.75	5846.0	5856.0	10.0	5.0	2.0
13	Ulterra	U616M	54131	16	8.75	5856.0	5858.0	2.0	0.5	4.0
14	CCI - Canamera 713	Core	Core	17	8.75	5858.0	5892.0	34.0	6.5	5.2
15	NOV ReedHycalog	TKC63-C7	A255857	18	8.75	5892.0	6360.0	468.0	15.5	30.2
16	NOV ReedHycalog	SKC613M-O1C	A232400	20	8.75	6360.0	6526.0	166.0	11.0	15.1
17	NOV ReedHycalog	SKC513M-O1C	A276122	22	8.75	6526.0	6945.0	419.0	21.0	20.0
18	NOV ReedHycalog	FTKC63-O1	A276121	23	8.75	6945.0	7389.0	444.0	18.0	24.7
19	NOV ReedHycalog	TKC63-C7	A255857	30	8.75	7389.0	8024.0	635.0	23.5	27.0
20	OTHER	Mill	Mill	-	-	8024.0	8025.0	1.0	-	-
21	NOV ReedHycalog	SKC513M-O1C	A276122	34	8.75	8025.0	8241.0	216.0	6.0	36.0
22/23	NOV ReedHycalog	SKC613M-O1C	A230682	35	8.75	8241.0	8535.0	294.0	6.0	24.0
24	NOV Reed Hycalog	TKC63-O1	A270819	38	8.75	8535.0	9064.0	529.0	12.5	42.3
25	NOV Reed Hycalog	TKC63-O1	A270978	39	8.75	9064.0	9748.0	684.0	20.5	33.4
26	NOV Reed Hycalog	TKC63-P1	A271436	41	8.75	9748.0	10490.0	742.0	17.5	42.4
27	NOV Reed Hycalog	TKC63-P1	A271437	42	8.75	10490.0	10955.0	465.0	14.0	33.2
28	CCI - Canamera 713	Core 713	3409-01	47	8.75	10955.0	10971.0	16.0	4.0	4.0
29	Ulterra	PDC U613M	47954	48	8.75	10971.0	10973.0	2.0	1.0	2.0
30	CCI - Canamera 713	Core 713	77302	49	8.75	10973.0	10987.0	14.0	4.5	3.1

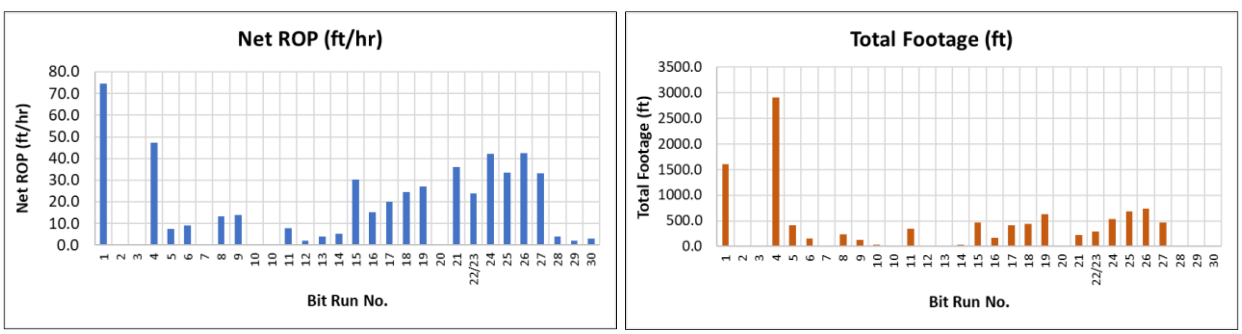


Figure 4-2. Utah FORGE Well 16A(78)-32 Bit Program and Performance Summary.

4.1.3. Bit Summaries and Processed Data

Individual bit performance for FORGE well 16A(78)-32 is summarized in Volume 2.

4.1.4. *Depth vs Days Summary*

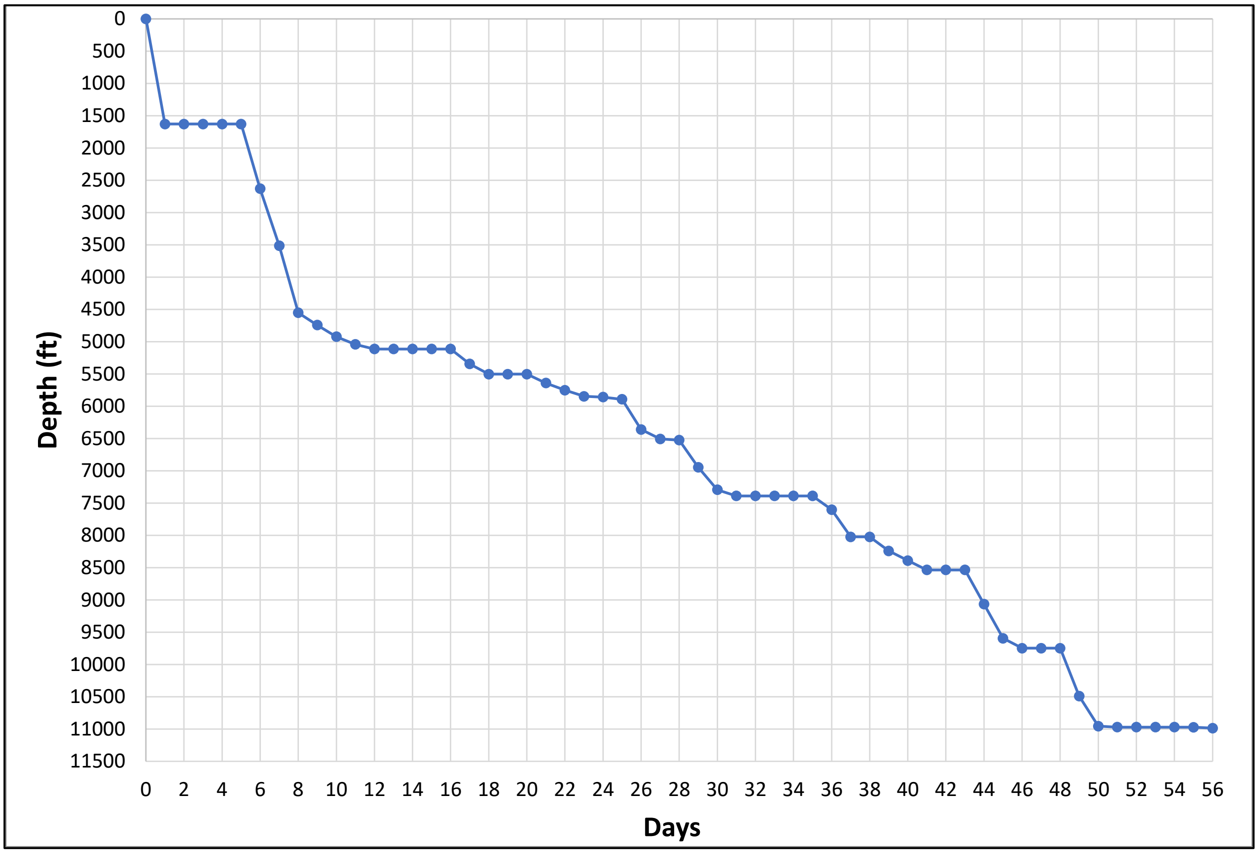


Figure 4-3. Depth vs Days Summary for Utah FORGE Well 16A(78)-32.

4.2. FORGE WELL 56-32

4.2.1. Well Program

Well 56-32 was a vertical hole that will be used for monitoring and research activities. The well profile is shown in Figure 4-4.

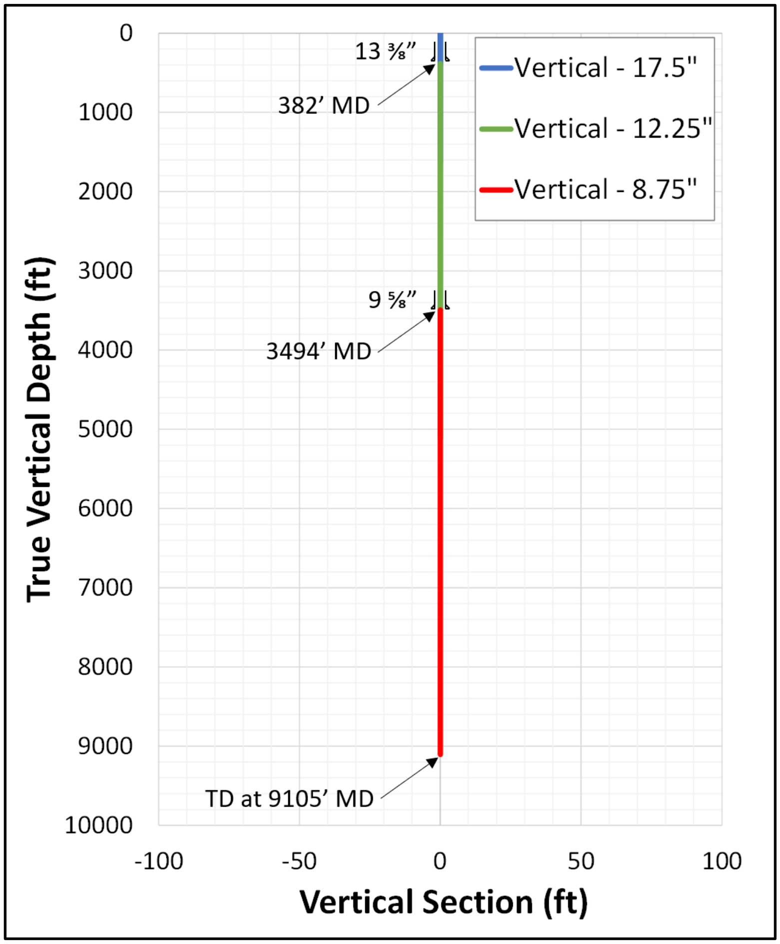


Figure 4-4. Utah FORGE Well 56-32 Profile.

4.2.2. Bit Program & Performance Summary

The bit program and resulting performance used on FORGE 56-32 are shown in Table 4-2 and Figure 4-5.

Table 4-2. FORGE Well 56-32 Bit Summary

Bit Run No.	Manufacturer	Type	Serial No.	BHA	Bit Dia. (in)	Depth Start (ft)	Depth End (ft)	Total Footage (ft)	Time on Bottom (hrs)	Net ROP (ft/hr)
1	ReedHycalog	TK59-B1	A252419	1	17.50	134.0	381.0	247.0	1.2	205.8
2	-	M-22	-	-	12.25	381.0	390.0	9.0	0.1	90.0
3	ReedHycalog	TKC66-R1	A266974	2	12.25	390.0	3309.0	2919.0	9.7	300.9
4	ReedHycalog	TK63-A1A	A268226	3	12.25	3309.0	3500.0	191.0	2.6	73.5
5	-	GX-177	-	4	8.75	3500.0	3506.0	6.0	0.8	7.5
6	ReedHycalog	TKC73-H1	A275660	4	8.75	3506.0	4595.0	1089.0	28.9	37.7
7	-	EP5475	5042714	5	8.75	4595.0	5143.0	548.0	26.2	20.9
8	ReedHycalog	TKC63-P1	A277166	6	8.75	5143.0	5610.0	467.0	15.5	30.1
9	ReedHycalog	TKC63-P1	A271436	7	8.75	5610.0	5999.0	389.0	14.8	26.3
10	ReedHycalog	FTKC73-A1	A275803	8	8.75	5999.0	7208.0	1209.0	52.1	23.2
11	ReedHycalog	FTKC73-A1	A276121	9	8.75	7208.0	7620.0	412.0	4.8	85.8
12	E6	Hammer	-	-	8.75	7620.0	7628.0	8.0	0.8	10.0
13	ReedHycalog	FTKC63-A1	A276121	-	8.75	7628.0	7663.0	35.0	1.1	31.8
14	E6	Hammer	-	-	8.75	7663.0	7667.0	4.0	0.8	5.0
15	ReedHycalog	TKC63-P1	A271437	10	8.75	7667.0	8900.0	1233.0	37.0	33.3
16	ReedHycalog	FTKC83-A3	A276071	11	8.75	8900.0	9145.0	245.0	3.2	76.6

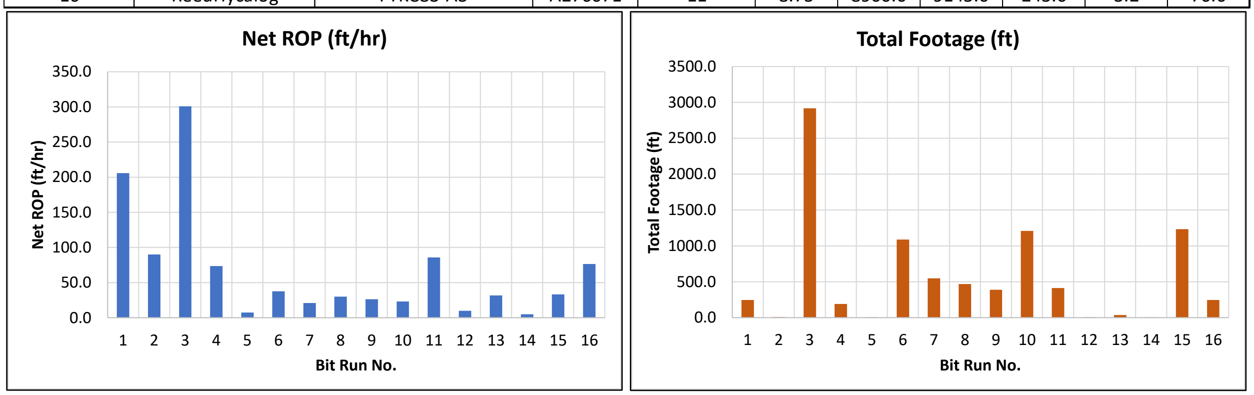


Figure 4-5. Utah FORGE Well 56-32 Bit Program and Performance Summary.

4.2.3. Bit Summaries and Processed Data

Individual bit performance for FORGE well 56-32 is summarized in Volume 3.

4.2.4. Depth vs Days Summary

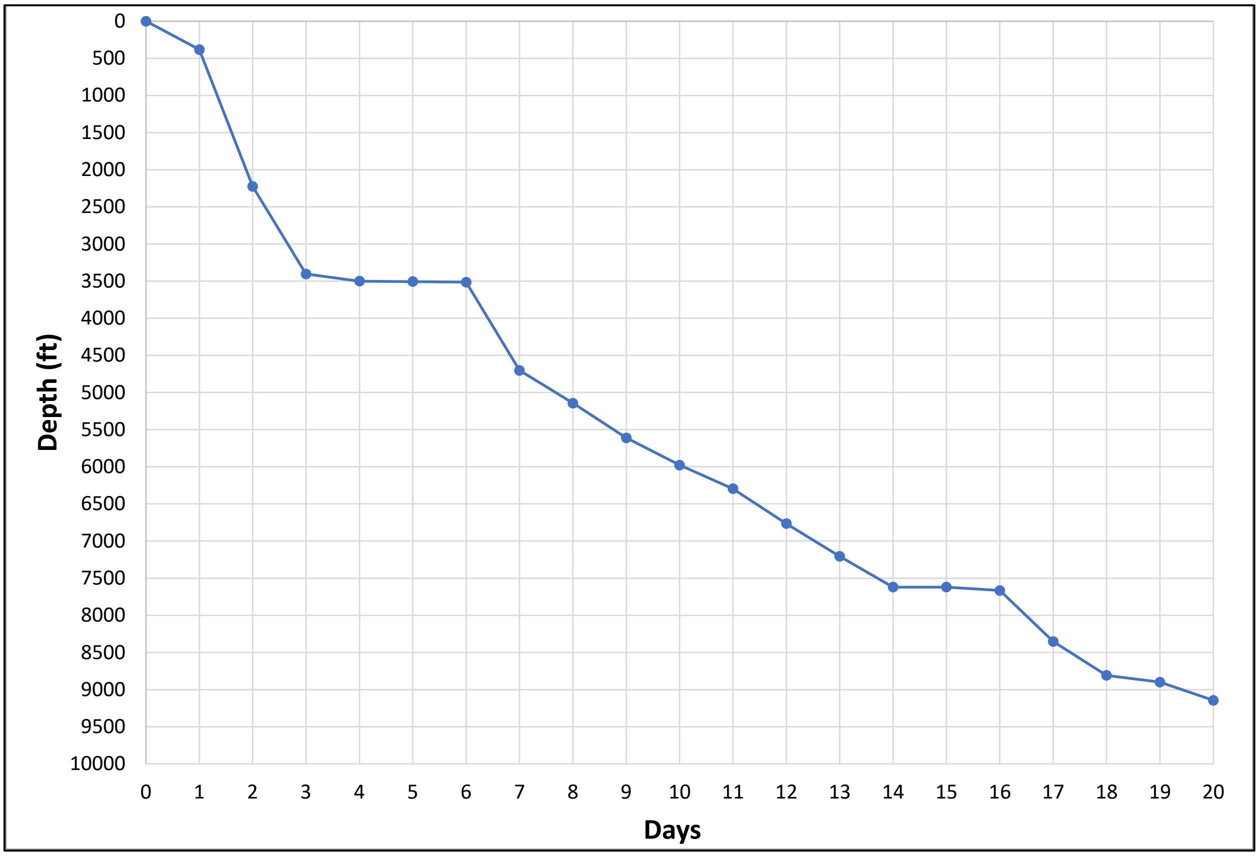


Figure 4-6. Depth vs Days Summary for Utah FORGE Well 56-32.

4.3. FORGE WELL 78B-32

4.3.1. Well Program

Utah FORGE Well 78B-32 was drilled vertically to a depth of 9500 ft. The well profile is shown in Figure 4-7.

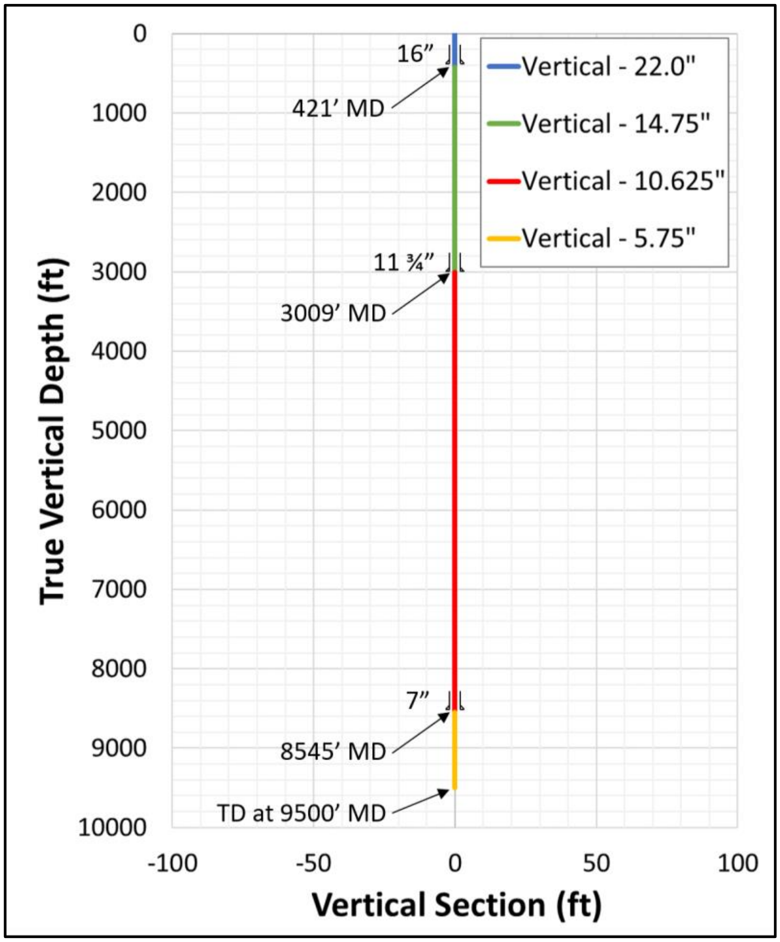


Figure 4-7. Utah FORGE Well 78B-32 Profile.

4.3.2. Bit Program & Performance Summary

The bit program and resulting performance experienced on FORGE 45-32 are shown in Table 4-3 and Figure 4-8.

Table 4-3. FORGE well 78B-32 Bit Summary

Bit Run No.	Manufacturer	Type	Serial No	BHA	Bit Dia.	Depth Start (ft)	Depth End (ft)	Total Footage (ft)	Time on Bottom (hrs)	Net ROP (ft/hr)
1	Smith	XR-C	-	1	22	128	421	293	4	84
2	BAKER	GT-C1	-	2	14.75	421	433	12	1	16
3	ReedHycalog	TKC66	A279635	3	14.75	433	2699	2266	10	239
4	ReedHycalog	TKC63	A279636	4	14.75	2699	3009	310	9	36
5	VAREL	VM-1	-	5	10.625	3009	3009	0	2	0
6	ReedHycalog	TKC83	A279637	6	10.625	3009	3651	642	13	50
7	ReedHycalog	TKC83	A279639	7	10.625	3651	5761	2110	28	76
8	ReedHycalog	TKC83	A279690	8	10.625	5761	5821	60	1	100
9	ReedHycalog	TKC83	A279692	9	10.625	5821	6700	879	11	81
10	HALLBTN	FC3843	13340636	10	8.75	6700	6728	28	2	19
11	HALLBTN	FC3843	12958459	11	8.75	6700	6740	40	1	44
12	BAKER	MYR547	1116990	12	10.625	6740	6742	2	1	3
13	ReedHycalog	TKC83	A279638	13	10.625	6742	7613	871	10	89
14	ReedHycalog	TKC83	A279691	14	10.625	7613	8500	887	10	89
15	HALLBTN	FC3843	13206404	15	10.625	8500	8530	30	3	11
16	-	Various	-	16	5.75	8530	8555	25	-	-
17	ReedHycalog	TKC63	A279641	17	5.75	8555	9500	945	8	121

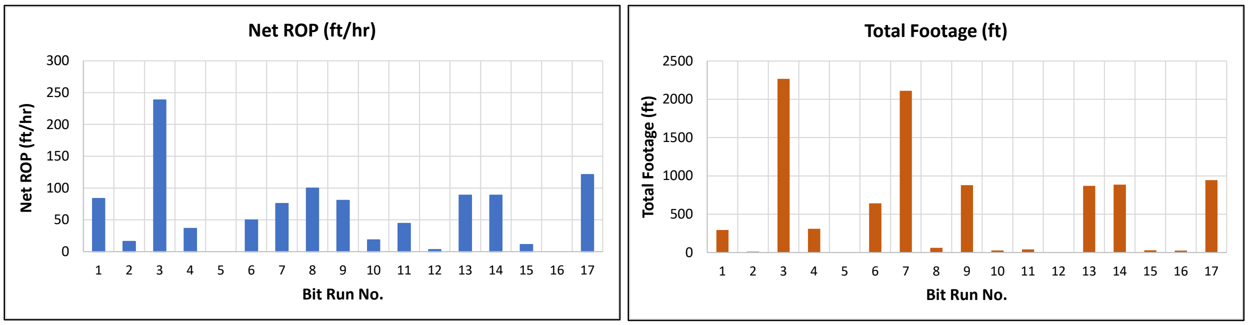


Figure 4-8. Utah FORGE Well 78B-32 Bit Program and Performance summary.

4.3.3. Bit Summaries and Processed Data

Individual bit performance for FORGE well 78B-32 is summarized in Volume 4.

4.3.4. *Depth vs Days Summary*

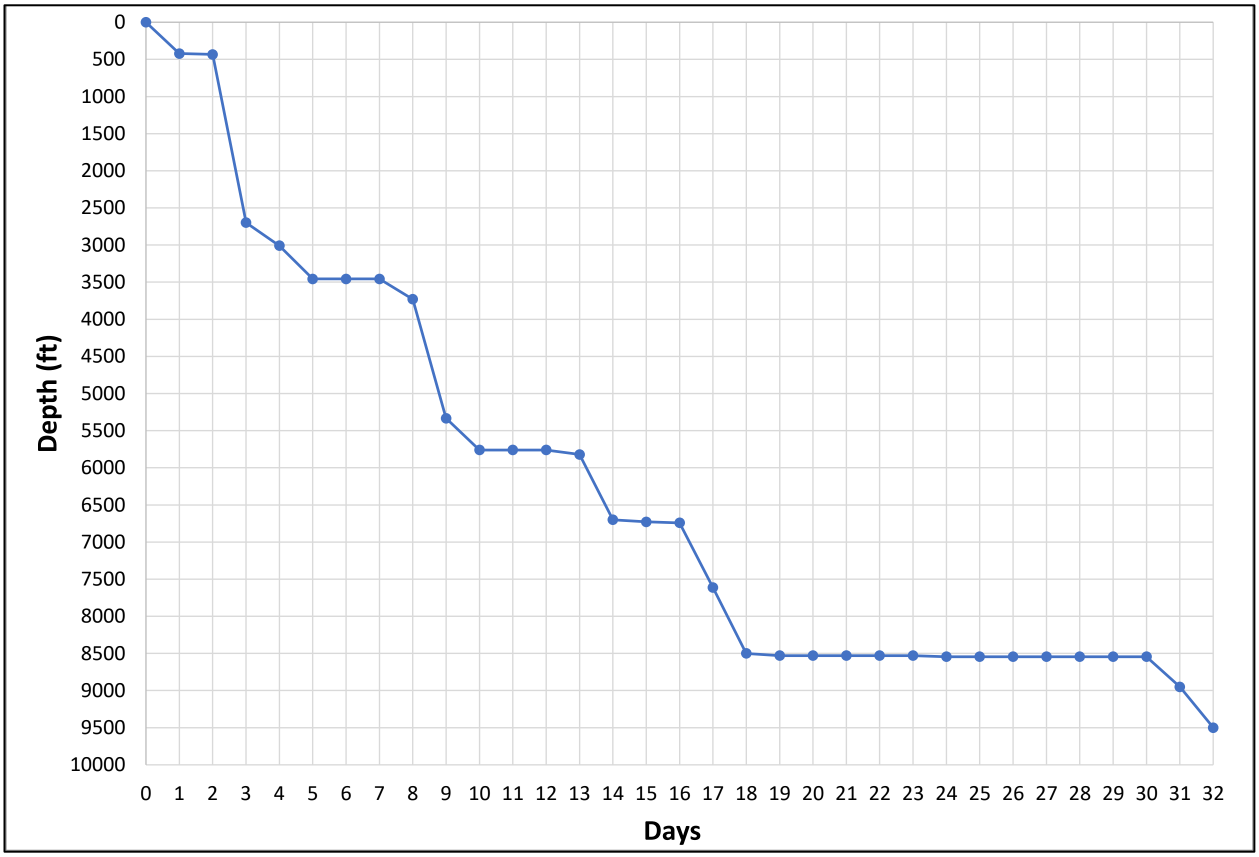


Figure 4-9. Depth vs Days Summary for Utah FORGE Well 78B-32.

4.4. FORGE WELL 16B(78)-32

4.4.1. Well Program

Utah FORGE Well 16B(78)-32 was drilled vertically to a kick-off point at 5269 ft, the curve was built at 5°/100 ft MD and a 65° tangent was drilled at an azimuth of 105° to a measured depth of 10947 ft. The well profile is shown in Figure 4-10.

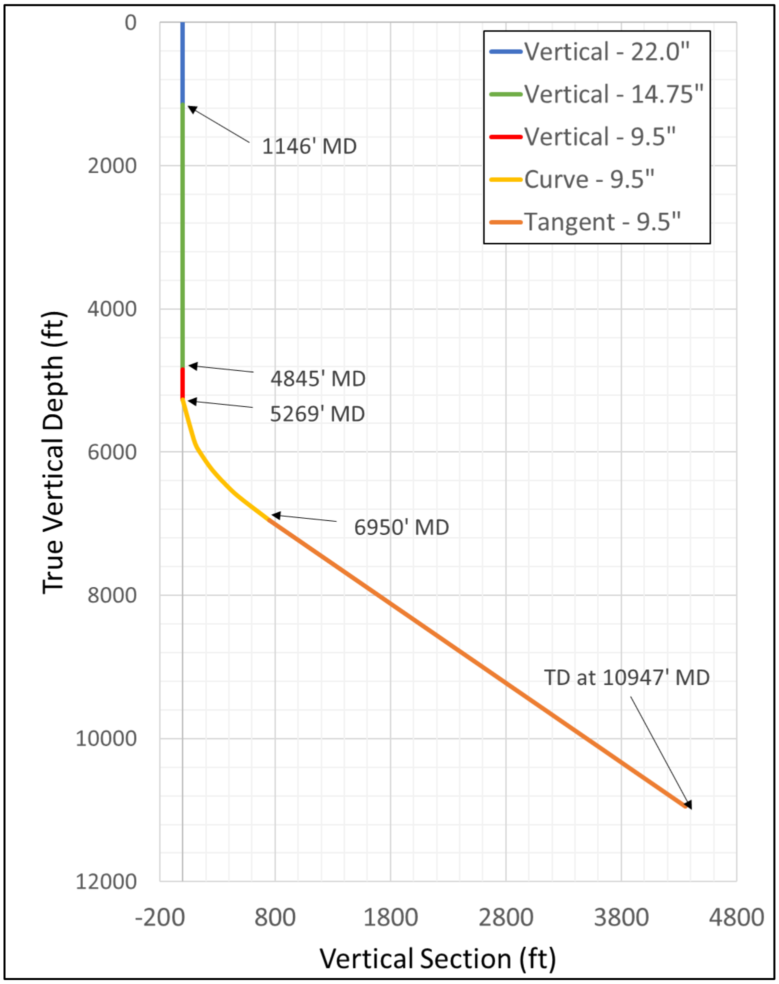


Figure 4-10. Utah FORGE Well 16B(78)-32 Profile.

4.4.2. Bit Program & Performance Summary

The bit program and resulting performance experienced on FORGE 16B(78)-32 are shown in Table 4-4 and Figure 4-11.

Table 4-4. FORGE Well 16B(78)-32 Bit Summary

Daily Drilling Report			Pason	SDI		Daily Drilling Report									
Bit Run #	BHA No.	Bit No.	Bit No.	Bit No.	BHA No.	Well Profile Interval	Manufacturer	Type	Serial # (Daily Drilling Report)	Bit Dia.	Depth Start (ft)	Depth End (ft)	Total Footage (ft)	Time on Bottom (hrs)	Net ROP (ft/hr)
1	1	1	1	1	1	Vertical	NOV ReedHycalog	TK99	A297420	22	120	1146	1026	9.00	114
2	2	2	-	-	Intermediate BHA	Clean out	Other	XR+C	-	14.75	1146	1181	35	1.25	28
3	3	3	2	2	2	Vertical	NOV ReedHycalog	0	A297421	14.75	1181	4353	3172	21.17	150
4	4	4	4	3	3	Vertical	SANJOAQ	TKC83	A298775	14.75	4353	4845	492	9.50	52
5	5	5	5	-	Insert Bit	Vertical	SANJOAQ	MX-S50R	W45JG	9.50	4845	4855	10	0.50	20
6	6	6	6	-	Core BHA 1	Core	CCI	CCI-913	3409-05	8.75	4855	4871	16	2.50	6
7	7	7	7	-	Core BHA 2	Core	CCI	CCI-713	4219-01	8.75	4871	4878	7	2.50	3
8	8	8	6	-	Particle Drilling BHA	Vertical	NOV ReedHycalog	E1451	A298243	9.50	4878	4910	32	2.00	16
9	9	9	7	-	Particle Drilling BHA	Vertical	NOV ReedHycalog	E1451	A298244	9.50	4910	4978	68	3.50	19
10	10	5	-	-	Clean out BHA	Ream	SANJOAQ	MX-S50R	W45JG	9.50	4978	4980	2	1.00	2
11	11	10	9	4	4	Vertical	NOV ReedHycalog	TKC73 A1	A298329	9.50	4980	5269	289	4.00	72
12	12	11	9	5	5	Curve	NOV ReedHycalog	TKC73 A1	A298328	9.50	5269	5957	688	14.50	47
13	13	12	10	6	6	Curve	NOV ReedHycalog	TKC73 A1	A208330	9.50	5957	6545	588	14.00	42
14	14	13	11	7	7	Curve	NOV ReedHycalog	8 BLADE PDC	A298355	9.50	6545	6610	65	1.00	65
15	15	14	12	8	8	Curve	NOV ReedHycalog	8 BLADE PDC	A298353	9.50	6610	6950	340	9.50	36
16	16	15	12	9	9	Tangent	NOV ReedHycalog	8 BLADE PDC	A298354	9.50	6950	7584	634	14.00	45
17	17	16	13	10	10	Tangent	NOV ReedHycalog	8 BLADE PDC	A298358	9.50	7584	8085	501	11.50	44
18	18	17	14	11	11	Tangent	NOV ReedHycalog	8 Blade PDC	A298356	9.50	8085	8585	500	10.50	48
19	19	18	15	12	12	Tangent	Baker Hughes	6 Blade PDC	5341818	9.50	8585	9255	670	8.50	79
20	20	19	16	13	13	Tangent	NOV ReedHycalog	TKC83	A298355	9.50	9255	9800	545	8.00	68
21	21	5	-	-	-	Circulate & Survey	SANJOAQ	MX-S50R	W45JG	9.50	9800	9800	0	3.00	0
22	22	20	18	-	Core BHA 3	Core	CCI	CCI-911	3409-05	8.75	9800	9817	17	13.75	1
23	23	5	-	-	-	Circulate & Survey	SANJOAQ	MX-S50R	W45JG	9.50	-	-	-	-	-
24	24	21	18	-	-	Ream	Baker Hughes	VGD-38CH	5344137	8.75	9780	9823	43	7.00	6
25	25	22	19	-	Core BHA 4	Core	CCI	CCI-713	3409	8.75	9823	9853	30	11.25	3
26	26	23	20	14	14	Tangent	NOV ReedHycalog	Insert RC	5243758	9.50	9853	9863	10	2.00	5
27	27	24	21	15	15	Tangent	Baker Hughes	D406VX	5342357	9.50	9863	10250	387	5.00	77
28	28	5 & 25	22	-	Core BHA 5	Ream	CCI	CCI-713	4219-01	8.75	10230	10256	26	9.50	3
29	29	26	23	-	Clean out BHA	Ream	NOV ReedHycalog	TRI CONE	T46ZX	8.75	10250	10264	14	1.00	14
30	30	27	24	-	Core BHA 6	Core	NOV ReedHycalog	CCI-913	CCI 3409-05	8.75	10264	10271	7	8.50	1
31	31	26	4	-	Clean out BHA	Tangent	NOV ReedHycalog	CCI-713	CCI-3409-01	8.75	10271	10274	3	0.50	6
32	32	28	26	-	Core BHA 7	Core	NOV ReedHycalog	CCI-713	CCI-3409-01	8.75	10274	10304	30	23.50	1
33	33	29	27	16	16	Tangent	NOV ReedHycalog	PDC 6 BLADE	A299586	8.75	10304	10430	126	0.75	168
34	34	30	28	-	Core BHA 8	Core	NOV ReedHycalog	CCI-913	CCI-3409-05	8.75	10430	10460	30	22.75	1
35	35	26	25	-	Clean out BHA	Tangent	NOV ReedHycalog	TRI CONE	T462X	8.75	10460	10462	2	0.25	8
36	36	31	29	-	Core BHA 9	Core	CCI	CCI-713	CCI-3409-03	8.75	10462	10493	31	22.50	1
37	37	23	29	17	17	Tangent	NOV ReedHycalog	TRI CONE	5243758	9.50	10493	10503	10	0.75	13
38	38	32	30	18	18	Tangent	Baker Hughes	6 BLADE PDC	5341859	9.50	10503	10947	444	5.00	89

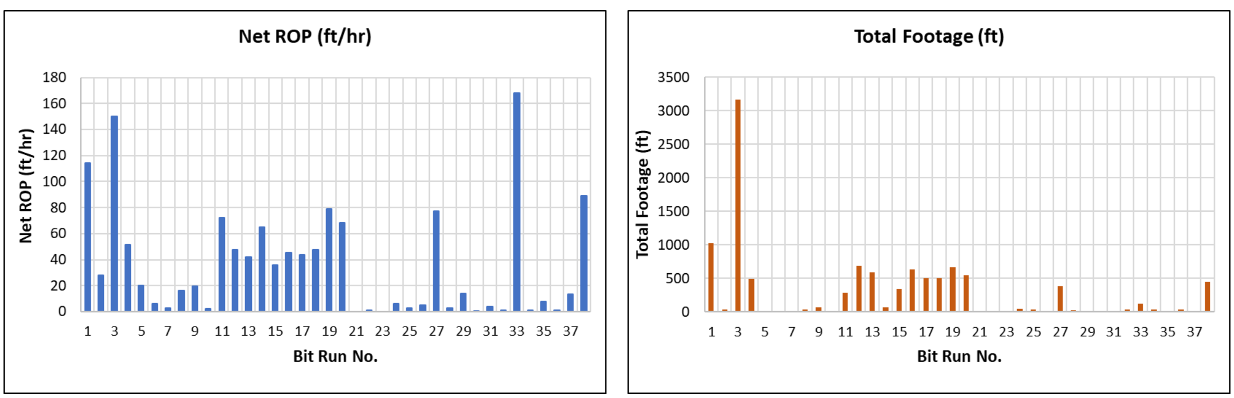


Figure 4-11. Utah FORGE Well 16B(78)-32 Bit Program and Performance Summary.

4.4.3. Bit Summaries and Processed Data

Individual bit performance for FORGE well 16B(78)-32 is summarized in Volume 5.

4.4.4. Depth vs Days Summary

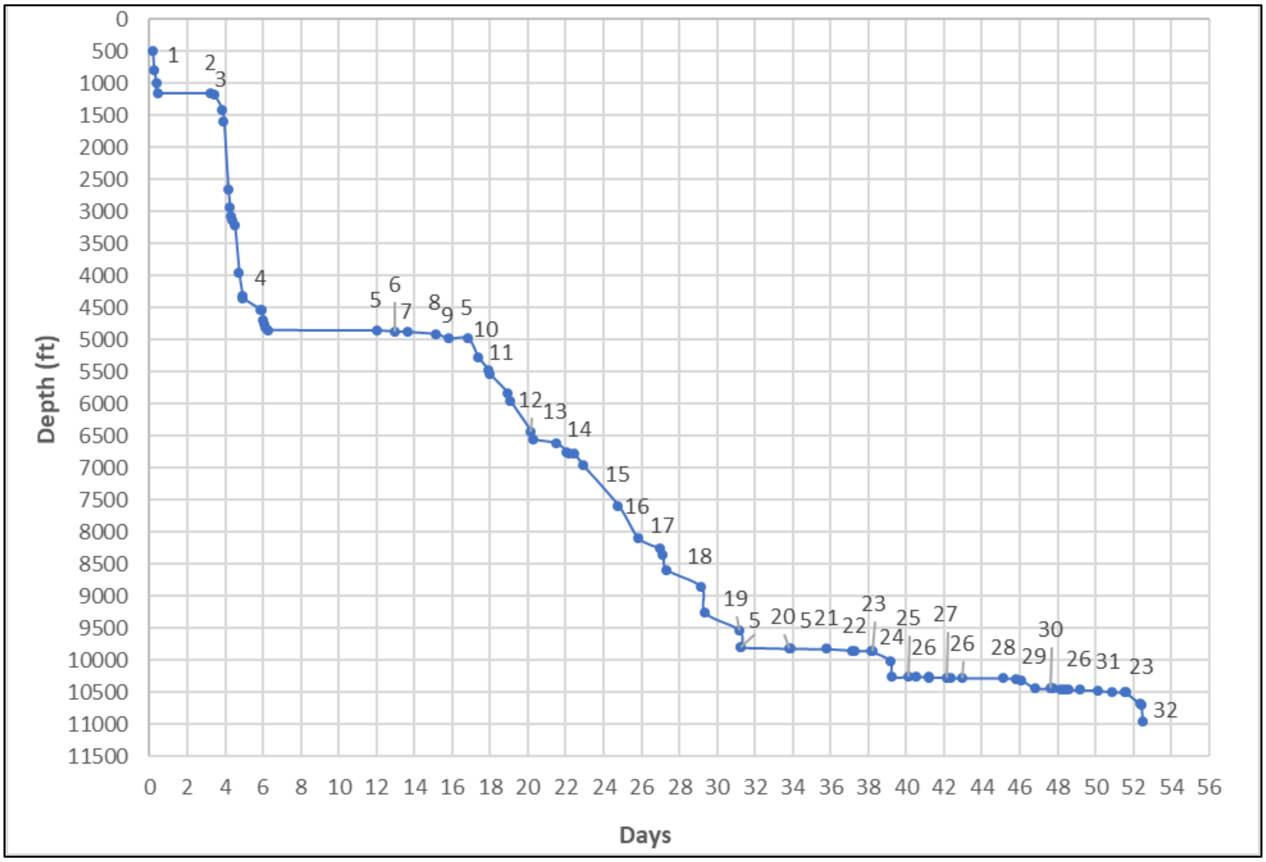


Figure 4-12. Depth vs Days Summary for Utah FORGE Well 16B(78)-32.

5. DRILLING PARAMETER DATA EVALUATION

The drilling constraint model is used as an advanced analytical tool to evaluate drilling parameter response. Representative data from the four Utah FORGE wells is used to demonstrate how drilling parameter data can be used to evaluate formation intrinsic specific energy, bit aggressiveness, bit wear, cutting structure damage and the presence of drilling dynamics dysfunctions. The data from the four wells is presented below as an example of these evaluations.

5.1. Formation Intrinsic Specific Energy

Bit 4 on Well 56-32 was used to complete the 12-¼" interval from 3308 to 3500 ft to complete drilling through alluvium before reaching the contact with the granitic material that characterizes the FORGE thermal reservoir. The drilling parameters, ES strip chart and ES diagram are shown in Figure 5-1. Referring to the ES diagram, the intrinsic specific energy (ε) can be approximated from the intersection of the friction line with the cutting locus, here with a slope of (1/0.7), representing the overburden at this depth. The evaluation of ε requires correcting for the running torque of the top drive and downhole motor; here, an offset of 4016 ft-lb was derived.

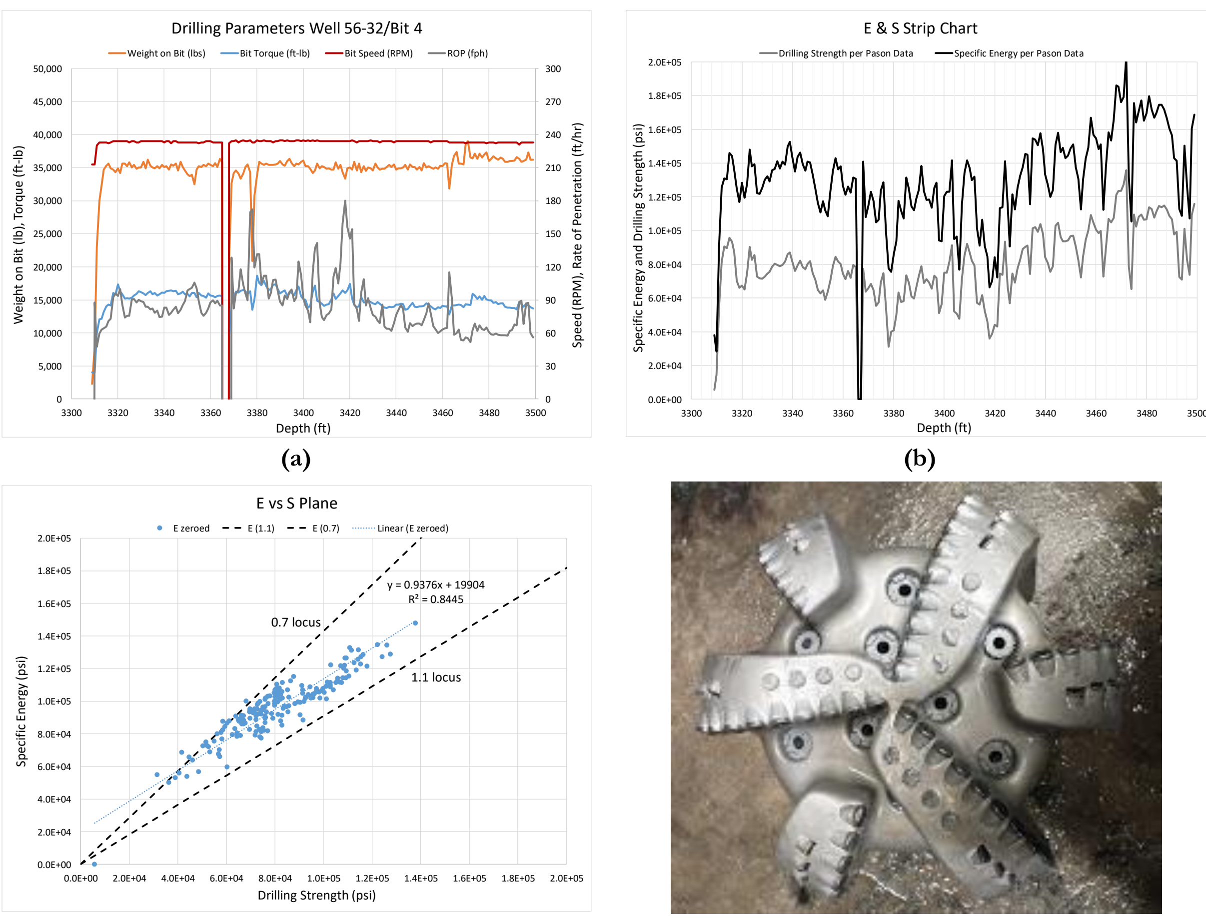


Figure 5-1. Estimate of intrinsic specific energy from field drilling parameters for Well 56-32/Bit 4: (a) Drilling parameters, (b) E& S strip chart, (c) ES plane, and (d) post run bit photo.

5.2. Bit Response

5.2.1. *Bit Aggressiveness*

The slope of the best-fit line to the ES data, μγ, represents the product of cutter wear-flat frictional coefficient (μ) and the bit constant (γ). If μ is assumed constant, μγ is directly representative of the aggressiveness of the bit, or a bit's ability to convert weight on bit to cutting torque.

Well 56-32 used a variety of bladed bits in the 8-¾" interval. Bits 8, 9, 13, and 15 were six-bladed; bit 6 was seven-bladed. In general, cutter densities increase with blade count and produce less torque response, yielding a lower rate of penetration but greater durability.

The bit cutting structures are shown in Figure 5-2 for bits 15 and 6, with their corresponding response in the ES plane. The respective μγ estimates are 0.1 and 0.05, indicating a decrease in μγ, and thus bit aggressiveness, with increasing blade count. Accurate μγ estimates are obtainable only when light to moderate scatter—which is largely indicative of bit dysfunction— is seen in the ES diagram. Dysfunction detection is discussed further in section 5.4.

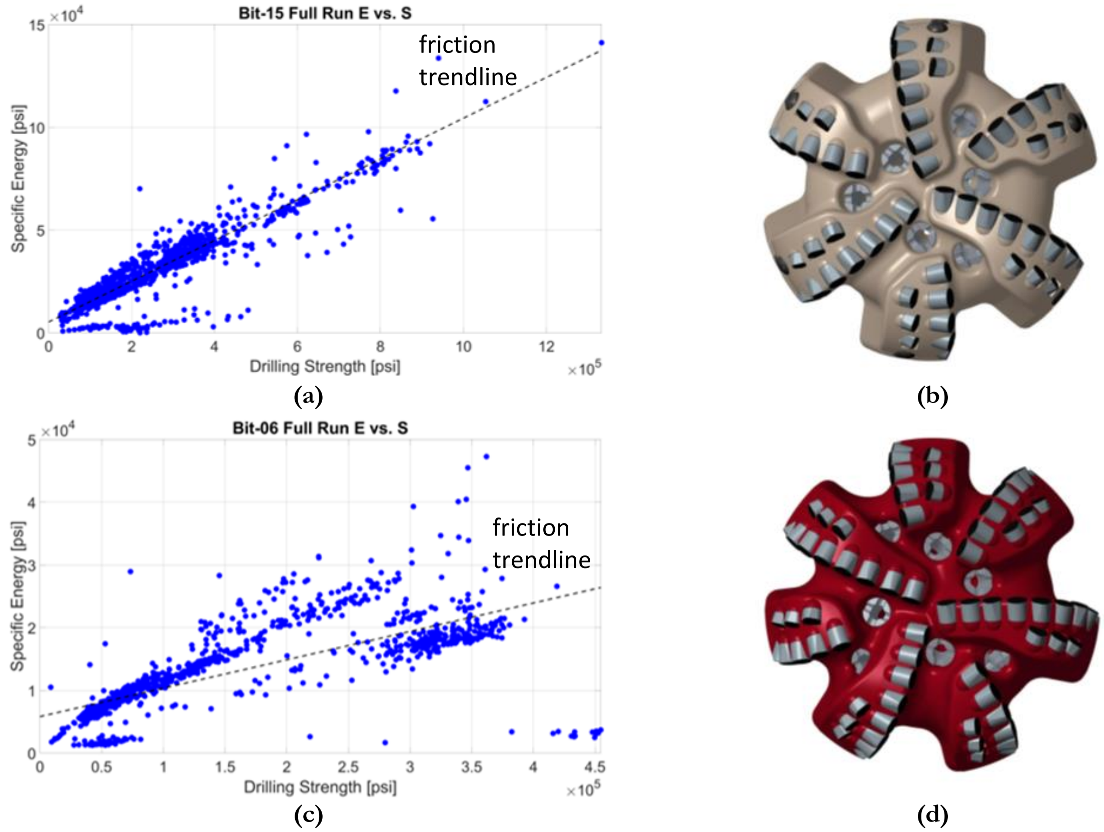


Figure 5-2. Evaluation of bit response via evaluation of the μγ product for Well 56-32 Bit 15 & 6 comprising six and seven blades, respectively: (a) Well 56-32/Bit 15 with μγ = 0.1, (b) Well 56-32/Bit 15 image, (c) Well 56-32/Bit 6 for depths above 4200 ft; μγ = 0.05, (d) Well 56-32/Bit 6 image.

5.2.2. *Frictional Wear*

Cutters naturally wear as a bit drills an interval. In the ES plane, this can be observed as a steady migration from left to right on the friction line with interval depth. For instance, Figure 5-3c shows the ES diagram with points color-coded according to measured depth. An alternative view of this migration is given in Figure 5-3d, in which the friction line (FL) has been parameterized and ES points are plotted according to their relative position along the friction line as a function of depth. Accordingly, a FL coordinate of (1.0) indicates the most inefficient drilling location and (0.0) the most efficient.

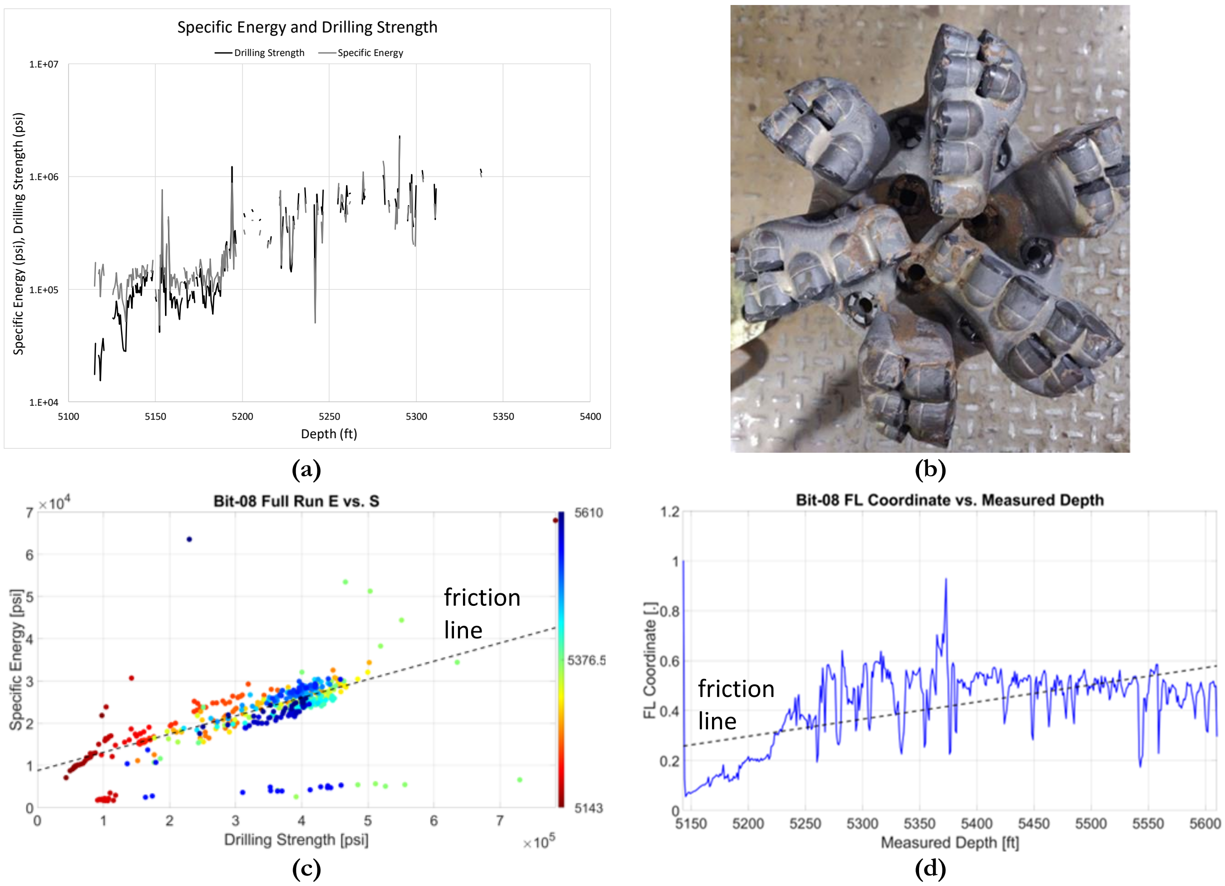


Figure 5-3. 16A(78)-32/Bit 8 performance: (a) E and S strip chart showing stable drilling, (b) post-run bit photo, (c) ES plane with points colored with depth showing rise on the friction line, and (d) scatter of individual state points with respect to the friction line.

As can be seen, there is a relatively steady migration along the friction line with depth (red indicates shallower depths, blue deeper depths), allowing for assessment of overall bit wear through a given interval. The scatter in the friction line coordinate is indicative of dysfunction, which if severe, can alter the bit's cutting structure and change the slope of the friction line.

5.3. Cutting Structure Damage

Structural damage to bits can be largely attributed to dysfunction resulting from vibration, including whirl, stick-slip, torsional vibrations and bit-bounce. The observable effect of dysfunction in the ES plane is point deviation from the friction line as energy is removed from the cutting process. High magnitude deviations and prolonged periods of deviation are of particular concern to bit integrity, as either situation can readily devolve into bit damage. As shown in Figure 5-4, Bit 6 on Well 56-32 displays proportionality in the ES strip chart and ES plane until a depth of approximately 4200 ft; at greater depths, the ES points are scattered indicative of damage to the cutting structure.

While many of the bits in the Utah FORGE drilling program performed well, some were pushed beyond their service life and this resulted in catastrophic cutting structure damage. These bits are deemed Damaged Beyond Repair (DBR) as they lack insufficient matrix material to re-tool the bit. By plotting the torque deviation of each point relative to the friction line, candidate intervals in which damage likely occurred are identified. As can be seen from Figure 5-5, Bits 5 and 11 from Well 16A experienced significant damage. Review of the corresponding point deviation plots indicates Bit 5 experienced significant but fleeting dysfunction in the 4775-4795 [ft] interval; Bit 11 experienced significant, prolonged dysfunction in the 5755-5845 [ft] interval. Reasonable confidence can be had that damage occurred in the identified intervals to allow for more targeted diagnostics.

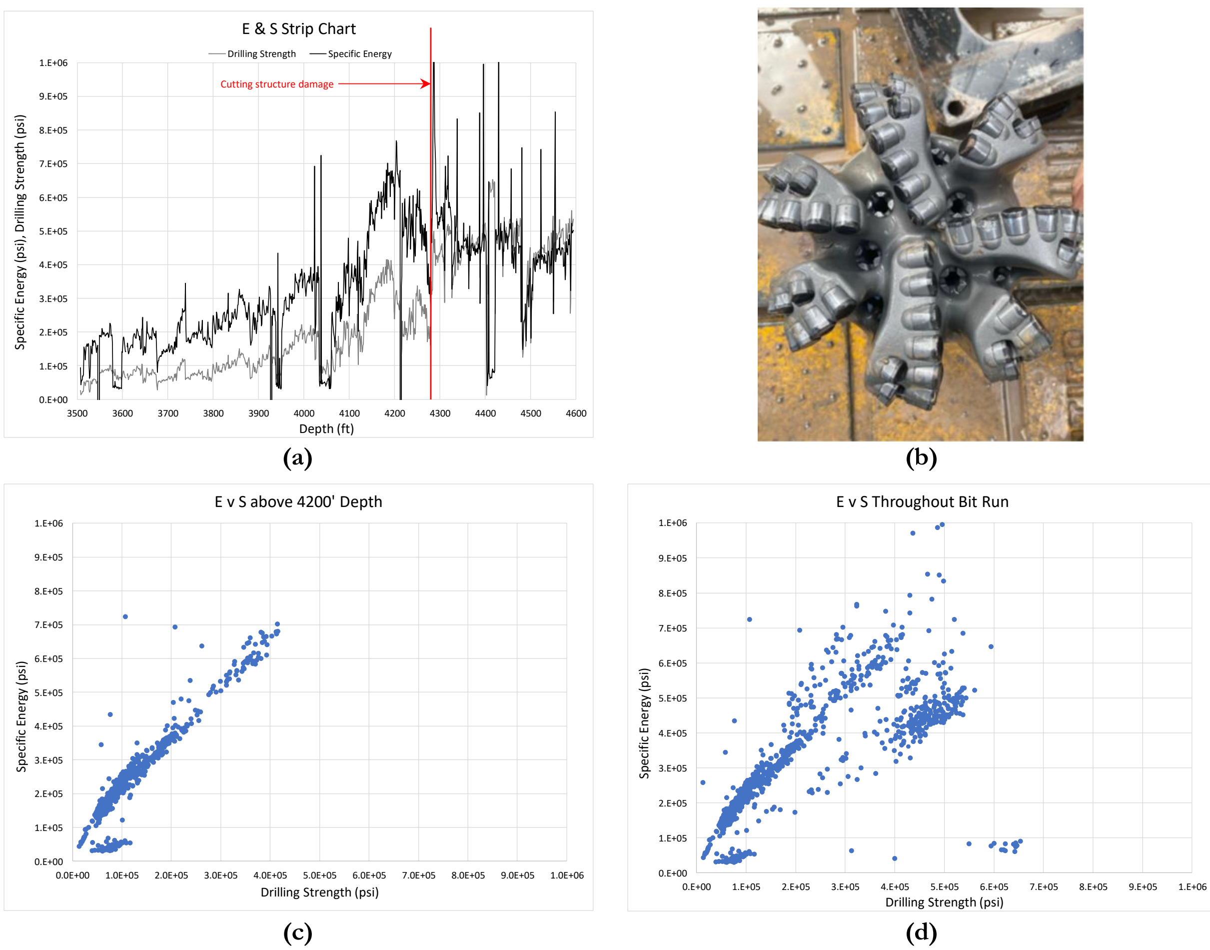


Figure 5-4. Cutting structure damage identification on 56-32/Bit 6 using E & S monitoring: (a) E & S strip chart, (b) post-drilling image, (c) ES plane response above 4200 ft, (d) ES plane response for entire bit run.

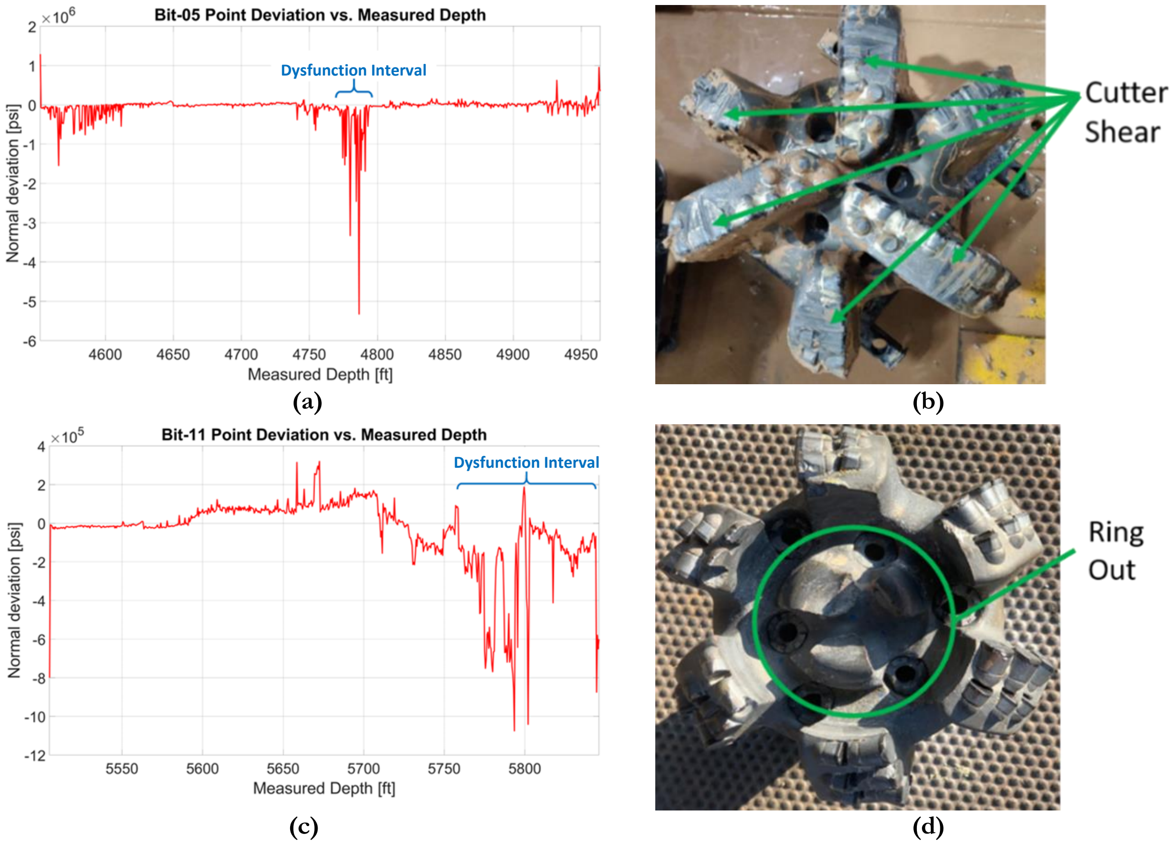


Figure 5-5. Cutting structure damage identification using E & S monitoring: (a) 16A(78)-32/Bit 5 dysfunction monitoring, (b) 16A(78)-32/Bit 5 post-drilling image, (c) 16A(78)-32/Bit 11 dysfunction monitoring, (d) 16A(78)-32/Bit 11 post-drilling image.

5.4. Drilling Vibrations Detection

Cutting structures are often damaged by the presence of drill string dynamic dysfunctions.

As noted, drilling industry recognized modes of vibration include axial chatter, torsional vibrations and stick-slip, lateral vibrations and whirl. These can be detected in the ES plane. Scatter in the ES plane can be attributed to several factors, including measurement variation/error, cutting structure failure, formation variability, drilling system perturbations, and others. Nevertheless, drilling vibrations can also be expected to introduce these variations as the bit response deviates from a quasi-static process to one dominated by variable drilling forces. The presence of compliance in the drill string reduces the drilling effectiveness resulting in increased scatter in the ES plane with higher resultant specific energy values and decreased torque delivered to the bit-rock interface.

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6. BIT PERFORMANCE SUMMARY

6.1. Performance Highlights

The bit program used on the subject Utah FORGE wells has demonstrated the capability of synthetic diamond drag bits drilling hard rock formations. As shown in Tables 4-1, 4-2, 4-3 and 4-4, many of the bits in the drilling program sustained drilling footages of several hundred feet with net penetration rates exceeding 100 ft/hr in the hard granitic basement of Utah FORGE. The PDC bits used to drill the overburden demonstrated even greater performance. The ROP and footage performance of all bits comprising the bit program for the four Utah FORGE wells are shown in Figure 6-1. The individual bit run summary for each bit comprising the drilling program are documented in the corresponding volume of this report. The preferential balance between Net ROP and footage drilled is governed by a constraint that predicts the cost of a drilled interval as presented in the next section.

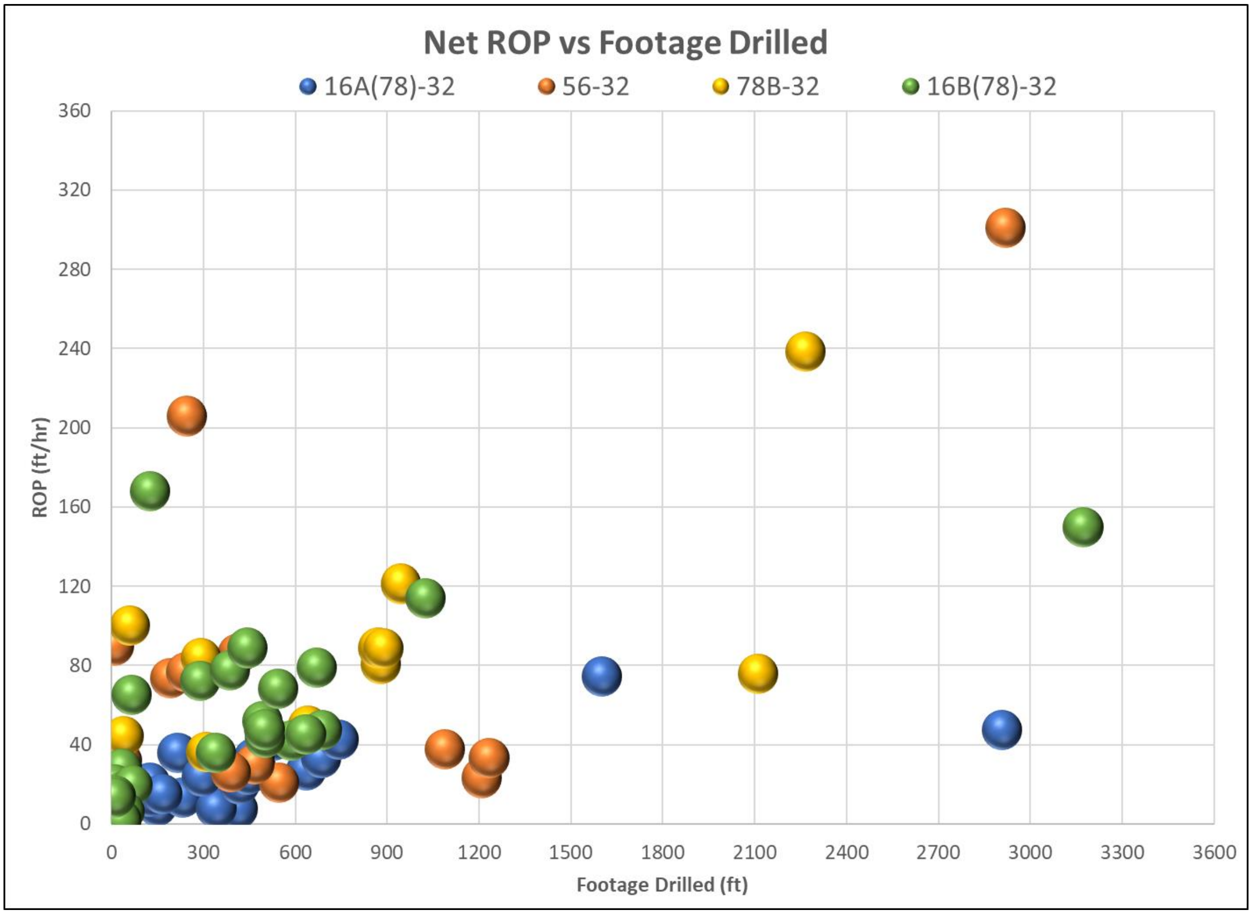


Figure 6-1. Net ROP (ft/hr) versus Footage Drilled (ft) for all bits used on Utah FORGE wells 16A(78)-32, 56-32, 78B-32 and 16B(78)-32.

6.2. Tradeoff between Rate of Penetration and Bit Life

Just as the drilling parameters are governed by a constraint equation, the overall drilling performance determines or constrains the cost of drilling an interval. The Rate of Penetration and Bit Life performance for each of the wells in the Utah FORGE drilling program have been presented in

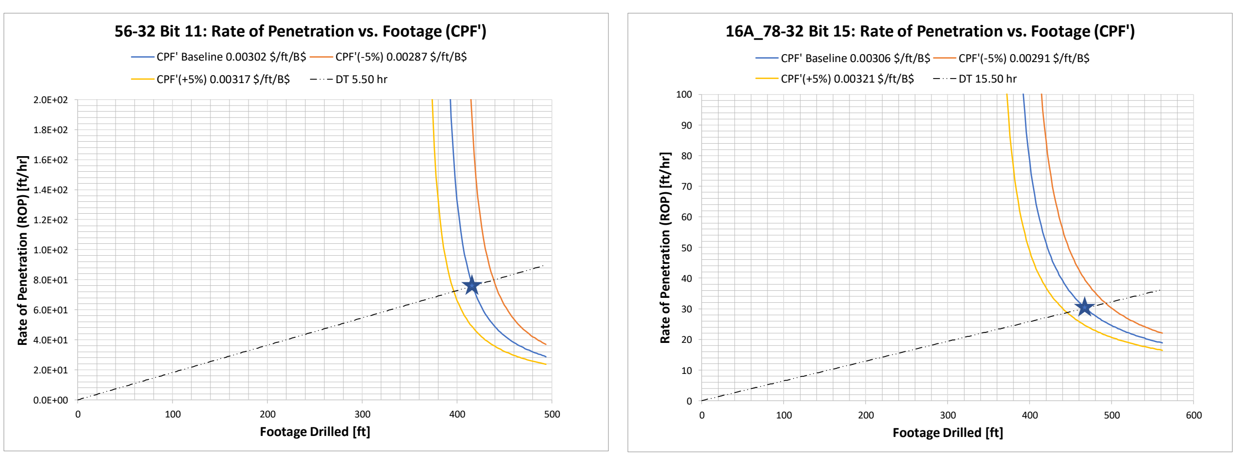
Section 4. A succeeding consideration is the cost of constructing an interval of the well attributed to constraints imposed by the balance of ROP and bit footage associated with drilling the interval.

Drilling costs for an interval are derived using the traditional expression that accounts for bit cost and rig rates distributed over the drilling interval (Bourgoyne, A.J.T., et al, 1986):

$$\text{CPF} = \frac{\text{BC} + \text{RR}(\text{DT} + \text{TT})}{\text{L}} \qquad (9.1)$$

where CPF = cost per foot [$/ft], BC = bit cost [$], RR = rig rate [$/hr], DT = drilling time [hr], TT = tripping time [hr], and L = footage drilled [ft].

The ROP and footage-drilled “state points” of each of the bit performances recorded in Section 4 can be mapped into the ROP-Footage (RF) plane to discern the relative cost savings performance that can be realized by performance increases in either of these metrics. The interval CPF associated with a final bit performance state point in the ROP-Footage plane can be computed; a constant CPF’ curve, defined as the CPF normalized to the Bit Cost, can be derived (see Appendix) and plotted in the ROP-Footage plane based upon the CPF’ constraint determined by ROP and footage-drilled. Variations in the ROP and footage-drilled with improved performance provide insight into the cost savings that can be derived from improvements in either ROP, footage or both. Figure 6-2a shows the end performance state points for 56-32/Bit 11 as an example of ROP, footage-drilled performance that would benefit from improved footage as the state point lies above the knee of the CPF’ curve; Figure 6-2b shows end performance state points for 16A(78)-32/Bit 15 as an example of ROP, footage-drilled state points that would benefit from either improved ROP or improved footage as the state point lies in the knee of the CPF’ curve. Each state point must be evaluated in the ROP-Footage plane that considers the trip time to get to the initial depth. Also shown are CPF’ plots for 5% excursions from the nominal condition. Table 6-1 summarizes the CPF’ values for the smaller diameter bits used on the four Utah FORGE wells based upon assumed rig rates, bit costs, and trip rates summarized in Figure 6-2.



(a) (b)

Figure 6-2. Rate of penetration and footage drilled performance influence on drilling costs assuming a rig rate (RR) of $1000/hr, individual bit costs (BC) of $50,000, and round-trip trip rates (TR) of 1000 ft/hr corresponding to respective constants (derived in Appendix) of k1=0.02 [1/hr] and k2 = 0.00001

[1/hr]: (a) Well 56-32/Bit 11 – example of bit benefiting from improved footage, (b) Well 16(A)-78-32/Bit 15 – example of bit benefiting from improved ROP and footage.

Table 6-1: Interval CPF' drilling costs bits used on the four Utah FORGE wells assuming a rig rate (RR) of $1000/hr, individual bit costs (BC) of $50,000, and round-trip trip rates (TR) of 1000 ft/hr corresponding to respective constants (derived in Appendix) of k

Well	Bit No.	Bit Diameter	Start Depth	Footage Drilled	End Depth	Dbar	ROP	CPF'
16A_78-32	7	8.75	4987	125	5112	5049.5	20.8	0.0098
16A_78-32	8	8.75	5113	232	5345	5229.0	13.3	0.0063
16A_78-32	15	8.75	5892	468	6360	6126.0	30.2	0.0031
16A_78-32	16	8.75	6360	166	6526	6443.0	15.1	0.0081
16A_78-32	17	8.75	6526	419	6945	6735.5	20.0	0.0037
16A_78-32	18	8.75	6945	444	7389	7167.0	24.7	0.0034
16A_78-32	19	8.75	7389	635	8024	7706.5	27.0	0.0026
16A_78-32	21	8.75	8025	216	8241	8133.0	36.0	0.0059
16A_78-32	22	8.75	8241	150	8391	8316.0	25.0	0.0086
16A_78-32	23	8.75	8391	144	8535	8463.0	24.0	0.0090
16A_78-32	24	8.75	8535	529	9064	8799.5	42.3	0.0027
16A_78-32	25	8.75	9064	684	9748	9406.0	33.4	0.0023
16A_78-32	26	8.75	9748	742	10490	10119.0	42.4	0.0021
16A_78-32	27	8.75	10490	465	10955	10722.5	33.2	0.0032
56-32	6	8.75	3506	1089	4595	4050.5	37.7	0.0015
56-32	7	8.75	4595	548	5143	4869.0	20.9	0.0030
56-32	8	8.75	5143	467	5610	5376.5	30.1	0.0030
56-32	9	8.75	5610	389	5999	5804.5	26.3	0.0036
56-32	10	8.75	5999	1209	7208	6603.5	23.2	0.0018
56-32	11	8.75	7208	412	7620	7414.0	85.8	0.0030
56-32	15	8.75	7667	1233	8900	8283.5	33.3	0.0015
56-32	16	8.75	8900	245	9145	9022.5	76.6	0.0051
78B-32	6	10.625	3009	642	3651	3330.0	49.8	0.0021
78B-32	7	10.625	3651	2110	5761	4706.0	75.6	0.0008
78B-32	8	10.625	5761	60	5821	5791.0	100.0	0.0188
78B-32	9	10.625	5821	879	6700	6260.5	80.6	0.0015
78B-32	10	8.75	6700	28	6728	6714.0	18.7	0.0416
78B-32	11	8.75	6700	40	6740	6720.0	44.4	0.0288
78B-32	12	10.625	6740	2	6742	6741.0	3.3	0.5735
78B-32	13	10.625	6742	871	7613	7177.5	88.9	0.0015
78B-32	14	10.625	7613	887	8500	8056.5	88.7	0.0015
78B-32	15	10.625	8500	30	8530	8515.0	10.7	0.0409
78B-32	17	5.75	8555	945	9500	9027.5	121.2	0.0014
16B_78-32	1	22	120	1026	1146	633	114	0.001162
16B_78-32	3	14.75	1181	3172	4353	2767	150	0.000508
16B_78-32	4	14.75	4353	492	4845	4599	52	0.002395
16B_78-32	11	9.5	4980	289	5269	5124.5	72	0.003990
16B_78-32	12	9.5	5269	688	5957	5613	47	0.001792
16B_78-32	13	9.5	5957	588	6545	6251	42	0.002089
16B_78-32	14	9.5	6545	65	6610	6577.5	65	0.017584
16B_78-32	15	9.5	6610	340	6950	6780	36	0.003515
16B_78-32	16	9.5	6950	634	7584	7267	45	0.001982
16B_78-32	17	9.5	7584	501	8085	7834.5	44	0.002484
16B_78-32	18	9.5	8085	500	8585	8335	48	0.002509
16B_78-32	19	9.5	8585	670	9255	8920	79	0.001934
16B_78-32	20	9.5	9255	545	9800	9527.5	68	0.002360
16B_78-32	27	9.5	9863	387	10250	10056.5	77	0.003279
16B_78-32	33	8.75	10304	126	10430	10367	168	0.009758
16B_78-32	38	9.5	10503	444	10947	10725	89	0.002960

6.3. Representative Bit Conditions

Bit conditions are determined by a dull grade designation when pulled from the well. These grades are typically documented in the daily drilling reports.

6.3.1. Normal Wear and Tear

Bit condition can be broadly categorized as either normal wear & tear or damage beyond repair. Normal wear and tear includes minor cutter chipping and wear in which the support structure of the bit is preserved to where the bit can be retooled with new diamond cutters. Many of the bits in the Utah FORGE well program were pulled in operable condition. Some of the noteworthy bit performance runs are summarized in Figure 6-3.

Figure 6-3. Normal wear and test observed on representative bits: a) NOV Bit 26 on 16A(78)-32 drilled 742 ft @ 42 ft/hr, b) Smith Bit 8 on 16A(78)-32 drilled 232 ft @ 13 ft/hr, c) Baker Hughes Bit 19 on 16B(78)-32 drilled 670 ft @ 78 ft/hr, and d) Ulterra Bit 9 on 16A(78)-32 drilled 124 ft @ 14 ft/hr.

6.3.2. Damage Beyond Repair

By contrast, the bit may experience Damage Beyond Repair (DBR) in which the support matrix of the bit is compromised such that the bit cannot be re-tooled. Damage Beyond Repair was a common bit failure mode as the PDC bits used throughout the Utah FORGE well drilling program were pushed to their limits. The support matrix of the bit was often compromised such that that the bit cannot be re-tooled. Examples of this include blade shear and ring outs. Some examples are summarized in Figure 6-4 and Figure 6-5.

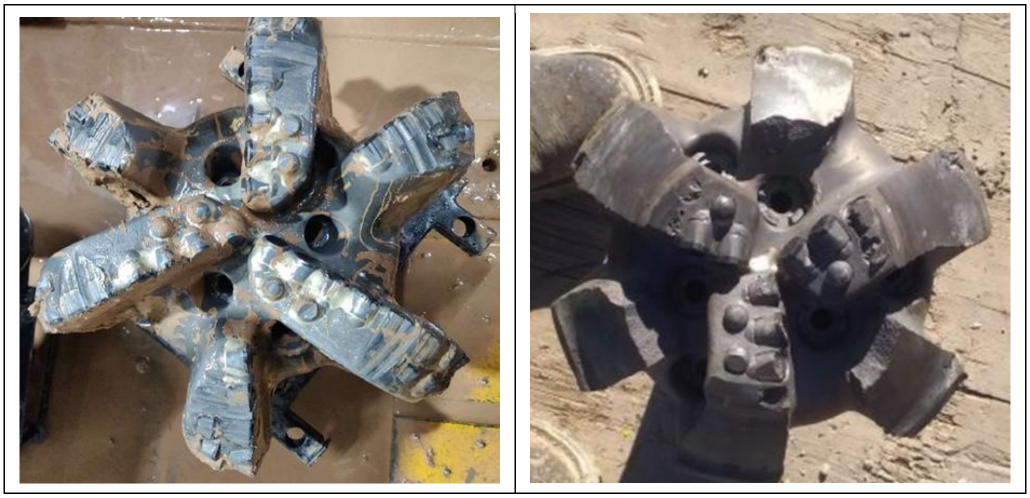


Figure 6-4. Damage beyond repair caused by blade shear: a) Bit 5 on 16A(78)-32, b) Bit 19 on 16A(78)-32.

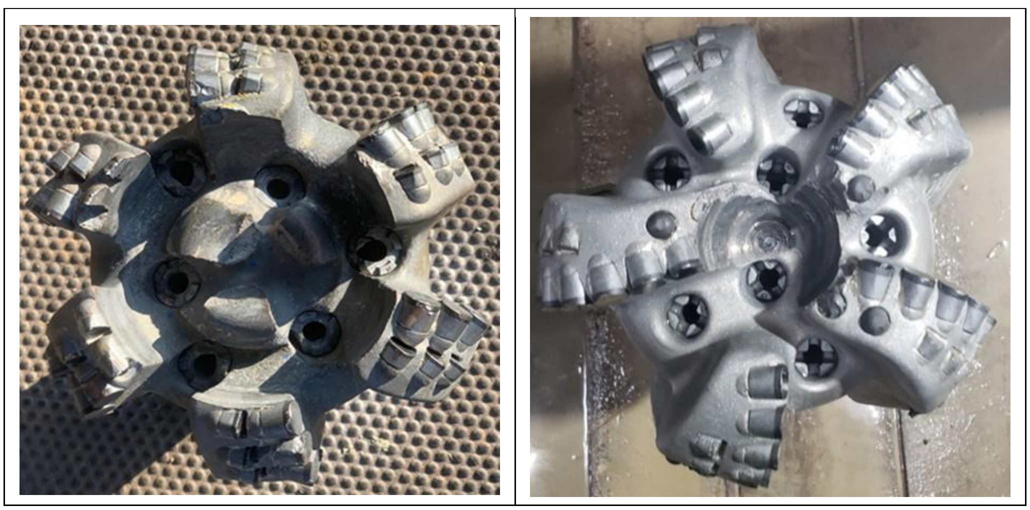


Figure 6-5. Damage beyond repair caused by ring outs: 1) Bit 11 on 16A(78)-32, b) Bit 21 on 16A(78)-32.

6.4. Feature Influence

A variety of features were used on the bits comprising the Utah FORGE well construction program. Some of these bits were intended to improve penetration rate and bit life, and additional features to protect the cutting structure of the bit from impact damage including torque control components, impact arrestors, and back up cutters. For hard-rock drilling many of the extra features added to the cutting structure are intended to guard against Damage Beyond Repair. Some of these features include the following:

- Torque Control Components (TCCs) are intended to limit the engagement of the bit with the formation so that the bit doesn't develop too large of a depth of cut contributing to torque over-loading. This is achieved by domed inserts on the leading face of the bit. The carbide inserts also serve to protect the cutting structure of the bit during drilling axial vibrations.

- Impact arrestors are similar yet are usually placed towards the outer edge of the bit to prevent cutting structure damage due to lateral vibrations and/or bit whirl.

- Many of the bits in the Utah FORGE well program included back up cutters, a secondary row of cutters that serve to continue bit performance should the leading row of cutters fail.

- Increased bit blade counts make a bit less penetration rate response aggressive. The increased blade count also allows for more diamond on the face of the bit essentially hardening the cutting structure to dynamic events.

- Other features may be used that influence the bit life, penetration rate, or bit impact damage and include diamond type, and BHA properties such as stabilizers and shock subs, etc.

All these features should work preferentially to allow an ideal balance between rate of penetration and bit life and prevent the bit from becoming damaged beyond repair.

6.5. Bit Run Summaries

The individual bit run summary for each bit comprising the drilling program are documented in the corresponding volume of this report and include: Volume 2: Utah FORGE Well 16A(78)-32, Volume 3: Utah FORGE Well 56-32, Volume 4: Utah FORGE Well 78B-32, and Volume 5: Utah FORGE Well 16B(78)-32.

7. CONCLUSIONS

Bit performance metrics for Utah FORGE Well 16A(78)-32, Well 56-32, Well 78B-32 and Well 16B(78)-32have been acquired, evaluated and reported. A rock reduction model has been presented with laboratory validation. This model may be used to provide insight into field drilling performance. This model has been applied to the drilling response of bits from the FORGE drilling campaigns. Examples presented allow insight into the methods used to evaluate bit response, formation hardness, wear rate, cutting structure damage, and drilling dynamic dysfunction conditions. The analyses have been conducted post drilling yet may be applied to real-time evaluations for improved drilling performance. The influence of various bit design features has been addressed. The relative cost-benefit tradeoff of improving the penetration rate response and bit durability has been addressed. In addition to bit design enhancements that may be evaluated using this method, the impact of ROP and bit life performance improvements on drilling cost savings can also be addressed using these methods.

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APPENDIX A. BIT PENETRATION RATE VS FOOTAGE CONSTRAINT

Here CPF = cost per foot [$/ft], BC = bit cost [$], RR = rig rate [$/hr], DT = drilling time [hr], TT = tripping time [hr], and L = footage drilled [ft].

$$\mathrm{CPF} = \frac{\mathrm{BC} + \mathrm{RR}(\mathrm{DT} + \mathrm{TT})}{\mathrm{L}} \tag{A-1}$$

Note where ROP = rate of penetration [ft/hr]:

$$\mathrm{ROP} = \frac{\mathrm{L}}{\mathrm{DT}}$$

Therefore

$$\mathrm{DT} = \frac{\mathrm{L}}{\mathrm{ROP}} \tag{A-2}$$

For an initial interval depth D_0 [ft], the average depth of the interval $\bar{D}$ [ft] is

$$\bar{\mathrm{D}} = \frac{1}{2}(\mathrm{D_0}+\mathrm{D_f}) = \frac{1}{2}(\mathrm{D_0}+\mathrm{D_0}+\mathrm{L})$$

where $D_f = D_0$+L.

$$\bar{\mathrm{D}} = \mathrm{D_0}+\frac{\mathrm{L}}{2} \tag{A-3}$$

and the average trip time is

$$\mathrm{TT} = \frac{\bar{\mathrm{D}}}{\mathrm{TR}}=\frac{\mathrm{D_0}}{\mathrm{TR}}+\frac{\mathrm{L}}{2\mathrm{TR}} \tag{A-4}$$

where TR = trip rate [ft/hr]. Substituting DT and TT into equation (A-1):

$$\mathrm{CPF} = \frac{\mathrm{BC}+\mathrm{RR}\left[\frac{\mathrm{L}}{\mathrm{ROP}} + \frac{D_0}{TR} + \frac{L}{2TR}\right]}{\mathrm{L}} \tag{A-5}$$

$$\mathrm{CPF} = \frac{\mathrm{BC}}{\mathrm{L}} + \frac{\mathrm{RR}}{\mathrm{ROP}} + \frac{\mathrm{RR}(2\mathrm{D_0}+\mathrm{L})}{2\cdot\mathrm{L}\cdot\mathrm{TR}} \tag{A-6}$$

$$\mathrm{CPF} = \frac{\mathrm{BC}}{\mathrm{L}} + \frac{\mathrm{RR}}{\mathrm{ROP}} + \frac{\mathrm{RR}}{2\mathrm{TR}}\left(1+\frac{2\mathrm{D_0}}{\mathrm{L}}\right) \tag{A-7}$$

Here, the first term corresponds to bit cost, the second corresponds to the rig cost while drilling, and the third corresponds to the rig cost while tripping.

Divide the CPF equation by BC to derive CPF' [1/ft]

$$\mathrm{CPF}' = \frac{\mathrm{CPF}}{\mathrm{BC}} = \frac{1}{\mathrm{L}} + \frac{\left(\frac{\mathrm{RR}}{\mathrm{BC}}\right)}{\mathrm{ROP}} + \frac{\left(\frac{\mathrm{RR}}{\mathrm{BC}}\right)}{2\mathrm{TR}}\left(1+\frac{2\mathrm{D_0}}{\mathrm{L}}\right) \tag{A-8}$$

Define k_1 [1/hr] and k_2 [1/ft]

$$\mathrm{k_1} = \frac{\mathrm{RR}}{\mathrm{BC}} \tag{A-9}$$

$$k_2 = \frac{\left(\frac{RR}{BC}\right)}{2TR} = \frac{k_1}{2TR} \tag{A-10}$$

Finally, CPF' is

$$CPF' = \frac{1}{L} + \frac{k_1}{ROP} + k_2\left(1+\frac{2D_0}{L}\right) \tag{A-11}$$

Now solving eq. (A-8)

$$CPF = CPF' \times BC \tag{A-12}$$

Now solve eq. (A-11) for ROP to prepare to plot constant CPF' contours in ROP-Footage plane

$$\frac{k_1}{ROP} = CPF' - \frac{1}{L} - k_2\left(1+\frac{2D_0}{L}\right) \text{ and}$$

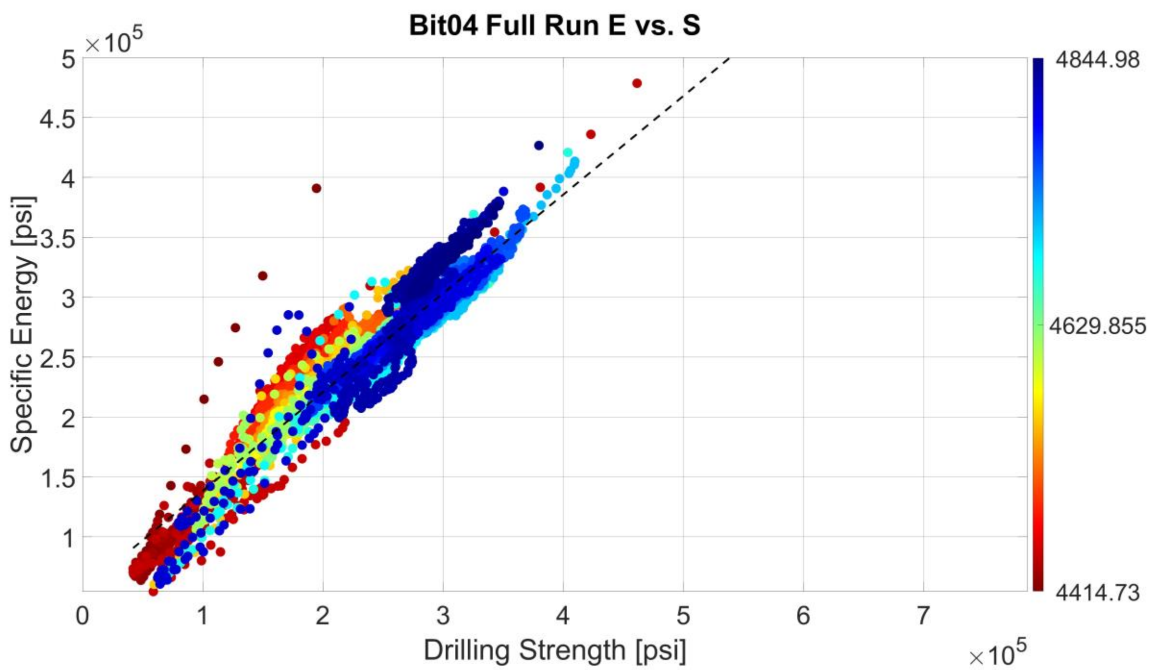
$$ROP = k_1\left[CPF' - \frac{1}{L} - k_2\left(1+\frac{2D_0}{L}\right)\right]^{-1} \tag{A-13}$$

APPENDIX B. DATA FILTERING AND FIT

The MATLAB data processing script for standardization of bit performance filtered the raw data through the following routines:

1. Remove zero/negative instances of WOB, ROP, RPM, differential pressure, top drive torque, and motor rpm.
2. Set differential pressure to zero if all data is negative.
3. Remove redundant data instances.
4. Average data at redundant depths

The fit line shown in the Full Run E vs. S plot which shows specific energy as a function of drilling strength used a function called "robustfit". This function uses robust regression to estimate a linear model by iteratively reweighing least squares.



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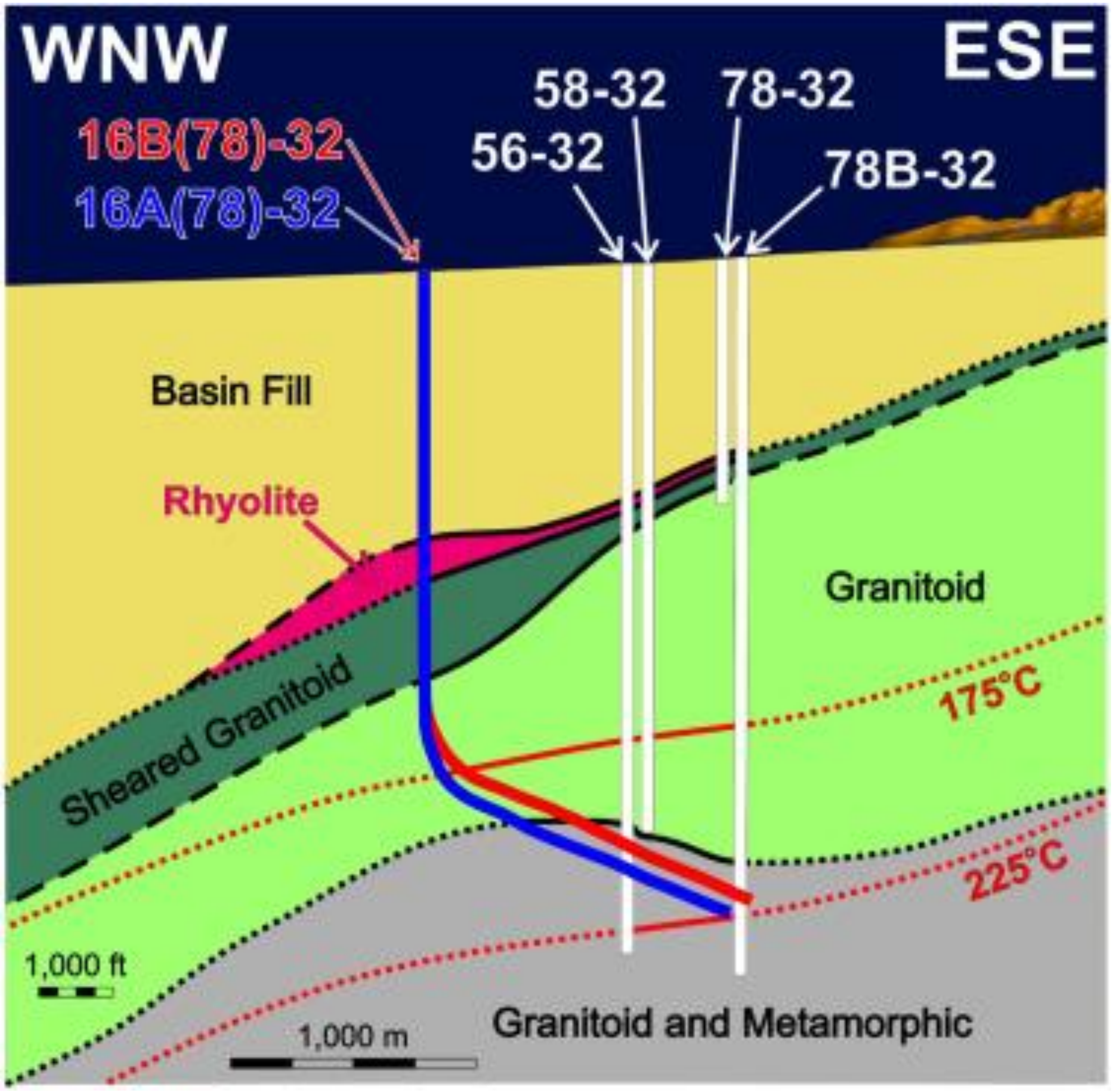
APPENDIX C. LITHOLOGY OF UTAH FORGE



Geologic cross-section (1:1) along the trajectory of the injection-production doublet showing well tracks, lithologies, and the temperature gradient in the reservoir. (Reference: Jones, C. et al, Geology of the Utah Frontier Observatory for Research in Geothermal Energy Enhanced Geothermal System Site, Geothermics, Sept 2024, Vol 122; used with permission).

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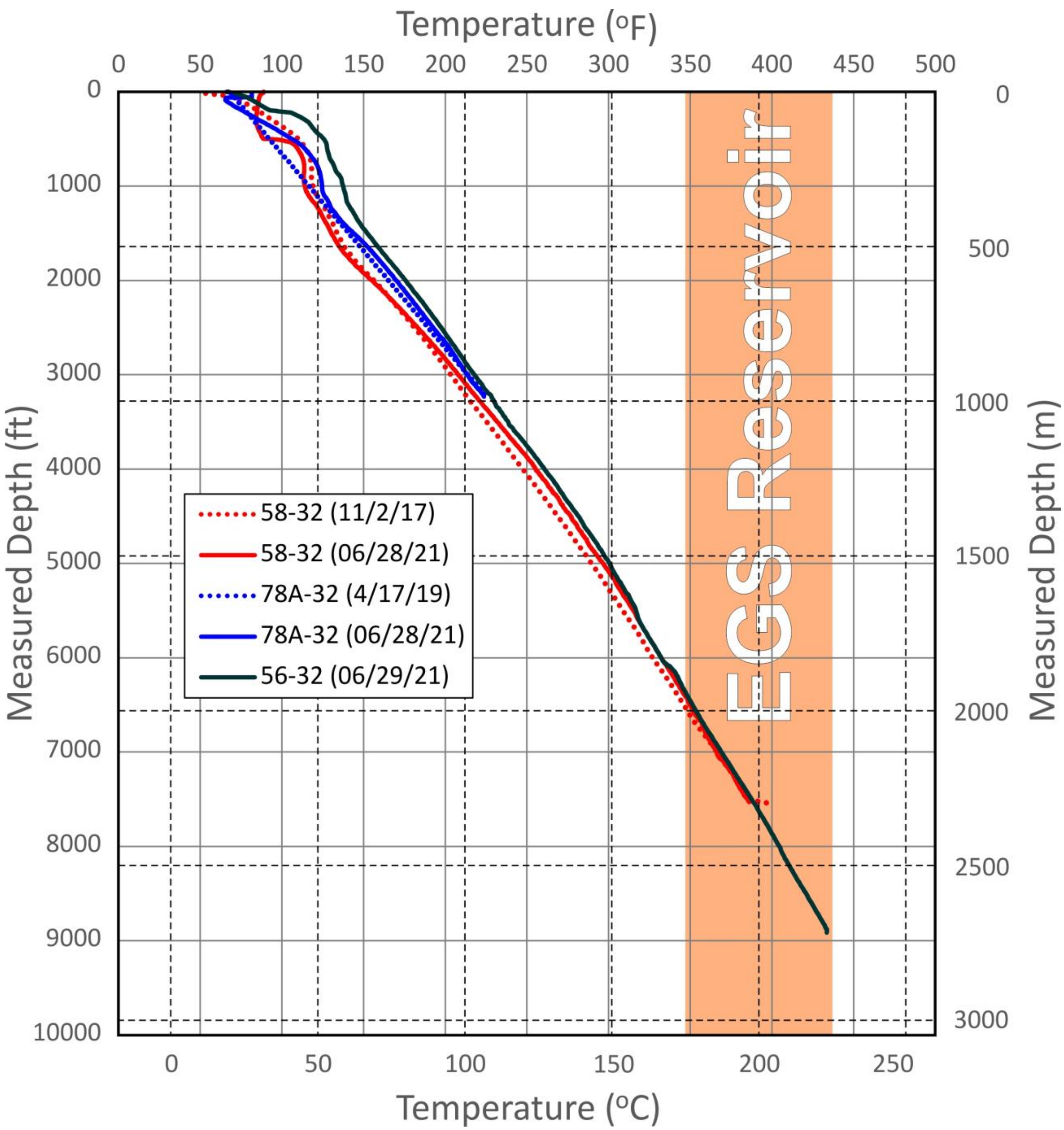
APPENDIX D. UTAH FORGE TEMPERATURE PROFILE



Temperature Profile of Utah FORGE Wells 58-32, 78A-32, and 56-32. (Reference: Stout, Frank. 2021. "Utah FORGE: Wells Updated Temperature and Pressure Logs (June 2021)". United States. https://dx.doi.org/10.15121/1812334. https://gdr.openei.org/submissions/1326.)

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