

PRACTICES FOR MAXIMIZING DRILLING PERFORMANCE THROUGH
INTERBEDDED FORMATIONS

A Thesis

by

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ABSTRACT

Drilling the highly interbedded Brushy Canyon in the Delaware Basin can force operators to use over three PDC bits to drill a 12.25” intermediate hole. A study was conducted in order to develop understanding of the mechanics involved in specific bit failures that were occurring when drilling across high-strength laminations. It was found that upon exiting high-strength interbedded laminations, sudden high-torque events were occurring that were leading to tangential overload of the trim and gauge cutters. The change from high-strength to low-strength rock at the transition reduces the resistance on the nose of the bit abruptly, transferring the axial load to the trim and gauge cutters in the high-strength rock. The redistribution of axial load across the cutters results in an instantaneous net gain in torque that is great enough to overload one to two rows of outside cutters tangentially.

To combat this, a rate of penetration (ROP) setpoint and constant bit RPM were utilized when drilling the Brushy, allowing for the depth of cut per revolution (DOC) to be controlled, prevent damaging bit whirl in high-strength laminations, and reducing tangential overload tendency due to entering and exiting laminations. Performance was tracked using a simple DOC tracer alongside MSE which helped in distinguishing between bit dysfunction and damage. Additionally, an operational practice for using the DOC tracer when control drilling with an ROP setpoint was developed.

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1. INTRODUCTION

1.1 Mechanical Specific Energy (MSE)

Being able to accurately relate drilling performance to back to rock strength in has long been sought after. Teale (1964) developed the concept of specific energy in rock drilling by combining the axial (indentation) and rotational (cutting) work required to fail the rock. The result is the amount of energy required to drill a unit volume of rock and is equal to the rock's compressive strength at atmospheric conditions (Teale 1964). Teal observed that if there was a sufficient depth of cut (DOC) when drilling then there was a linear relationship between rate of penetration (ROP) and torque when plotted, with the slope of the line being equal to rock strength. However, at low DOC there was high specific energy values due to the bit's inability to consistently generate torque (Teale 1964). The concept of mechanical specific energy (MSE) was further developed by Pessier and Fear (1992) by introducing a unit-less bit specific coefficient of sliding friction (COF) to express torque as a function of weight on bit (WOB). The MSE was therefore defined as:

$$\text{MSE} = \frac{4 * \text{WOB}}{\pi * \text{Dia}^2} + \frac{13.33 * \text{COF} * \text{RPM}}{\text{ROP} * \text{Dia}^2} \text{ (ksi)}$$

Where COF is equal to:

$$\text{COF} = \frac{36 * \text{Torque}}{\text{WOB} * \text{Dia}}$$

The purpose for including a bit specific coefficient of sliding friction is that it expresses bit torque and WOB as a linear relationship. Teale (1964) developed the concept of specific energy in a lab setting where bit torque was easily calculated.

However, it is difficult to accurately measure downhole torque in the field, so Pessier and Fear (1992) introduced the COF to account for downhole torque when estimating the specific energy.

Pessier and Fear (1992) also aimed to validate Teale's (1992) concepts for drilling rock that is under hydrostatic pressure and therefore make them applicable to oilfield drilling. It was found that under hydrostatic conditions, specific energy values were much larger than when at atmospheric conditions but this was due to the increase in rock strength (Pessier and Fear 1992). However, if the bit was efficient and not damaged, there was still a linear relationship between ROP and torque, meaning MSE stayed the same (Pessier and Fear 1992).

Expanding the COF gives the more commonly recognized form of MSE:

$$\text{MSE} = \frac{4 \cdot \text{WOB}}{\pi \cdot \text{Dia}^2} + \frac{480 \cdot \text{Torque} \cdot \text{RPM}}{\text{ROP} \cdot \text{Dia}^2} \text{ (ksi)}$$

The role of the above form of MSE in performance surveillance at the rig in identifying drilling dysfunctions has been examined thoroughly over the past decade and has proven to be the most effective means of maximizing drilling performance in real-time (Dupriest and Koederitz 2005). It was found that proper workflow allowed for rig-personnel to effectively recognize and respond to bit founder (Fig. 1), with penetration rates increasing by 133% on the rigs that were selected for the field trials (Dupriest and Koederitz 2005). Further workflow was developed around the concepts established by Teale (1964) and Pessier and Fear (1992), primarily that if the bit was efficient and not

damaged, then there will be linear relationship between torque, WOB, and ROP

(Dupriest 2006). The workflow was simple (Dupriest 2006):

1. Raise the WOB. If the ROP response is linear (as determined through MSE surveillance), the bit is efficient.
2. Continue raising WOB until non-linear response is observed, or the ROP becomes non-bit limited
3. In the first case, make operational adjustments to the extent possible to minimize MSE then operate at just below the founder. For both bit and non-bit limiters, identify and document the nature of the founder and communicate it to engineering.
4. Redesign the system appropriately to extend the identified limiter and repeat step 1-4.

The workflow was based on the fact that there can only be one limiter (bit and non-bit) that can prevent WOB from being raised at any point in time (Dupriest 2006). Prioritizing the limiters means that rig personnel are constantly trying to find what is preventing them from maximizing WOB and therefore maximizing their ROP (Dupriest 2006).

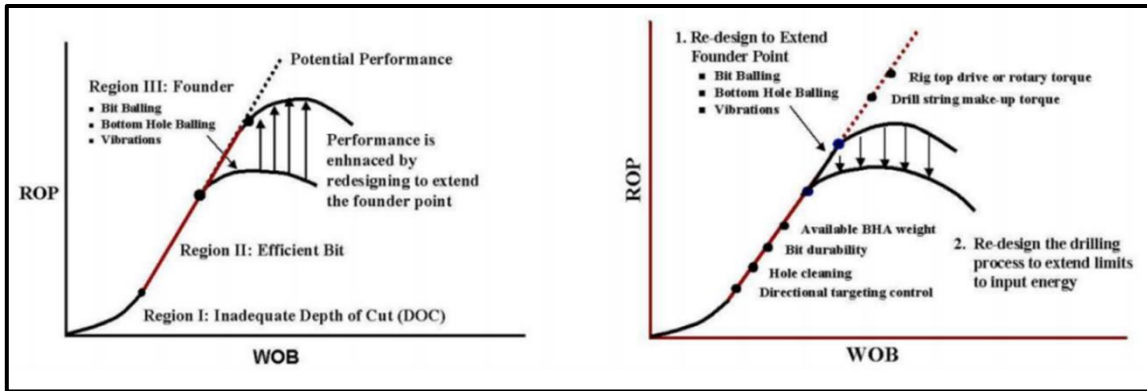


Figure 1 – Plots used to show the linear relationship between WOB and ROP when the bit is efficient, as well as bit founder. Reprinted from Maximizing Drill Rates with Real-Time Surveillance of Mechanical Specific Energy (Dupriest and Koederitz 2005).

The use of downhole mud motors in today’s unconventional wells allows rig personnel to calculate two forms of MSE: Downhole (Bit) and Surface MSE. Surface MSE is calculated using torque and rotary speed values that are recorded from the top drive, while bit MSE is calculated using motor performance specifications to calculate torque at the bit and bit RPM (Rev/gal, Max Operating Differential, and Torque at Max Operating Differential) (Neufeldt et al. 2018).

The two forms are calculated using the following equations:

$$\text{Bit MSE} = \frac{4 \cdot \text{WOB}}{\pi \cdot \text{Dia}^2} + \frac{480 \cdot \text{Bit RPM} \cdot \text{Bit Torque}}{\text{ROP} \cdot \text{Dia}^2} \text{ (ksi)}$$

$$\text{Surface MSE} = \frac{4 \cdot \text{WOB}}{\pi \cdot \text{Dia}^2} + \frac{480 \cdot \text{Bit RPM} \cdot \text{Rotary Torque}}{\text{ROP} \cdot \text{Dia}^2} \text{ (ksi)}$$

All bottom hole assemblies (BHA) have some level of mass eccentricity, which results in a significant angular mass momentum when the string is rotated (Dykstra et al.

1996). The imbalance is what generates and sustains the lateral vibration (whirl) in the BHA which forces the bit to move laterally with potentially damaging force (Brett et al. 1989). The reduction in drilling efficiency is seen as an increase in both the Bit and Surface MSE. When using MSE surveillance in operational practices to maximize drilling performance, it's important to monitor both Surface MSE and Bit MSE if a mud motor is in use, as the relationship between the two can help pinpoint the onset of dysfunction. For example, many factors while rotating that do not go into the rock cutting process can add torque to the drill string (spiral borehole patterns, stabilizer drag/impact, etc.) that will cause Surface MSE to increase disproportionately to Bit MSE (Rahmani et al. 2015).

A concern that arises when using MSE surveillance operationally is whether or not an increase in MSE indicates bit damage, dysfunction, or simply a change in rock strength. A practice to track bit performance throughout a run is to establish a baseline MSE value (Waughman et al. 2003, Dupriest et al. 2005). The baseline MSE is the bit's maximum efficiency and only changes with lithology, allowing MSE values from intervals of the same rock type to be compared (Waughman et al. 2003, Dupriest et al. 2005).

1.2 Whirl

The most common form a bit dysfunction is bit whirl, which is lateral movement of the drill bit due to the mass imbalance in the BHA that generate significant lateral displacement when the drill string is rotated (Brett et al. 1990, Dykstra et al. 1996). The lateral movement of the bit can result in high impact loads on the outside PDC cutters when they come in contact with the borehole wall (Brett et al. 1990). Damage due to bit whirl appears as beach marks (chipping) on the outside cutters from point loading of the tip of the PDC cutter, with the damage propagating down the diamond face (Brett et al. 1990). This damage type will lead to wear flat development as long as drilling operations are continued (Brett et al. 1990).

Whirl is identified through MSE surveillance (Fig. 2), as it is the only bit dysfunction that sees MSE decrease when WOB is raised (Dupriest et al. 2005). Whirl results in elevate levels of MSE and the real-time response to whirl is to raise WOB, allowing DOC to increase sufficiently enough that the bit is constrained from moving laterally (Dupriest et al. 2005).

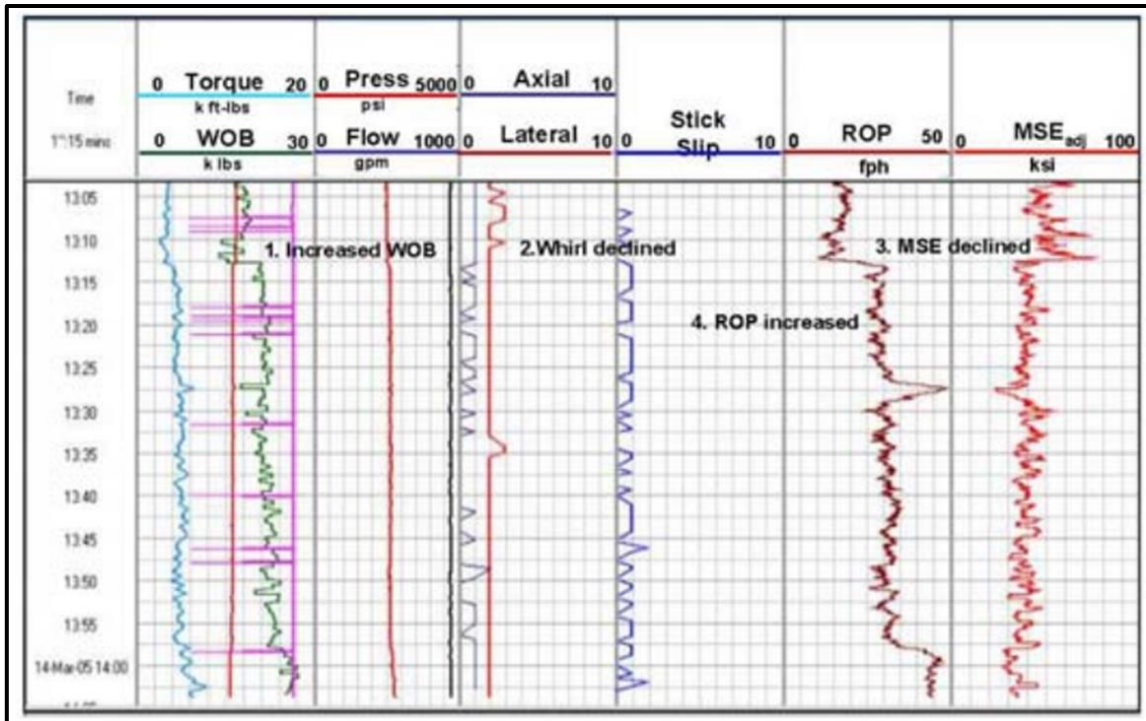


Figure 2 – Plot showing the decrease in both lateral vibrations and MSE, as well as the gain in ROP due to an increase in the WOB. Reprinted from Maximizing ROP With Real-Time Analysis of Digital Data and MSE (Dupriest et al. 2005).

1.3 Interfacial Severity and Stick-Slip

Interfacial severity (IFS) is one of the most damaging dysfunctions that is faced. Two forms of interfacial severity exist in the Delaware Basin that limit drilling performance: laminar and nodular. Laminar IFS is when high-strength rock is interbedded between lower-strength rock while nodular IFS is when small, high-strength inclusions (nodular chert, gravel, etc.) are spread throughout lower strength rock. The result is point loading of the cutters across the entire face of the bit that results in hinge (tangential) failures (Fig. 3). This makes nodular IFS extremely damaging and forces operators to reduce WOB for survivability (Remmert et al. 2007).

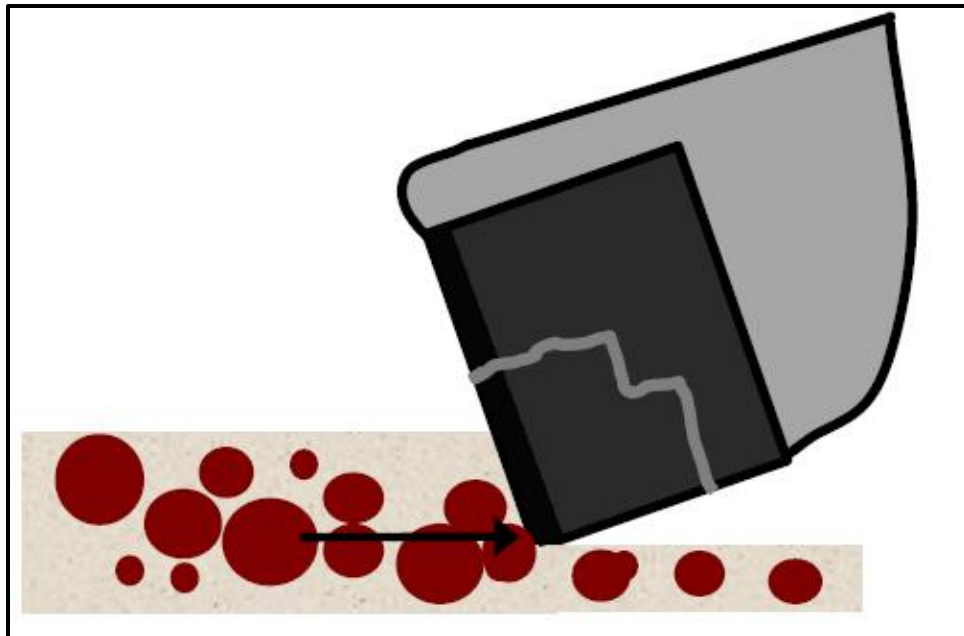


Figure 3 – Point loading on the tip of the cutter occurs when drilling nodular IFS that results in hinge (tangential) failure. Reprinted from High Performance Drilling, Lesson 10: Axial Vibrations, Interfacial Severity, Bottom Hole Balling (Dupriest 2016).

However, there are situations where laminar IFS (without proper workflow and engineering redesign) can be just as damaging as nodular IFS. This is due in part because laminations can range from a few feet to a few inches in thickness and there is no way to tell when individual laminations will be encountered until the bit actually enters one. This is problematic, for it is common to see small streaks of rock in excess of 25ksi interbedded in 15ksi rock in while drilling through the Brushy (Phillips et al. 2018). The high-contrast in strength as the bit enters and exits the lamination can load the bit non-uniformly, induce severe stick-slip (speed oscillations), or even allow severe

whirl that is coupled with full stick, all of which can critically damage the bit (Mann et al. 2016).

The most common dysfunction that occurs when laminar IFS is encountered is severe stick-slip. As the bit indents and rotates, the reactive torque causes the drill string to wind-up counterclockwise. As the bit reaches a lamination, DOC is lost due to the increased rock strength. The stored elastic energy from the twist of the drill string is released due to the reduced resistance at the bit, allowing the string to unwind clockwise which accelerates the bit at a speed greater than the top drive. The angular mass momentum of the string causes it to over-twist in the clockwise direction, creating a restoring force that unwinds the string counter-clockwise, slowing the speed of the bit relative to the top drive. The cycle is maintained due to the achieving a high DOC when the string unwinds. Full stick is observed when the string unwinds at the same speed as the top drive in the counterclockwise direction, resulting in the bit coming to a complete stop at a very high DOC. (Detournay et al. 1992, Mann et al. 2016).

A known dysfunction when drilling interfacial severity is severe whirl coupled with stick-slip, known as synchronous torsional oscillations (STO) (Ertas et al. 2013). STOs occur when the drill string is turned at a torsionally resonant speed that creates high-frequency torsional oscillations in addition to the primary cycling of torque and bit speed from stick-slip (Mann et al. 2016). The result sufficient loss in DOC that allows the bit to move laterally with damaging force. However, in the case of this study it is believed that STO's were not limiting performance. STO's tend to occur as the bit enters a lamination due to the loss of DOC from the increase in rock strength. Additionally,

STO's create a distinct damage characteristic in that the bit exhibits whirl damage to the outside cutters but the underlying bit dysfunction is actually stick-slip (Mann et al. 2016).

1.4 Tangential Overload

Drilling through laminar interfacial severity can yield a distinct damage characteristic in PDC bit. Pastusek et al. (2018) found that PDC cutters can be overloaded in the tangential (cutting) direction as the nose of the bit enters a lamination at a high DOC per revolution. This type of overload can also occur on the trim and gauge cutters when exiting a lamination as these cutters are at a larger radius than the nose cutters, increasing the inertia of impacts (Taylor et al. 1998). The engineering response to prevent these failures was to implement DOCC on the nose of the bit (Pastusek et al. 2018) and redesign the cone angle of the PDC bit so that the axial load was more evenly distributed when drilling out of high-strength laminations (Taylor et al. 1998).

Laboratory testing by Kanyanta et al. (2014) on single PDC cutters has shown the force required to fail a cutter tangentially in a single impact is upwards of 725,000 psi on the cutting area. Much like what is seen in the field, the cutters that were failed tangentially in the lab exhibited a distinct hinge (step) in the back stud (Fig. 4). It was also found that a smaller, single impact could initiate a fracture on the diamond face of the PDC cutter and the cutter could still withstand thousands of impacts with a lower force before the cutter finally failed (Kanyanta et al. 2014). Applying this to what is seen

in the field, it is believed that if a full stick event was not great enough to completely fail the cutter, it could still initiate a fracture on the diamond body itself and fail sometime later after additional high-impact/torque events had occurred. This hypothesis will be tested following the conclusion of this study.

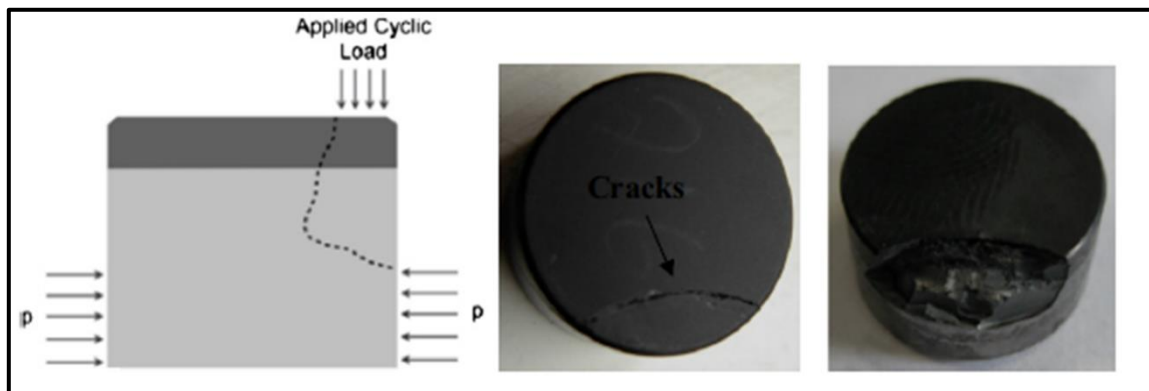


Figure 4 – Picture of Kanyanta et al. (2014) tangential failure due cyclical impact loading in the tangential direction. The cutter on the right mirrors what is seen in the field, with a distinct hinge (step) in the backing stud. Reprinted from Impact Fatigue Fracture of Polycrystalline Diamond Compact (PDC) Cutters and the Effect of Microstructure (Kanyanta et al. 2014).

1.5 Performance Tracking

Being able to determine the state of the bit in real-time has long been sought after. The most applicable technique to this study for monitoring bit performance and wear is through MSE surveillance. Waughman et al. (2003) developed a way to track performance using a baseline MSE approach. Real-time MSE data and gamma ray data were used to monitor bit dull state by comparing the value of MSE when drilling shale

(Waughman et al. 2003). Gamma ray data was used to identify transitions to shale and the baseline MSE value was used to compare the MSE to the previous baseline values in shale (Waughman et al. 2003). If the bit was damaged, MSE would not return to the baseline value upon reentering shale (Waughman et al. 2003).

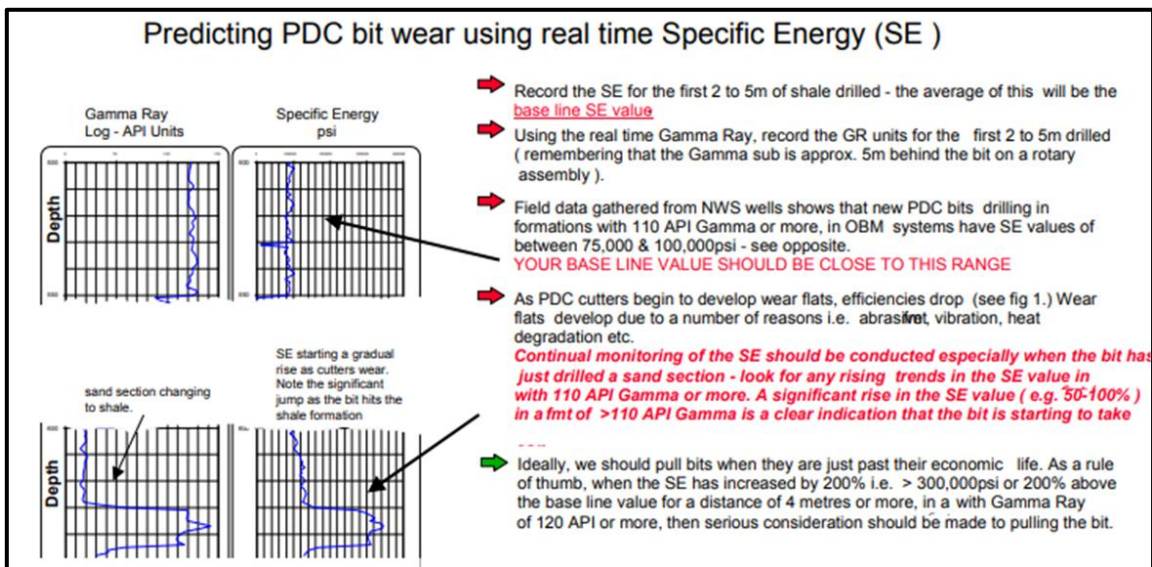


Figure 5 – Overview of the workflow developed by Waughman et al. (2003) to track bit performance and wear. A rule of thumb was developed in that when MSE exceeded the baseline value (when drilling shale for more than 4 meters) by 200% that serious consideration should be made to pull the bit. Reprinted from Real-Time Specific Energy Monitoring Enhances the Understanding of When To Pull Worn PDC Bits (Waughman et al. 2003).

2. METHODOLOGY

2.1 Bit Forensics and Tangential Overload Identification

Through the use of bit forensics in post-run analysis, bits that exhibited tangential overload to the trim and gauge cutters could be differentiated from those that showed simple whirl damage. Damage from whirl is identified by beach marks to the outside cutters due to the high-lateral impact with the borehole wall. Since both whirl and tangential overload damage occur on the trim and gauge cutters, high-quality photos of unique damage are required to distinguish between the two failures. The most obvious difference is that cutters that were failed due to tangential overload will exhibit a “hinge”, or a step in the tungsten-carbide backing stud (Fig. 6).



Figure 6 – Picture of typical tangential (hinge) failure that occurs on the trim and gauge cutters when drilling out of high-strength laminations.

With all of the bits that exhibited tangential overload failure to the trim and gauge cutters identified, the wells that they came out and the depths at which they were pulled in the Brushy Canyon could be flagged for future drilling performance analysis.

2.2 Mechanical Specific Energy (MSE) Surveillance

Due to its ability to illuminate intervals of bit dysfunction and subsequent damage, MSE was used in post-run analysis to determine where bit damage became severe enough that it began to limit performance. With the wells and depths flagged where tangential overload to the outside cutters was observed, MSE was tracked on through these intervals to identify the initial event that caused the failures. The state of the bit was tracked by establishing a baseline MSE that could be compared to across the run. The baseline MSE is the bit's maximum efficiency (lowest MSE) and will not change for thousands of feet if the bit is not damaged and WOB is being maximized (Fig. 7a). Bit MSE was chosen to monitor the baseline as it is affected less by BHA interference with the borehole wall compared to Surface MSE, thus giving a more realistic estimate of the bit's cutting efficiency.

The baseline Bit MSE will change with rock strength, but for this project the average rock strength was relatively constant, meaning the baseline did not vary substantially. If dysfunction was limiting performance, MSE was elevated above the baseline. Identifying and addressing the root-cause of the dysfunction during drilling operations (whirl, stick-slip, etc.) saw MSE return to baseline as long as the bit was not

damaged. If the bit was damaged, then Bit MSE began trending away from the baseline value (Fig. 7b).

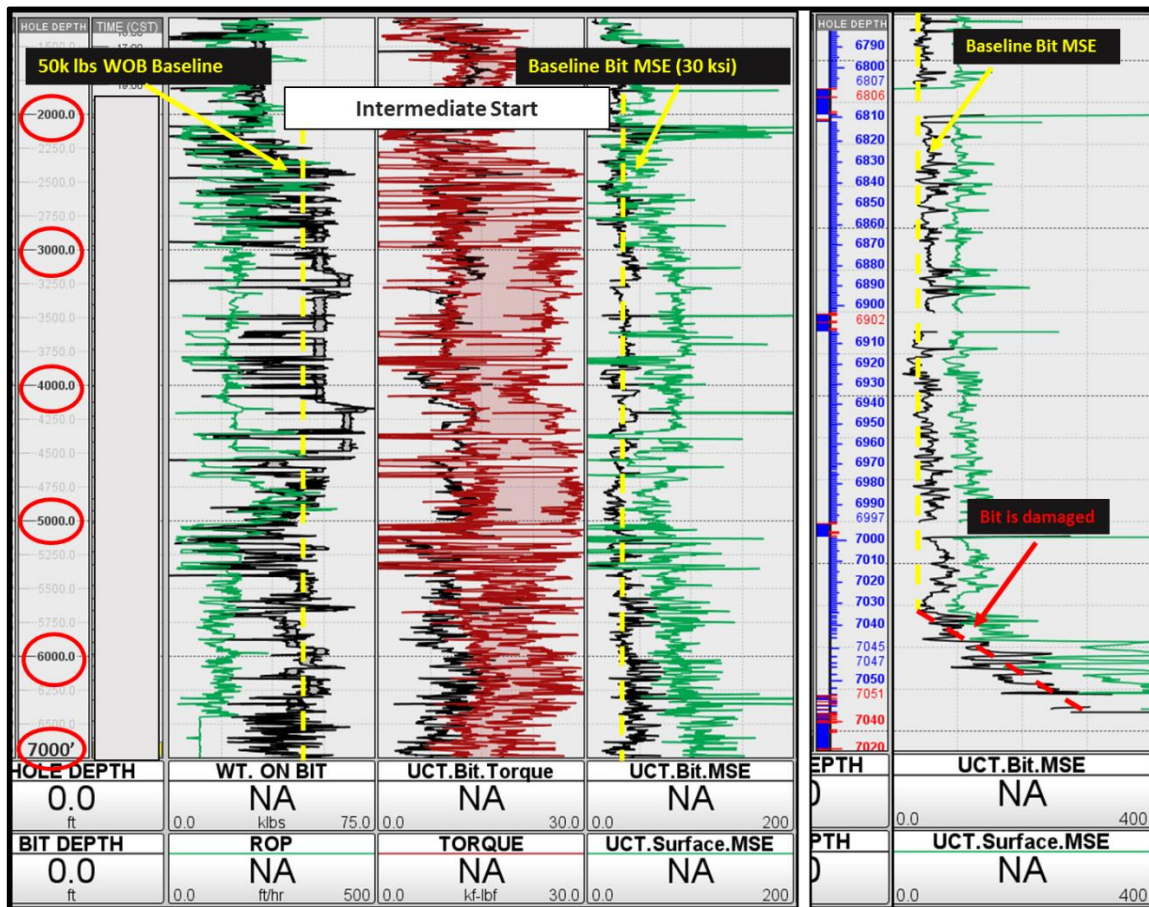


Figure 7 – The LRV plot on the left (a) shows that the baseline Bit MSE does not change for thousands of feet despite high WOB. The plot on the right (b) shows the baseline Bit MSE and the subsequent increase in MSE after the bit is damaged.

Once the initial event at which the damage was believed to have occurred was identified through MSE surveillance, all other operating and performance parameters (WOB, Rotary Torque, Differential Pressure, etc.) as well as formation characteristics

(gamma) were recorded. It was found that runs with bits that exhibited tangential overload to the trim and gauge cutters saw sustained increases in Bit MSE away from the baseline that were traced back to near instantaneous high-torque event.

2.3 Rotary Torque and Gamma Ray Correlation

The original belief was that the distinct tangential overload failures to the trim and shoulder cutters of the PDC bits were the result of a high-torque event that occurred while drilling out of a high-strength lamination into lower-strength rock. The failure mechanism that results in tangential failure to PDC cutters is simply too great of torque being applied on the face of the cutter. Lab testing and confidential discussions with the bit vendor indicate that the torque on the bit observed during normal drilling operations is simply not high-enough to result in tangential overload of the PDC cutters. In order for the applied load to be great enough to fail the cutters, high levels of torque would have to be focused predominately on the 1-2 rows of cutters in a near instantaneous loading event. Unfortunately, near-bit sensors that would record the accelerations and shocks occurring while exiting laminations were not utilized at the time of this study, so the exact chain of events that led to failure cannot be quantified. However, 1-second surface data was available that gave some clarity to the torque events observed. Surface (rotary) torque was used to identify the high-torque events instead of estimating bit torque as it is direct measurement of the torque from the rig's top drive. Bit torque is commonly estimated using differential pressure and the motor manufacturer's torque factor, but the time-delay in differential pressure readings and possible variability of the

torque factor under different loading conditions could have led to inaccurate measurements and trend observation during the study.

In homogenous rock, the majority of the applied axial load (WOB) is distributed on the nose and face cutters, while the trim and gauge cutters see very little of the applied load. However, when exiting a high-strength lamination into lower-strength rock, the axial load is transferred to the outside cutters due to the reduction in axial resistance (rock strength) on the nose and face cutters. The nose and face cutters want to advance further into the lower-strength rock since there is less resistance. In order to do so the trim and gauge cutters must advance as well, meaning they are indenting further into rock with high-axial resistance. The high-torque events are believed to be generated from this contrast in axial resistance across the face of the bit that force the trim and gauge cutters to take a large DOC in the high-strength rock (Fig. 8). The result is a net gain in torque due to the 1-2 rows of outside cutters being at larger radii and having a much greater DOC in the high-strength rock than before.

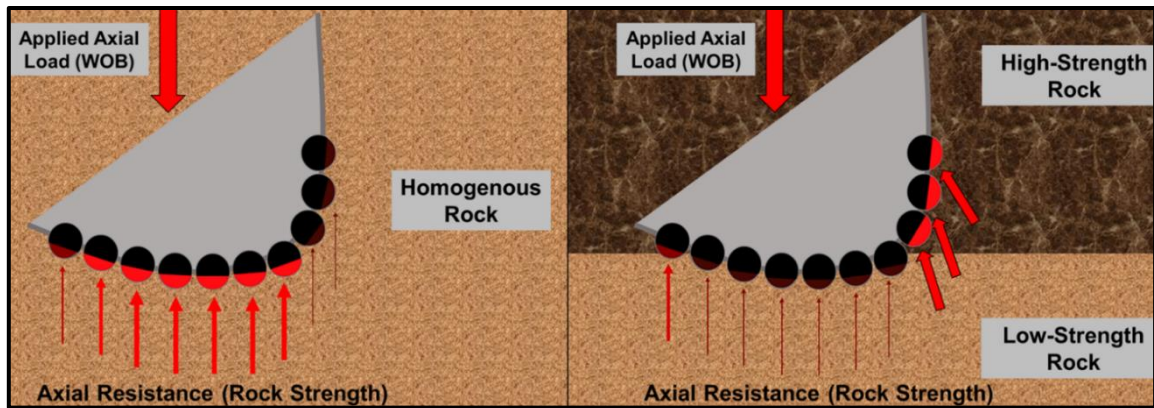


Figure 8 – Drawing of how the axial load is believed to be transferred from the nose cutters to the trim and gauge cutters in the high-strength rock when exiting a lamination. The figure on the right depicts the load distribution across the cutters while drilling normal (homogenous) rock, with the majority of the load being carried by nose and face cutters (bright red).

High-torque events were differentiated from normal periods of stick-slip by looking at individual torque cycles. Individual cycles were found by determining the bottom of each cycle (lowest torque) and then finding the mathematical midpoint between them. Normal stick-slip will see torque cycles being symmetrical relative to the midpoint. However, torque cycles during full stick appear asymmetrical, as the torque build-up while the bit is stopped is longer than the fall-off as the bit is released (Fig. 9).

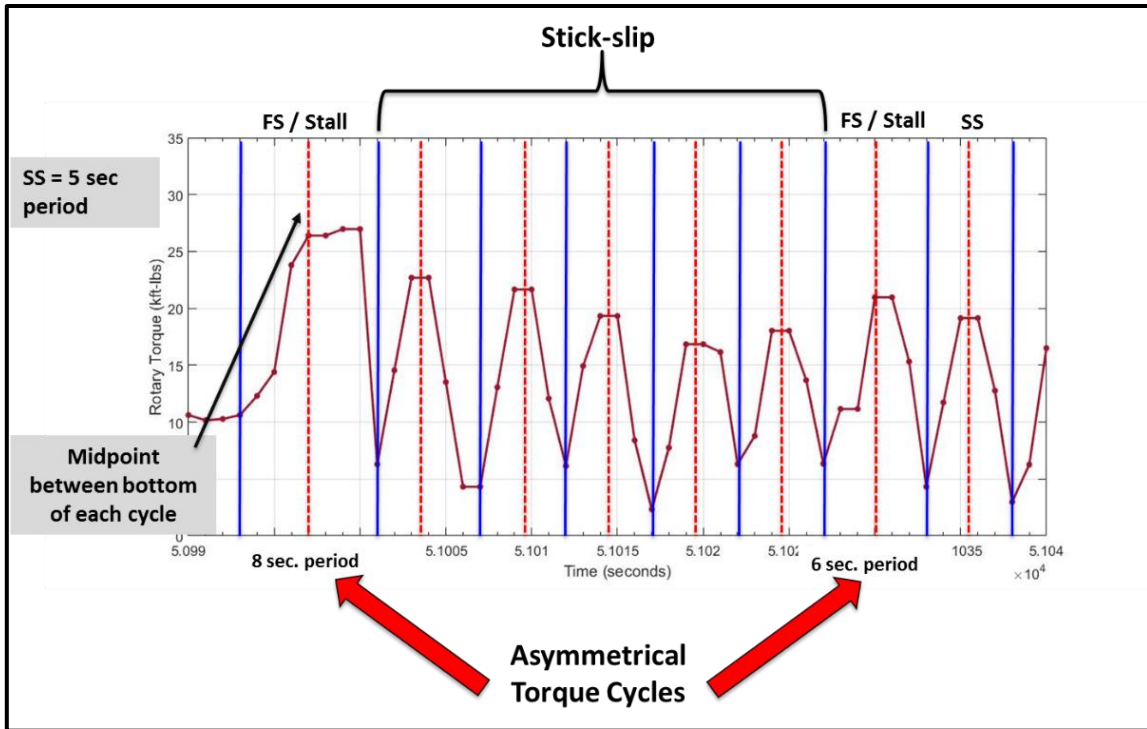


Figure 9 – Plot of 1-second rotary torque data showing how torque cycles were determined to be either symmetrical or asymmetrical.

In order to verify that the observed high-torque events were indeed occurring when exiting laminations, gamma ray readings from a sensor in the MWD sub were used to identify changes in lithology and rock strength. Due to the gamma sensor being some 50 odd feet away from the bit, all hole depths for those readings had to be adjusted so that the torque events and gamma readings could be correlated accurately. Changes from a high-strength lamination to a lower strength rock would see a change from a lower gamma reading to a higher gamma reading. Gamma ray sensors are used to measure the degree of radioactive material that is present in the formation naturally and tend to correspond to amount of clay content present in the rock's pore space. Recorded in API

units, higher gamma readings tend to correspond to higher clay content and vice versa, which is used to identify changes in lithology and therefore changes in rock strength. Low-strength shales tend to exhibit higher gamma readings due to their high clay content, so changes in rock strength can typically be determined by observing changes from low gamma readings to high gamma readings, that is low gamma tends to correspond to higher-strength rock while high gamma readings tend to correspond to lower-strength rock.

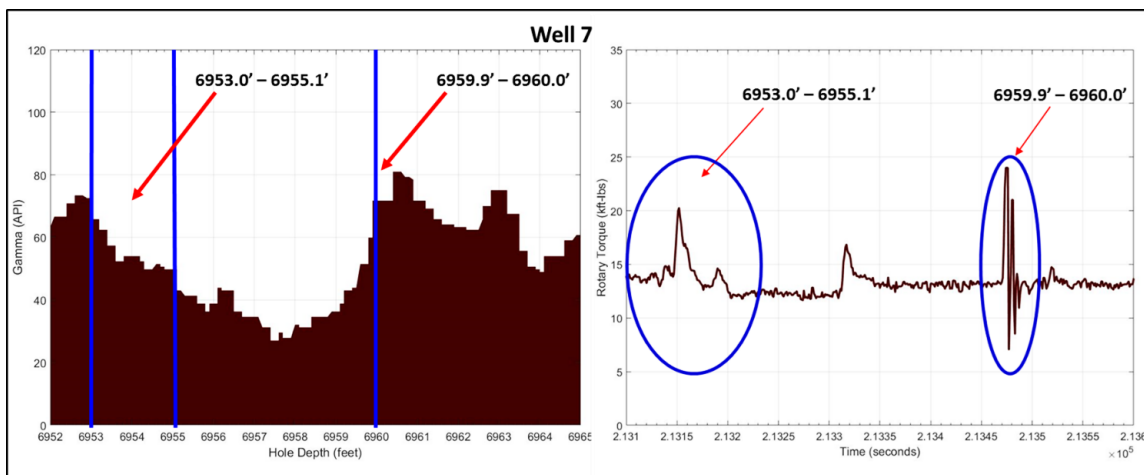


Figure 10 – A plot showing the changes in gamma and the subsequent torque events that were observed when entering and exiting the lamination.

Once the gamma readings were adjusted correctly to account for the offset, the high-torque events that were found could be correlated to the changes in lithology and therefore changes in rock strength that the bit was encountering when the event occurred (Fig. 10).

2.4 Rate of Penetration (ROP) Setpoint

Since the exact nature of the high-torque events that are tangentially failing the outside cutters when drilling in the Brushy Canyon are not yet quantified, no true engineering redesign of the drill bit could be conducted deterministically. However, a real-time operational practice of utilizing an ROP setpoint on the auto-driller with a constant bit speed was implemented. Auto-drillers are a device on the drilling rig that controls the rate at which the drill string can advance by adjusting the drum (drawworks) rotational speed (Pastusek et al. 2016). Various setpoints, such as WOB, differential pressure, and ROP, can be monitored and maintained through the use of an auto-driller (Pastusek et al. 2016). The concept of utilizing an ROP setpoint is that the bit is able to maintain a constant DOC if the bit speed (RPM) is held constant, as:

$$\text{DOC} = \frac{(\text{ROP})}{5 * \text{Bit RPM}} \text{ (inch/rev)}$$

The constant DOC ensures that the cutting area on the face of the PDC wafer is held relatively constant. If the cutting area is constant by controlling the rate at which the bit can advance, then when the bit exits a lamination the auto-driller will be able to reduce WOB so that the a lower applied axial load is transferred to the trim and gauge cutters. The rate at which the outside cutters are loaded as well as the magnitude of the applied load are controlled if the DOC is held constant.

Various ROP setpoints that maintained different DOC's were utilized during this study while drilling through the Brushy Canyon. The desired DOC's that the setpoint would generate were found by tracking the DOC/Rev that the bit was drilling at when

the failure event occurred. Normally, the operational practice that is used in industry when drilling through high-strength laminations is to choose a survival WOB, that is a WOB that is low enough that it won't overload the cutters yet high enough that it will limit damage from bit whirl. The problem with this technique is that higher-strength lamination requires more WOB to achieve a great enough DOC that suppresses whirl. Often the WOB require to avoid overloading cutters at transitions is not high enough to achieve the DOC required to combat whirl when the bit enters the high-strength lamination fully, resulting in the bit failing due to impact damage.

The benefit of control drilling with an ROP setpoint that maintains a constant DOC is that when the bit encounters a transition, the auto-driller will raise or lower WOB in order to maintain the DOC. This means the WOB will be raised in the high-strength rock (limiting bit whirl) and reduced when exiting into lower-strength rock (preventing tangential overload).

3. RESEARCH OBJECTIVES

The main objective of this research project was to prove that tangential overload can occur on the outside (trim and gauge) cutters of a PDC drill bit when drilling out of high-strength laminations into lower-strength rock. Although the desired downhole data was not able to be acquired over the course of this study, the work and findings of this study will direct the focus of the scheduled future work that is aimed at quantifying these high-torque events, where near-bit sensors will be utilized.

A secondary objective was to compare the performance of various ROP setpoints that were used when drilling through the Brushy to determine if the operational practice was effectively increasing drilling performance. The final objective was to develop a performance monitoring practice that would allow DOC to be tracked, identifying dysfunction and bit damage. Doing so would allow for the operator to have an operational practice that would maximize their performance and until physics-based engineering redesign of the drill bit could be achieved.

4. RESULTS

4.1 High-Torque Events when Exiting Laminations

Although only one-second surface data was available for this project, this sampling rate was high enough when plotting rotary torque to reveal interesting trends that were consistently seen when drilling out of higher-strength laminations into lower strength rock. The biggest takeaway was that if the contrast in rock strength was great enough between the two rock types, then apparent micro-stalls would occur. What was observed when drilling out of laminations was that rotary torque would have a large increase in a matter of seconds, hold for a few seconds, and then drop off quickly (one to two seconds) to a very low level. The cycle of these high-torque events appeared asymmetrical in shape and the peak torque that was achieved was often high enough reach the rig's torque limit, which led to the original belief that this was the result of an instantaneous full stick event occurring that saw the bit coming to a complete stop.

But the high-torque events were found to be rather non-periodic (Fig. 11 and Fig. 13) unlike what is seen during full stick, corresponding more to what is seen when a mud motor stalls. At the moment that a motor stalls due to high differential pressure (bit torque), the bit begins rotating only at the speed that the top drive is turning at (ignoring the angular mass deceleration of the motor stator). However, the top drive is still advancing at the previous rate (ROP) while the bit RPM is much lower. This creates a very high DOC that sees torque continue to build until it reaches the top drives torque limit and the auto-driller begins drilling off weight (Fig. 12). As WOB drills off, DOC is reduced and subsequently torque (motor differential) until the motor can begin rotating

again. Due to not having the proper downhole data to definitely classify these events as stalls, they will continued to be referred to as simply “high-torque events”.

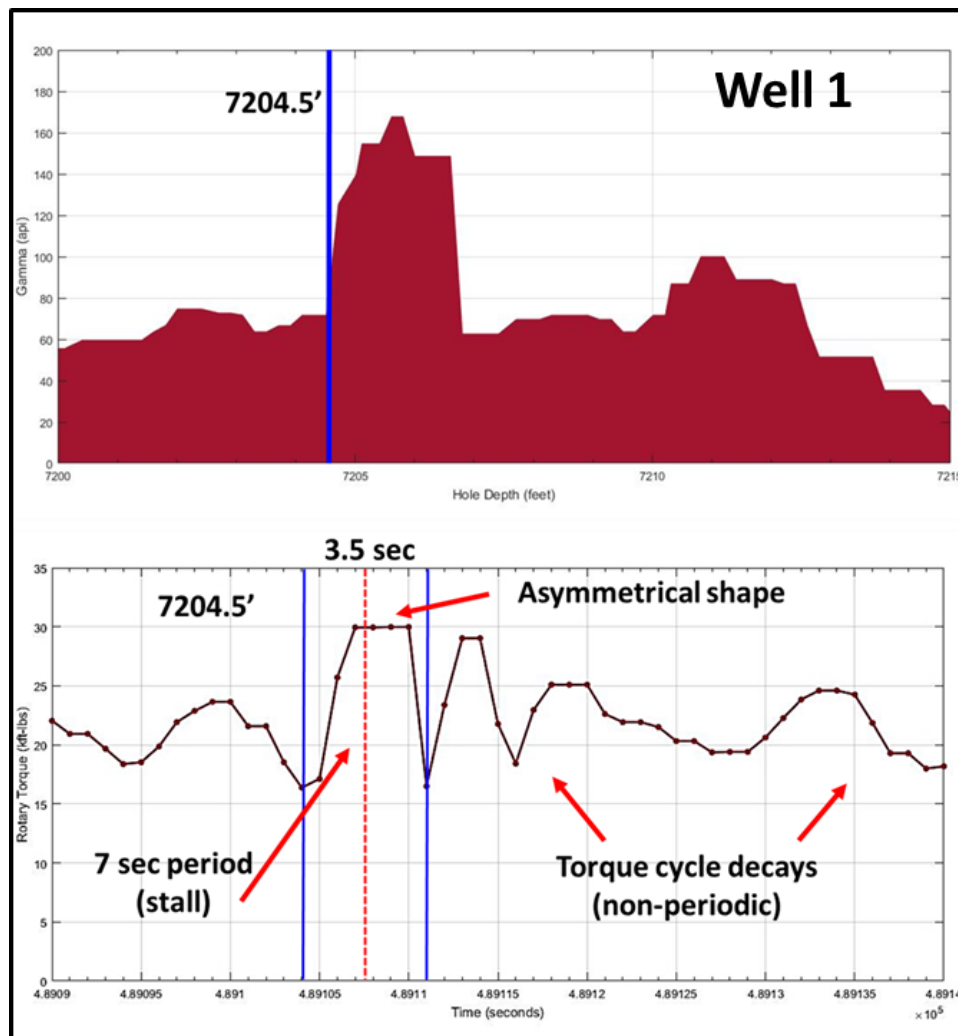


Figure 11 – Plot of both gamma ray and rotary torque. A high-torque event occurs as the bit exits from higher-strength rock into lower strength rock at 7,204.5 feet.

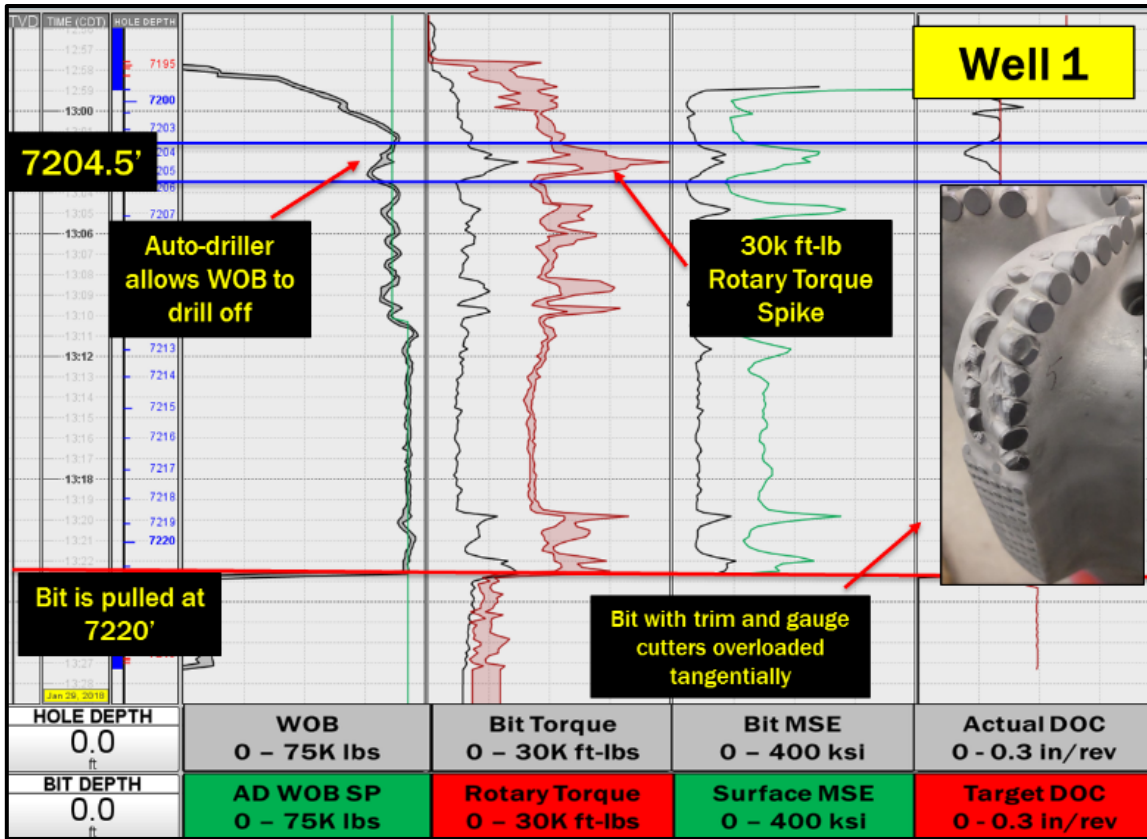


Figure 12 – A Live Rig View (LRV) screenshot of the last 20 feet of hole corresponding to the high-torque event shown in Figure 11. The bit exhibited tangential overload of the trim and gauge cutters when it came out of the hole.

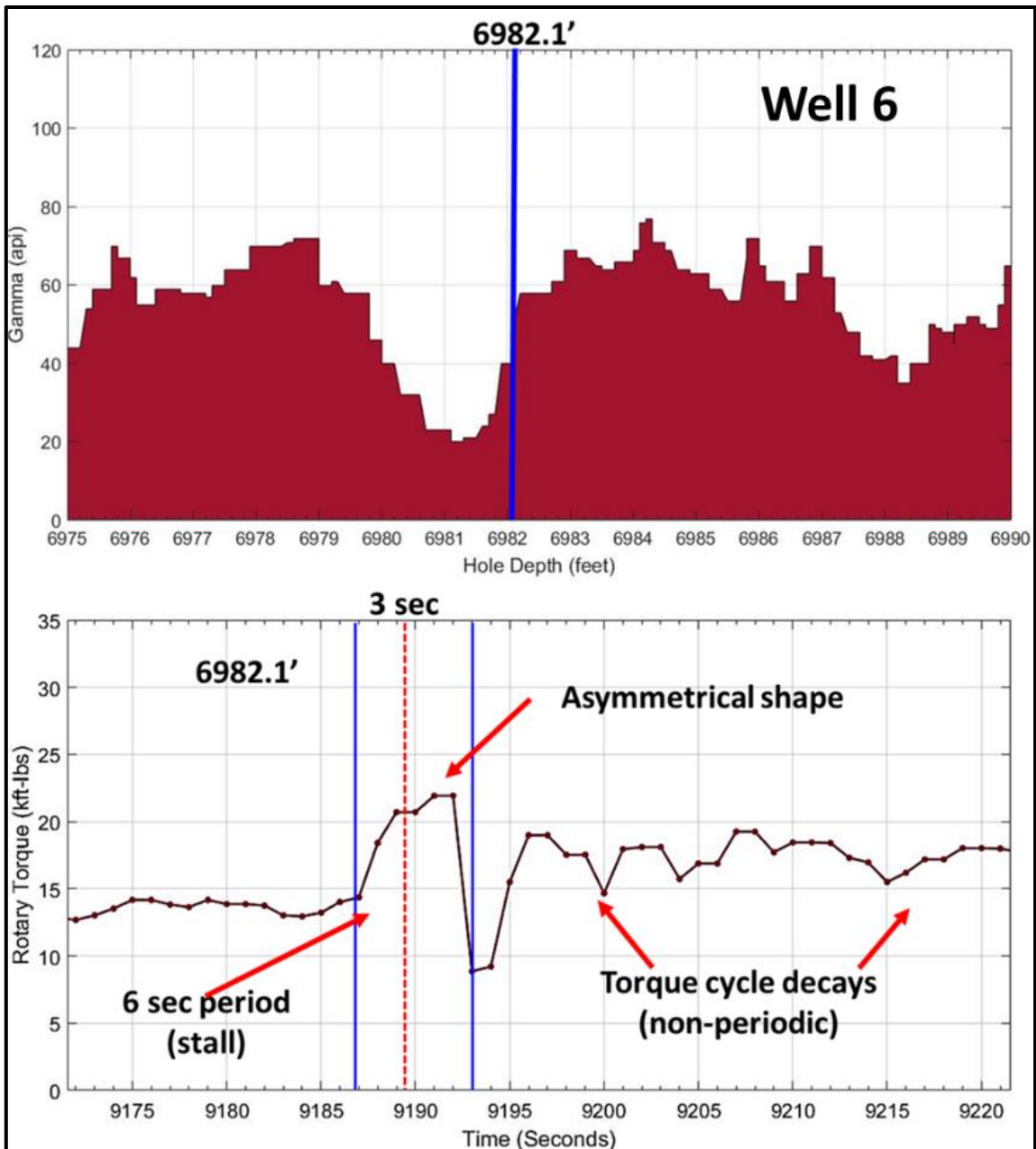


Figure 13 – Another example of a high-torque event observed when drilling out of a high-strength lamination into lower-strength rock. The period of the asymmetrical high-torque event is 6 seconds and decays quickly after the torque is released.

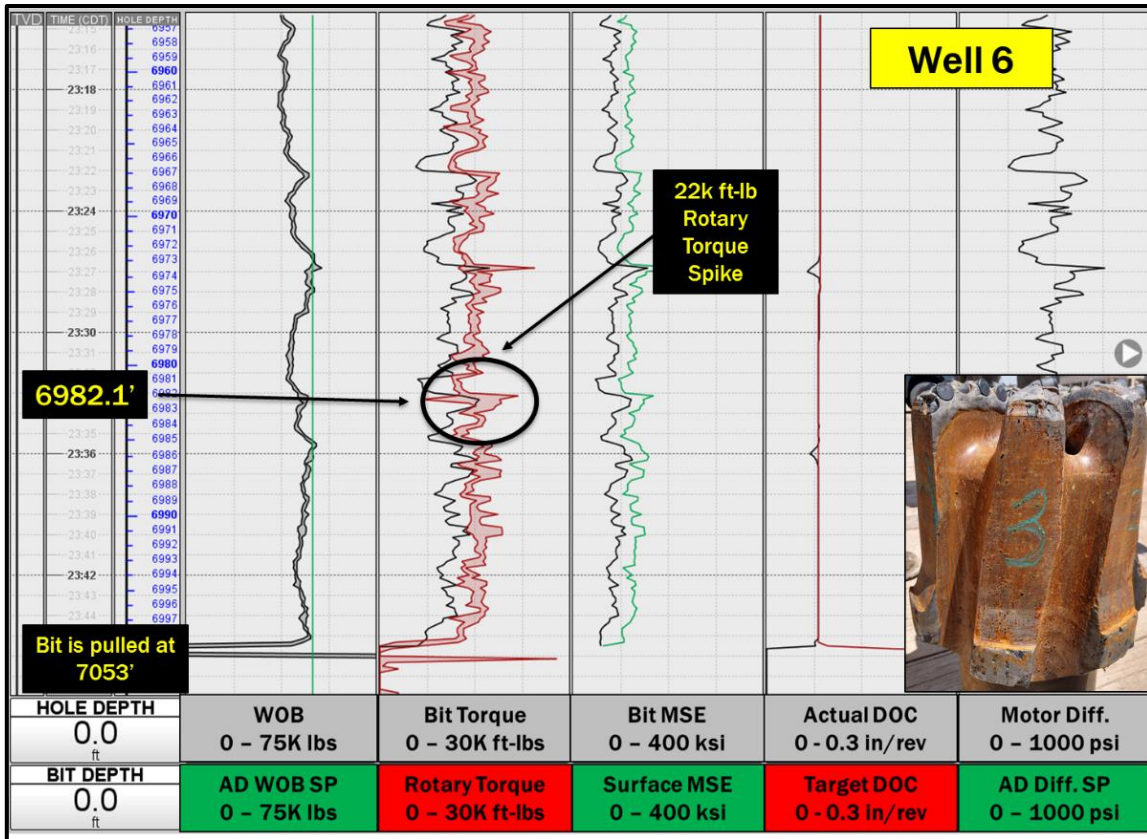


Figure 14 – Plot of high torque event (Figure 13) that occurred roughly 70 feet before the bit was pulled. The bit encountered multiple high-torque events similar to this one before it was critically damaged.

All of these high-torque events corresponded to sharp increases the gamma reading. With the understanding that higher gamma readings ultimately correspond to changes in lithology, it was deduced that these events had to be due to an abrupt change in rock strength. More specifically, a transition from high-strength rock to a much lower-strength rock. This agreed with the original belief that high-torque events could occur when drilling out of high-strength laminations. The magnitude of these high-torque

events will be quantified in the future data collection and research that is scheduled to be conducted after the conclusion of this study.

4.2 Rate of Penetration (ROP) Setpoint

Multiple field trials were conducted where an ROP setpoint with a constant bit RPM was utilized to drill through the Brushy Canyon. Various DOC's were tested, ranging from 0.08 in./rev to 0.115 in./rev. Analyzing bit forensics of offset wells, it was found that bits that exhibited tangential overload on the shoulder in the Brushy Canyon failed when the DOC exceeded 0.115 in./rev and showed impact damage to the shoulder cutters from whirl with anything below 0.08 in./rev.

The first field trial used an ROP setpoint and bit speed combination that achieved a rate of 0.115 in./rev. The bit drilled further into the Brushy than offset wells utilizing a WOB setpoint, but the bit still failed without drilling the interval entirely. Post-run analysis found high levels of MSE with multiple high-torque events occurring when exiting laminations right before the bit failed (Fig. 18), with the bit exhibiting tangential overload to the trim and gauge cutters. Performance was tracked using a baseline Bit MSE and subsequent offset wells with lower DOC's all saw increases in MSE through the same interval. However, all surrounding footage saw Bit MSE at or near baseline even with DOC as high as 0.115 in./rev.

This showed that the Brushy itself could be broken up into subsections where different DOC could be used. The worst part of the Brushy was roughly a 200 foot interval that required a 0.08 in./rev DOC be used in order to prevent full stick and subsequent

tangential overload of the trim and gauge cutters, while the surrounding footage could be drilled with a DOC up to 0.115 in./rev without failure occurring. Having proper workflow in place would allow the driller to maximize the different where possible, preventing failure yet maximizing performance.

Performance wise, there was an increase in the baseline MSE through the Brushy relative to the surrounding formations. This is due to both the increase in average rock strength through the Brushy as well as the constant adjustment in WOB creating fluctuations in torque. Drilling with the ROP setpoint saw Bit MSE constantly return to baseline as long as the chosen DOC did not induce full stick events. Figure 15 shows a trial where a 0.08 in./rev. DOC was used to drill through the Brushy Canyon in its entirety with a single bit. The bit drilled well into the Bone Springs before ultimately failing due to high levels of whirl from low WOB.

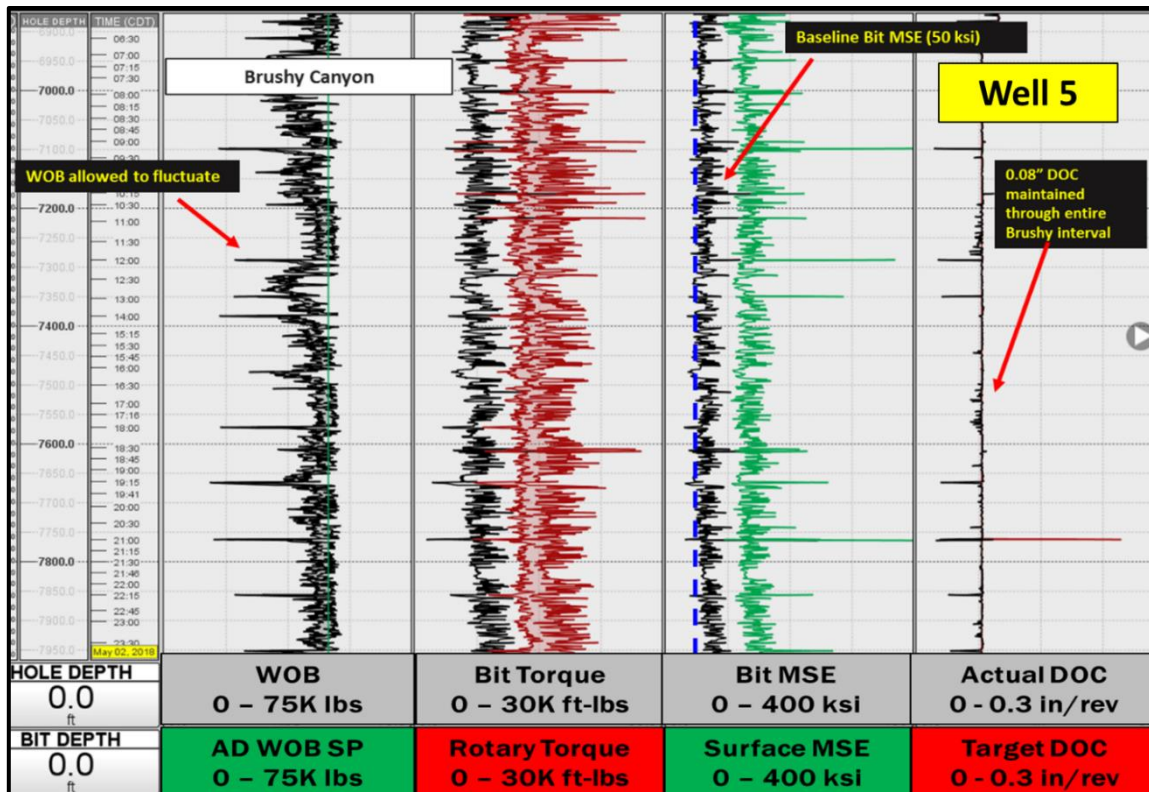


Figure 15 – An LRV plot showing the performance of a 0.08 in./rev DOC through the Brushy Canyon. Bit MSE always returns to the baseline value of 50 ksi and WOB is allowed to adjust as required. This bit drilled through the Brushy entirely.

In terms of overall intermediate performance, implementing the ROP setpoint saw nearly the same number of bits required to drill the intermediate but the average number of days per intermediate decrease by 1.5 days (Fig. 16). This can be attributed to the increased footage into the Brushy Canyon before failure as well as the overall increase in average sustained ROP. Wells 6 and 7 saw increases in the number of days per intermediate compared to the first five wells and this was simply due to a lack of workflow at the rig to recognize and respond to bit dysfunction. High MSE and low ROP were lived with when the bit should have been pulled out of hole due to damage.

The result was that both wells had bits that were damaged beyond repair by simply drilling on them too long.

Intermediate Hole Performance (ROP Setpoint)				
Well Number	Number of Bits	Number of Days	Brushy DOC (inch/rev)	Depth in Brushy when Pulled (feet)
1	3	5	0.115	7,220
2	3	4.5	0.077	7,380
3	3	5	0.077	Drilled
4	3	5	0.077	6,981
5	2	3.5	0.080	Drilled
6	3	7	0.083	7,053
7	3	6	0.080	7,114
Average	2.86	5.14	-	-
Pre-ROP Setpoint Average	3	6.62	-	-

Figure 16 – A table showing the gain in performance from utilizing an ROP setpoint with a constant bit RPM that maintains a constant DOC. The same number of bits were required to drill the intermediate hole but the overall number of days per intermediate was decreased by 1.5 days.

The practice of control drilling with an ROP setpoint on the auto-driller was found to be only a temporary fix for drilling the Brushy Canyon, as the same number of bits were required to drill the intermediate hole and only two bits were able to drill through the Brushy entirely (Fig. 16). Bits also continued to exhibit tangential overload

to the trim and gauge cutters (Fig. 17) when they came out of the Brushy, meaning physics-based engineering redesign of the bit was still required for performance to truly be maximized.



Figure 17 – Example of bits that had tangential overload of the gauge and shoulder cutters with no damage to the nose. Numbers on blade correspond to blade number, not well number.

4.3 Operational Practice – Tracking DOC

An effective practice that was utilized during the field trials (alongside MSE surveillance) to determine the state of the bit when control drilling with an ROP setpoint was monitoring the actual DOC versus the target DOC. The actual DOC was calculated using the on-bottom ROP while the target DOC was calculated using the ROP setpoint being used on the auto-driller. This practice allowed the driller to compare the actual drilling performance of the bit to a target (or baseline) value. When used in conjunction

with MSE, WOB, and the auto-driller's WOB limit, this practice proved effective in determining when the bit was damaged.

Due to the high-strength of the laminations, the DOC required to drill without the cutters being overloaded tangentially is low relative to normal operations where control drilling is not required. Since this indentation is being maintained through the entire interval, the bit does not require the same WOB to achieve the target DOC in the lower strength rock.

The limit that is chosen for WOB on the auto-driller is critical. It is important that the chosen WOB limit is high enough that it allows the driller to distinguish between the bit being damaged and an increase in rock strength. When a bit is damaged, its overall aggressiveness is decreased, reducing the achievable DOC for an applied WOB. Alternatively, the average rock strength increases across the Brushy Canyon, so the WOB required to maintain the DOC between laminations increases as well. What is seen operationally is that when either bit dysfunction or damage occur that reduce the bit's efficiency to the point that the ROP setpoint cannot be maintained, the auto-driller will switch from ROP and begin to prioritize the WOB setpoint (Fig. 18).

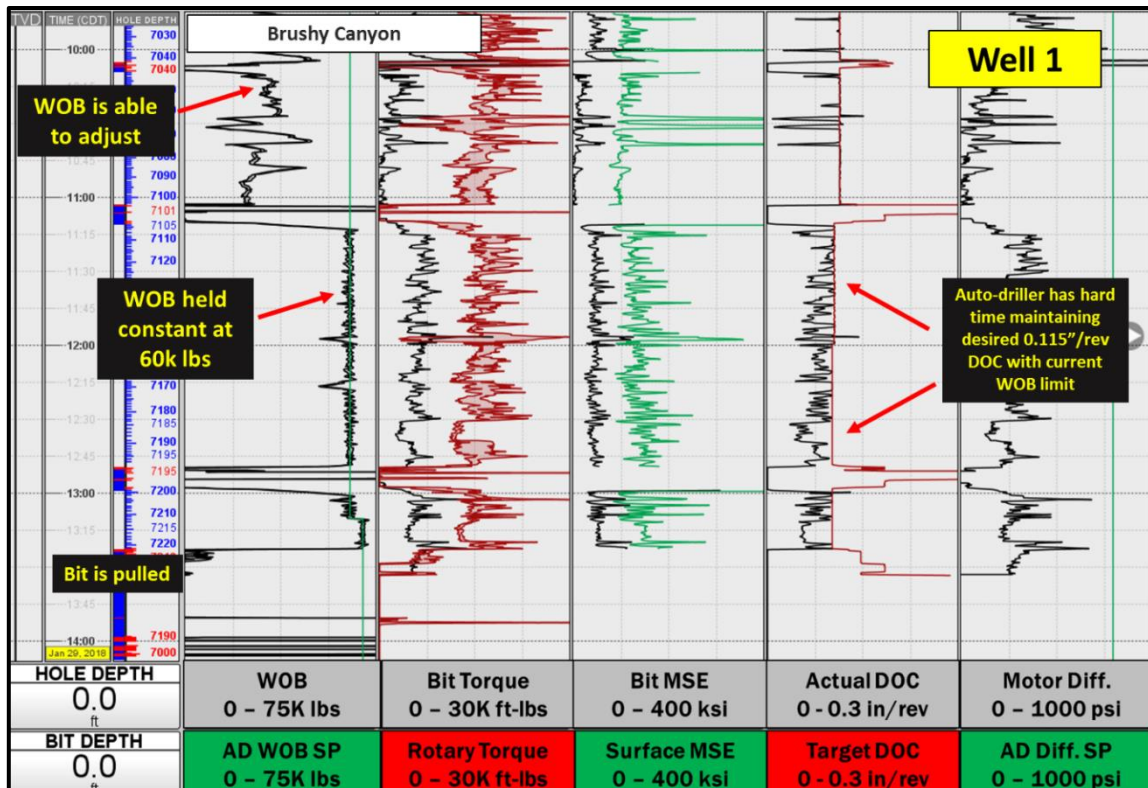


Figure 18 – Captured learnings from the first ROP setpoint field trial utilizing a 0.115 in./rev DOC. The large DOC led to a high-torque event occurred when drilling out of a lamination, resulting in the trim and gauge cutters being overloaded tangentially (see Figures 11 and 12).

In order to differentiate between change in rock strength and bit dysfunction, the most effective real-time response was found to be (Fig. 19):

1. If DOC begins falling below the target and WOB is already at the limit, raise the auto-driller WOB limit in small increments (5k – 10k lbs) and monitor the change in MSE, DOC, and the parameter that the auto-driller is prioritizing.
2. If MSE returns to baseline and DOC increases proportionately, keep raising the WOB limit in small increments until DOC reaches the target (ROP becomes priority).

3. If the DOC or MSE never respond to increases in WOB, then the bit has likely sustained damage as opposed to an increase in rock strength. The bit should be pulled before critical failure occurs.

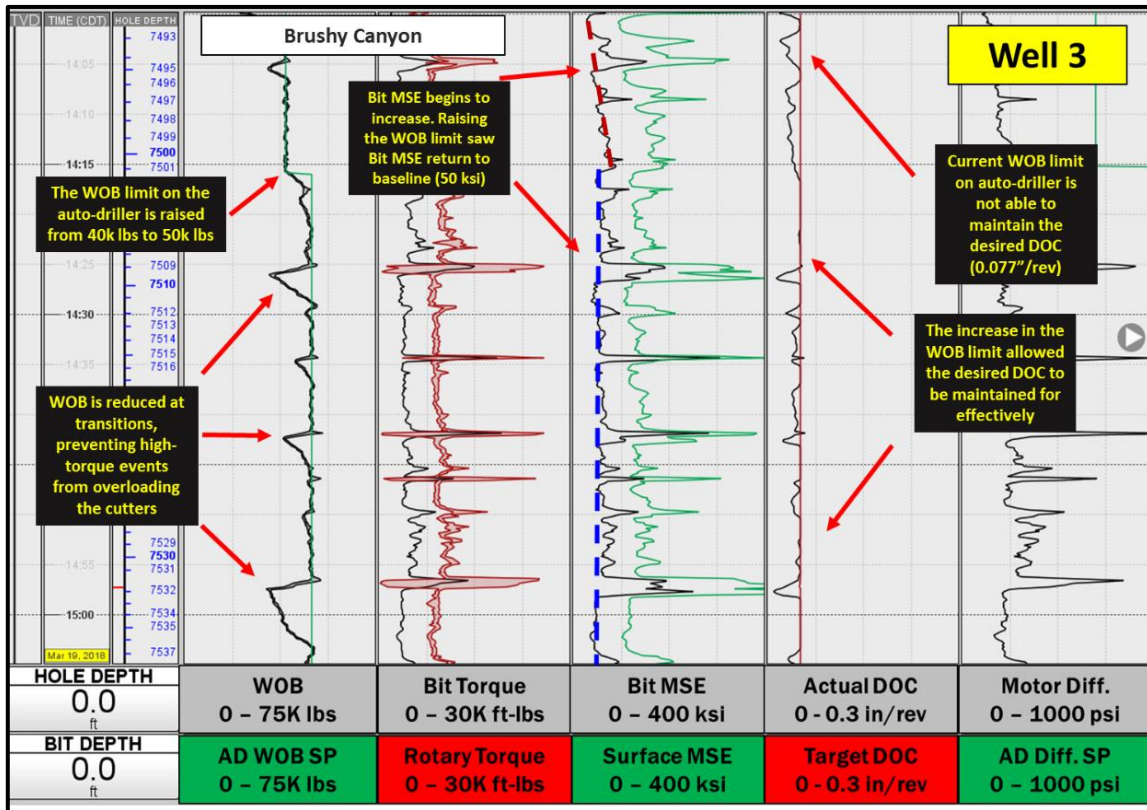


Figure 19 - Example of the above real-time response of raising the WOB limit on the auto-driller. Increasing the WOB limit by 10k lbs saw DOC return to the target and Bit MSE return to baseline. A single bit was used on this well to drill through the Brushy Canyon entirely.

Unlike a conventional step test, WOB should only be increased when using this practice. The DOC required to prevent the cutters from being tangentially overloaded tends to be low enough that the dysfunction limiting performance is whirl. Lowering the

WOB limit will ensure that WOB remains prioritized, resulting in the bit experiencing higher levels of whirl and further reduction in the DOC being achieved. The increase in WOB will either offset the increase in rock strength or illuminate damage.

5. CONCLUSIONS

It was found that drill bits that exhibited tangential overload to the trim and gauge cutters corresponding to wells where high-torque events occurred when drilling out of high-strength laminations into lower strength rock in the Brushy Canyon. The torque events are believed to be a result of the applied axial load being redistributed to the outside cutters as the nose and face cutters lose axial resistance upon entering the lower-strength rock. Further data collection and research are scheduled to take place in the months following the completion of this study in order to quantify the magnitude of the high-torque events as well as determine if they are in fact motor stalls. This work will be used to achieve physics-based engineering redesign of the bit that will reduce the likelihood of failures in the Brushy Canyon.

The effectiveness of control drilling with an ROP setpoint and constant bit RPM through the Brushy Canyon was also analyzed. It was found that drilling with an ROP setpoint in order to maintain a constant DOC while drilling across laminations led to a decrease in the number of days per intermediate by 1.5 days, although the number of bits required to drill the intermediate stayed the same. However, the use of an ROP setpoint was found to only be a temporary fix for drilling the Brushy Canyon, as only two of the seven wells had a single bit drill across the interval without failing.

Finally, it was found that tracking DOC alongside Bit MSE when control drilling with an ROP setpoint in the Brushy was effective at illuminating bit dysfunction and damage. When a bit was either in dysfunction or damaged, the Actual DOC would begin trending away from the Target DOC. The auto-driller would then begin prioritizing the

WOB setpoint (limit), as it could no longer maintain the ROP setpoint. Raising the WOB limit in small, 5k-10k lbs increments allowed the auto-driller to either overcome the dysfunction, allowing Actual DOC to return to the target value, or illuminate damage.

NOMENCLATURE

BHA	Bottom hole assembly
Dia	Bit diameter (inches)
DOC	Depth of cut (in./rev)
IFS	Interfacial severity
MSE	Mechanical specific energy (ksi)
PDC	Polycrystalline diamond compact
ROP	Rate of penetration (ft./hr.)
RPM	Rotations per minute (rev/min)
STO	Synchronous torsional oscillation
WOB	Weight on bit (klbs)
COF	Bit specific coefficient of sliding friction (unitless)

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