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Use of Mechanical Specific Energy Calculation in Real-Time to Better Detect Vibrations and Bit Wear While Drilling

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Abstract

Mechanical Specific Energy (MSE) is now a well-known concept to quantify the cutting efficiency of the rock. Thanks to its simplicity, its utilization has significantly increased over the last few years with electronic drilling recorders, especially in unconventional wells to optimize the drilling process and eventually reduce cost. A typical use is to compare the MSE to the rock strength to see whether the right amount of energy is utilized at the bit and not wasted or dispersed somewhere else. However, MSE alone cannot tell if drilling inefficiency is due to a change in the rock hardness, or due to vibrations, or bit wear or bit balling. This paper presents a new methodology that enables to fill the gap, in combining the MSE to the drilling strength (DS) to detect dysfunctions, such as vibrations or bit wear.

As MSE is mainly affected by the level of downhole torque (TOB), the effect of WOB is often neglected and is not taken into account in standard MSE analysis. In re-introducing the concept of drilling strength (DS) which is a function of WOB, and using the ratio of MSE over DS, a simple methodology can be derived to not only detect drilling inefficiencies but also determine the type of dysfunctions, such as vibrations or bit wear.

This paper shows how the new methodology has been successfully used and validated in unconventional wells.

Introduction

MSE has become a common way to analyze drilling efficiency post-run and, in some cases, make corrections in real-time to improve rate of penetration (ROP)[1]. Much can be learned from studying what has been done in past wells and applying lessons learned to the next well. To be the most effective however, MSE must be combined with other data and field knowledge to determine the root cause of MSE changes which are generally due to a formation change, bit wear, bit vibrations or bit balling just to name a few. A new methodology proposed in this paper reveals an effective way to dig deeper into MSE data and conclude why it could be changing and what can be done to improve drilling efficiency. When used in real-time, this methodology has the potential to save time, improve drilling efficiency, reduce vibration and therefore wear and tear on tools, and make the decision to trip for bit change easier by providing a way to analyze bit-wear at surface.

Terms

Mechanical Specific Energy

The mechanical specific energy or MSE, is commonly defined as the amount of energy required to destroy a unit volume of rock. It is expressed in terms of lbs/in^2 (psi) or N/m^2 (more commonly referred to as a Pascal, Pa). Teale[2] pioneered this methodology in 1964, however it was mostly used by bit vendors to determine the drilling efficiency of drill bit designs[2,3] until 2005 when it was introduced by an instrumentation vendor to the industry for real-time use[1,4,5]. Since that time, its use has expanded within the industry to become an easy to use and understand method of improving ROP and maximizing drilling efficiency.

Teale's equation for mechanical specific energy is defined as the following for the purposes of this paper[2]:

$$MSE = \frac{WOB}{A_B} + \frac{120\pi * RPM * TOB}{A_B * ROP} \quad \text{(Eq. 1)}$$

Where:
MSE = Mechanical Specific Energy, psi
A_B = Bit Area, in^2
RPM = Bit rotation speed, rpm
TOB = Torque on bit, ft-lbs
ROP = Rate of penetration, ft/hr

It is important to mention that the torque term used in the above equation should be the torque on the bit in order to estimate the amount of downhole energy required to cut the rock. If surface torque is used instead, MSE will be highly over-estimated, especially in deviated wells, because of the overall friction along the drill string. Additionally, RPM should always be the bit RPM, therefore when using a mud motor the revolutions per gallon (rev/gal) and flow rate should be used to calculate the bit RPM and then added to the string RPM for use in MSE calculations.

WOB

MSE is made up by adding together two main terms, one dictated by the WOB and the other dictated by the TOB. Often the WOB term is neglected due to its insignificance compared to the TOB term which makes up over 99% of the total MSE term. This can be seen illustrated in Figure 1 where the difference between an MSE calculated using the WOB term and the MSE calculated without the WOB term is seen to be less than 1% in an actual well. In this paper, MSE calculations will be based on Eq. 1 in neglecting the WOB term. WOB will be utilized in deriving another parameter, the drilling strength, which is defined later in the paper.

Torque on Bit

The torque on bit is particularly important to measuring drilling efficiency using MSE and thus an accurate torque measurement is vital. Unfortunately, TOB measurements close to the bit with downhole sensors are still rare in the industry, but should be utilized preferably when available. TOB measurements are often only available post-run as instrumented subs are usually memory only tools, except when combined with wired drill pipe technology[6]. Some MWD tools are now equipped with downhole TOB sensors and when telemetry rates allow, data can be sent to surface at a frequency which allows good TOB data to be used for MSE analysis.

In the absence of measurement sensors close to the bit or along the BHA, mud motor differential pressure can also provide valuable information about the torque delivered at the bit and be used as a TOB measurement[1]. However, this depends entirely on the diligence of the driller to zero out the differential pressure at every change in pump rate. This method also requires an accurate motor performance curve to describe the relationship between torque and differential pressure which is assumed here to be linear[7].

$$TOB_{\Delta P\ Motor} = \frac{T_{max}}{P_{max}} * \Delta P \qquad \text{(Eq.2)}$$

Where:
ΔP = Differential Pressure (psi)
T_{max} = Mud Motor max-rated torque (ft-lbs)
P_{max} = Mud Motor max-rated ΔP (psi)

While this method potentially misses a portion of the torque added to the bit by the rotation of the string, it has been proven to yield a TOB that very closely matches values measured by sensors in the BHA, as seen in Figure 2. Another observation is that the TOB from the downhole sensor shows much more variation, which could be due to stick-slip, however TOB derived from the motor ΔP is not able to catch these variations.

The viability of TOB from ΔP depends entirely on an accurate differential pressure. In the absence of an accurate differential pressure, data processing can create a viable differential pressure. Standpipe pressure (SPP) is due to mud flow, mud rheology, and frictional forces between the mud and drill pipe. Assuming none of these factors change while drilling a stand, the SPP can be selected from a period while the bit is off bottom and the pumps are at the drilling flow rate. This SPP can be used as a baseline for the next drilled stand. Any changes between the off bottom SPP and the drilling SPP represent the differential pressure.

$$\Delta P = SPP_{drilling} - SPP_{off\ bottom} \qquad \text{(Eq.3)}$$

Where:
ΔP = Differential Pressure (psi)
$SPP_{drilling}$ = Standpipe Pressure while drilling
$SPP_{off\ bottom}$ = Standpipe Pressure while off bottom

In the absence of a mud motor, TOB can be estimated using torque and drag models to subtract from the surface torque measurement the friction loss along the drill string. With this method, it is highly recommended to calibrate the friction factor based on rotating off bottom torque readings with similar rotation speed utilized while drilling. Indeed, several field observations have shown that the rotating off bottom depends on rotation speed when drill pipe whirling occurs. TOB estimated from measured surface torque and torque and drag models at a given depth is then:

$$TOB = TOR_{Surface} - TOR_{Drillstring} \qquad \text{(Eq.4)}$$

Where:
$TOR_{Surface}$= Torque measured at surface while drilling (ft-lbs)
$TOR_{Drillstring}$ = Torque calculated by torque and drag model and calibrated with nearest rotating off bottom measurement

The resulting MSE curves from these different methods can be seen in Figure 3. All three curves are within a margin of error of each other, but the differences are what make this analysis interesting. Stand to stand, the trend of MSE never shifts dramatically due to the method used but there is an obvious difference in the level of MSE depending on the method. The most obvious difference comes in the section drilled between 12,350 and 12,400ft. The uncorrected ΔP shows a significantly lower MSE than when the ΔP is corrected or when torque and drag is used to derive downhole torque. Conversely, in the next section, 12,400 to 12,470ft, the MSE calculated using both the ΔP methods overlays very well but the MSE using a torque and drag analysis shows a higher peak. Consequently, MSE trend or change along the well is not significantly affected by the method chosen, whereas the absolute value of MSE, and consequently the drilling efficiency could vary per the method selected.

MSE Changes

MSE has often been used to quantify the drilling efficiency[1,4,5], and it is generally accepted that efficient drilling is when MSE is about equal to three times the confined compressive strength (CCS) of the rock[4], meaning that the drilling efficiency (also known as a mechanical efficiency factor4) is about 0.3-0.35. CCS is always preferred over the more commonly used UCS (Unconfined Compressive Strength) as it includes the effect of confining pressure that can significantly affect the resistance of the rock. The downside is that a thorough determination of CCS can be difficult to estimate as pore pressure and rock permeability are often not well known. Rock lab testing at different confining pressures is ideal to determine the ductility or fragility of the rock and thus quantify the effect of confining pressure, but rarely conducted.

While MSE can possibly detect variations of CCS or UCS in the formation, MSE trends can also be used to observe changes in the drilling system efficiency. The problem arises when, after drilling for some time at a consistent MSE, a change is observed. Then the question becomes, what changed? If drilling parameters have remained the same, then there are four main distinct possibilities: a formation change, vibration, bit balling or bit wear. Until now, answering this question has been challenging and until the bit can be examined, hard to answer definitively. Increasingly, technology is being developed aimed at analyzing MSE to deduce formation properties (i.e. pore pressure[8], frac-ability, completions decisions[7] etc.) and thus the elimination of other causes of MSE change is more important than ever.

Drilling Strength

Drilling strength[9] is defined as the following for the purposes of this paper:

$$DS = \frac{WOB}{R * DOC} \quad \text{(Eq.5)}$$

Where:
WOB = Weight On Bit (lbs)
DOC = Depth of Cut (in)
R = Bit Radius (in)

Drilling strength (DS) can be used to analyze the contribution of WOB to drilling efficiency, and derives originally from the normal force applied on each PDC cutter divided by the cross-sectional area of the cut. MSE is a term that most directly examines the TOB, that is the contribution of the cutting force applied on each PDC cutter. Using DS in conjunction with MSE broadens a drilling efficiency study to include WOB and its effects. Indeed, numerous studies[10] have shown that the ratio between the cutting force and normal force on the PDC cutter reveals numerous insights about rock and cutting efficiency.

Drilling strength derives its usefulness from analyzing WOB much in the same way that MSE uses TOB. Thus, the data quality for WOB is of similar importance to that of TOB. Like TOB, WOB measurement are often only available post-run as many instrumented subs are memory only tools, except for when combined with a proper telemetry system as discussed before. In most cases the surface WOB, if properly calibrated, is sufficient, with a few considerations. Horizontal wells will have an inaccurate WOB at surface, particularly during sliding intervals and towards the end of the lateral section. Torque and drag analysis can help approximate the loss of WOB along the string, however the calibration of friction factors will be very important in such an analysis. Appropriate sensor calibration is also important, along with diligence on the part of the driller to zero out the WOB after the addition of every stand of drill pipe in the correct way.

MSE/DS Ratio

A new patented method has been recently developed for detecting drilling dysfunction during drilling operations[11]. This method, based on several years of research, lab and field tests, utilizes mainly two indicators: MSE and the ratio between MSE and DS (MSE/DS). By comparing the level of these two indicators and their evolution during the drilling process (increasing, stable, decreasing), drilling dysfunctions can be detected. In this way, it becomes easier to determine what kind of drilling dysfunction is changing the MSE.

Any change in MSE can be attributed to a change in formation, however many of the wells drilled today include, at a minimum, gamma-ray logging while drilling tools (LWD) and thus formation changes can be more easily determined or ruled out as appropriate. This leaves the other three common causes of an increase in MSE: bit balling, vibration, bit wear. Traditionally, determining which of these causes is responsible has involved a qualitative analysis of formation, bit hydraulics, field knowledge of bit wear rates etc. Using this new methodology and examining the DS and MSE/DS ratio, a user can more quickly determine a potential cause and take immediate action. Figure 4 illustrates schematically how changes in the MSE/DS ratio along with MSE and DS can be analyzed to determine the source of a dysfunction. For example, if both MSE, DS and MSE/DS increase at the same time over several feet of drilling downhole vibrations are probably occurring and the user can consider mitigating these vibrations.

A typical MSE/DS ratio for efficient drilling is between 1 and 1.5 and can be largely above 5 in case of severe drilling inefficiencies. An increased MSE/DS can indicate the presence of vibrations, whereas a decreasing MSE/DS can indicate bit balling or bit wear, depending on the behavior of the UCS. Like MSE examining the trend of MSE/DS is more important than the absolute value. The usefulness of MSE/DS comes in analyzing it next to MSE and DS as a method for detecting a drilling dysfunction.

Data Collection and Processing

Data frequency is often thought to be a hindrance in drilling efficiency analysis, and a lack of high density data could mean that detailed MSE trend might be missed. To better understand the minimum data density required to provide a thorough MSE picture, an analysis was performed to compare MSE data using different data densities.

Figure 5 shows MSE calculated using data collected every second and averaged over 1ft, 3ft, 5ft and 10ft. Moving from 1ft data to 3ft data overwhelmingly shows the same trends and peaks, though the amplitude is somewhat diminished. Comparing 1ft data to 5ft data shows further deterioration of the overall trend, however again the main peaks and straightaways are visible. Scaling up to 10ft deteriorates the overall trend to the point that some variations are lost and it could be harder to identify drilling inefficiencies. Therefore, data acquired every second or so, depending on the ROP, and then processed to deliver a density between 1-3ft should be sufficient for an accurate analysis to be performed.

Whenever performing an analysis on large volumes of data, whether in real-time or post-run, some amount of data processing will occur. Some of these decisions are innocuous to clean up the data, such as removing the null values and use only drilling data from when the bit was on bottom drilling. More decisions must be made around the use of data processing and filtering: removing points that are not reasonable, an impossible WOB, or a highly negative TOB, etc... These filters are easy to establish and enforce, either in real time or post run analysis. Further filtering or data smoothing and averaging should be avoided until after MSE, DS and MSE/DS have all been calculated. Analysis has shown that data responds best when minimum filtering is performed before calculations are done. Smoothing can be completed on the final MSE, DS and MSE/DS curves to help with clarity and interpretation.

Case Study

The analysis has been conducted on several wells drilled in Eagle Ford formation in Texas. All wells are typical Eagle Ford shale wells with a vertical section drilled to a 9 5/8in casing shoe around 9,000ft and then a build-up section to 90deg with an average 6,000ft lateral section following it, as shown in Figure 6. High density surface data was collected on four of the wells and analyzed for the purposes of this paper. Only the analysis conducted on one well along the 8 ¾in section is presented here in this paper. The BHAs used were all similar (see Figure 7), with 8 ¾in drilling bit, 6 3/4in steerable mud motor (4/5 lobes, 7.0 stages and a fixed 2.0deg bend), pony collar, and MWD with 5in S135, 19.5# drill pipe to surface. The drilling bit utilized in this example was a PDC bit with 5 blades and 13mm cutters. A bit change occurred midway through the run, at 14,163ft, due to wear as discussed later in more details. In all cases the formation was considered to be homogenous along the lateral section as the well was geosteered using gamma ray logs to stay in zone. Therefore, major changes in MSE will be considered formation independent in the next analysis.

Results

All the following MSE has been calculated using the TOB with a ΔP that did not require corrections as it was regularly zeroed during drilling. Sliding intervals were also removed for clarity as high MSE during sliding make it harder to interpret results. Figure 8 shows in red the MSE spikes due to a sliding interval versus the blue baseline steady state drilling MSE obtained during rotary drilling. While in real time it is obvious if MSE changes are due to sliding, during post-analysis it can be important to separate the data so as not to confuse an inefficiency with a sliding period. Moreover, it's not rare now to have less than 5% sliding along the lateral with neutral and stabilized BHA, meaning that analyzing only the rotating phases can be sufficient.

Figure 9 shows the lateral section of the subject well and the plot used for most of the detailed analysis below. The curves represent rotating data averaged over a 3ft interval. Annotations on the plot show a few overall trends that can be observed from looking at the overlay of the MSE and MSE/DS together. Even though the aim of the paper is to look mainly at drilling inefficiencies, it is interesting to notice that the MSE level was slightly greater than three times the UCS of the formation (estimated at 8,000psi) which means that drilling was quite efficient most of the time.

Vibration Detection

A few obvious trends observed are highlighted in red around 12,500ft (see Figure 9), just before 14,000ft and later at around 14,200ft. During these periods the MSE and MSE/DS both increase together, strongly indicating the presence of vibrations. Further investigation was performed to look for the root cause. First, the critical rotary speeds were calculated for the BHA and trajectory used at these depths. Figure 10 shows that a torsional critical RPM was discovered at the same RPM at which the drill string was rotating confirming our first presumption. Indeed, as torsional vibration can initiate stick-slip, an analysis was performed to see if stick-slip could be computer modeled in the same drilling conditions present during the vibration events. The modeled stick-slip was compared with the surface torque (1 sec data) that shows torque oscillations (see Figure 9), confirming the presence of vibrations detected with the methodology. It is important to mention here that 1 sec data at surface is not sufficient to catch actual torque oscillations which are generally much higher as shown by the stick-slip model.

Pump Dysfunction

Evolution of MSE and MSE/DS around 13,000ft suggests presence of vibration (see Figure 9). However, deeper examination at the data showed that the increase of both MSE and MSE/DS ratio was due to a pump problem and the inability of the pump to maintain a constant standpipe pressure and thus differential pressure, generating torque oscillations over a period of 75 sec.

Wear Detection

In addition to vibration detection MSE and MSE/DS ratio can also detect bit wear. Highlighted in blue in Figure 9 is an area where the MSE increases dramatically, right after a vibration event. At the same time, the MSE/DS ratio decreases, clearly differentiating this change in MSE from the previous cases caused by vibration. The MSE/DS ratio continues to decrease until 14,163ft at which point a bit trip was performed. While the bit records were not made available, it is logical to conclude that the bit was worn, due to the downhole efficiency markers and examining offset wells' bit records where bits regularly drilled only about 2,500ft before being pulled with a 2-2 dull grade.

Optimization

Besides MSE and DS analysis, looking at other standard parameters, such as ROP and WOB, can bring interesting insights in the drilling optimization process. Figure 12 shows the evolution of ROP as a function of WOB along the lateral section, from the heel (in red) to the toe (in yellow). It's interesting to notice that a higher WOB does not necessarily translate into a higher ROP, enabling to determine an optimum WOB to maximize ROP.

As always, MSE is most useful when utilized in real time to optimize drilling efficiency. While traditionally it is plotted against depth to observe trends while drilling, cross-plotting against individual parameters can also be beneficial[9]. Figure 13 shows a MSE-DS plot along the lateral section from the heel (in red) to the toe (in yellow). As DS involves the WOB and MSE involves the TOB, cross plotting the two terms together creates an easy way to examine the bit aggressivity and give also an indication of its efficiency. In Figure 13 two individual trends are easily identifiable, aided by overlaid dotted lines. A change is the slope might indicate a change in the rock formation[9], a different bit design, wear on the bit, or different ROP. In the present case, as the rock formation and the bit design are the same (same design but new bit), the lower slope at the toe is explained by a slightly lower ROP during the second half of the lateral section (see Figure 14), making the bit less aggressive and efficient.

Conclusions

MSE has long been used as a drilling efficiency indicator both in post-analysis and more recently in real-time as an aid to the driller. The concept is well known, if MSE is lower, drilling is considered more efficient, if it increases then likely an inefficiency has been encountered. The problem has been in identifying the source of the inefficiency from surface quickly. Using the ratio of MSE/DS, as presented here, can provide additional information which makes decision making easier when it comes to reading MSE values. Combining the MSE and MSE/DS ratio enables the detection of vibration, bit wear and bit balling. The case study presented provided examples of stick-slip vibration and bit wear and how real time application of this method can provide instant feedback to the driller. The ability to quickly and confidently make decisions about what is affecting the MSE in real time can result in further drilling efficiency gains past what is possible using just MSE.

Nomenclature

ΔP =*Differential Pressure along the Mud motor (psi)*
BHA = *Bottomhole Assembly*
DOC = *Depth of Cut (inch)*
DS = *Drilling Strength (psi)*
MSE = *Mechanical Specific Energy (psi)*
MSE/DS = *Ratio of MSE/DS to identify drilling dysfunction*
MWD =*Measurement While Drilling*
PDC =*Polycrystalline diamond compact*
P_{Max} =*Mud Motor max rated pressure (psi)*
R = *Bit radius (inch)*
ROP = *Rate of Penetration (ft/hr)*
RPM =*Revolutions per Minute (rev/min)*
SPP =*Standpipe Pressure (psi)*
T_{Max} = *Mud Motor max rated torque (ft.lbs)*
TOB = *Torque on Bit (ft.lbs)*
TOR = *Rotary Torque (ft.lbs)*
WOB =*Weight on Bit (klbs)*

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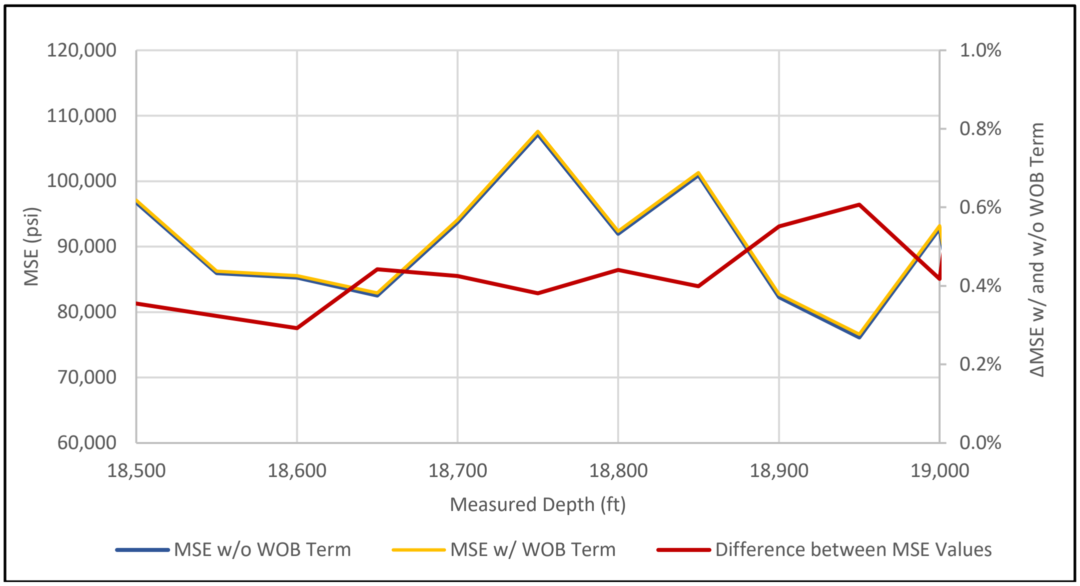

Figure 1: MSE Comparison with and without using WOB term in calculations – An offset example well

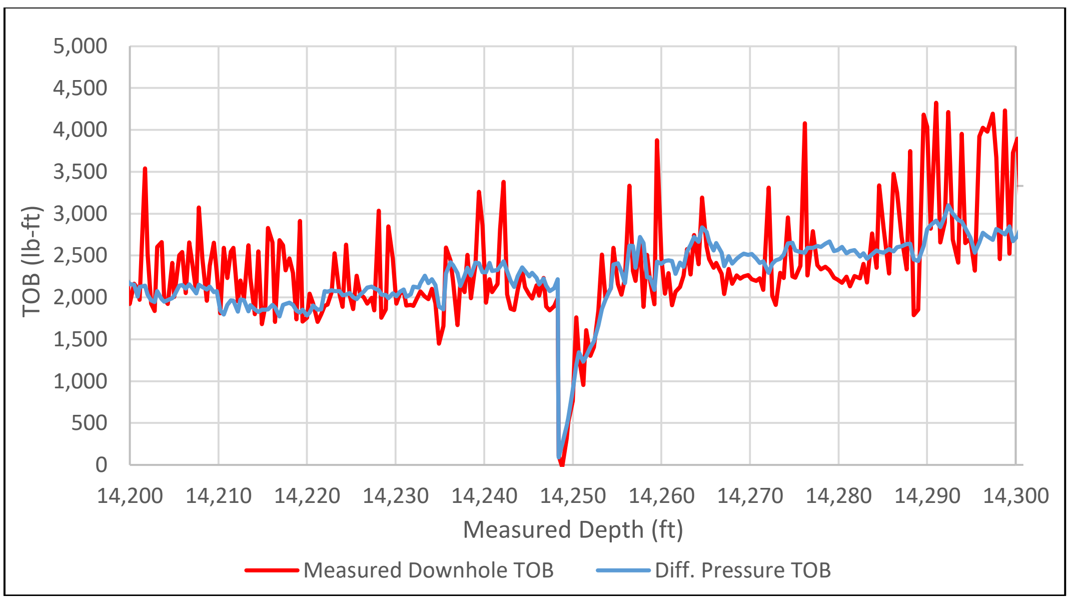

Figure 2: TOB from Differential Pressure and Downhole Sensor – An offset example well

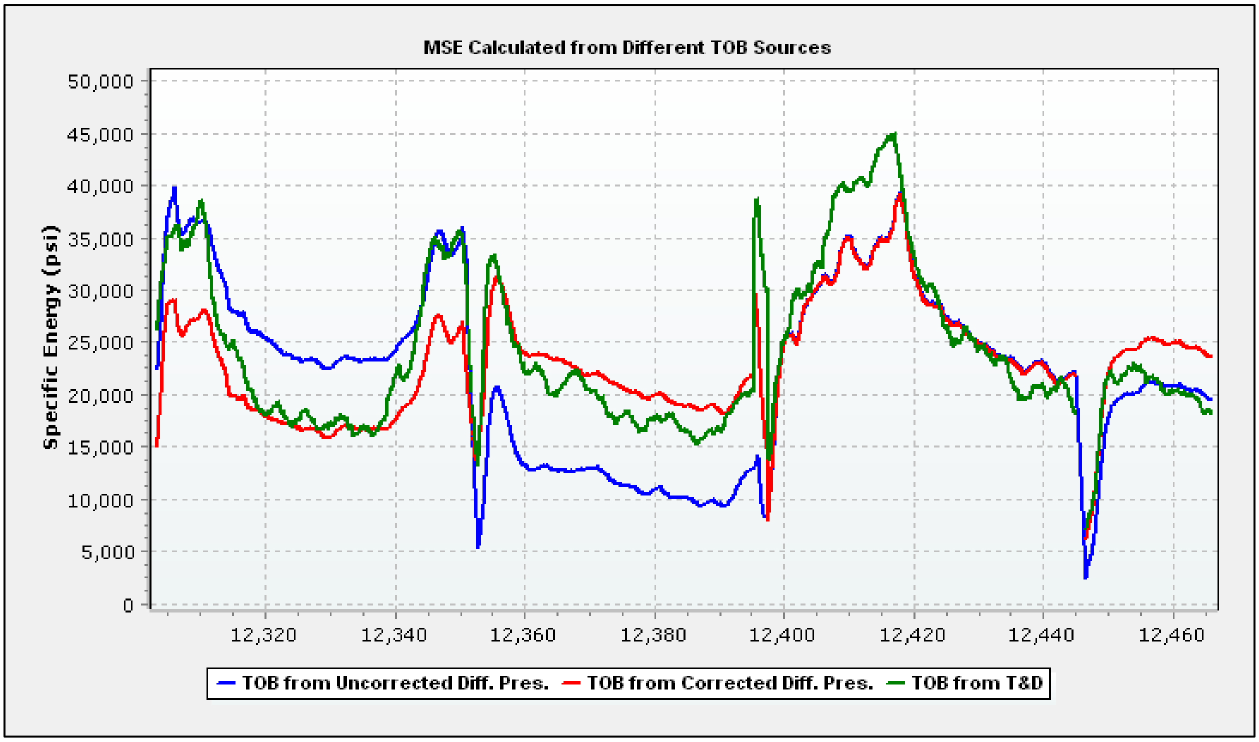

Figure 3: MSE calculated using different sources of TOB

MSE	DS	MSE/DS	Dysfunction	
↗	↗	↘	UCS	↗
→	→	→		→
↘	↘	↗		↘
↗	↗	↘	Bit Balling	↗
↗	↗	↗	Vibration	↗
↗	↗	↘	Wear	↗

Figure 4: MSE/DS interpretation guide[11]

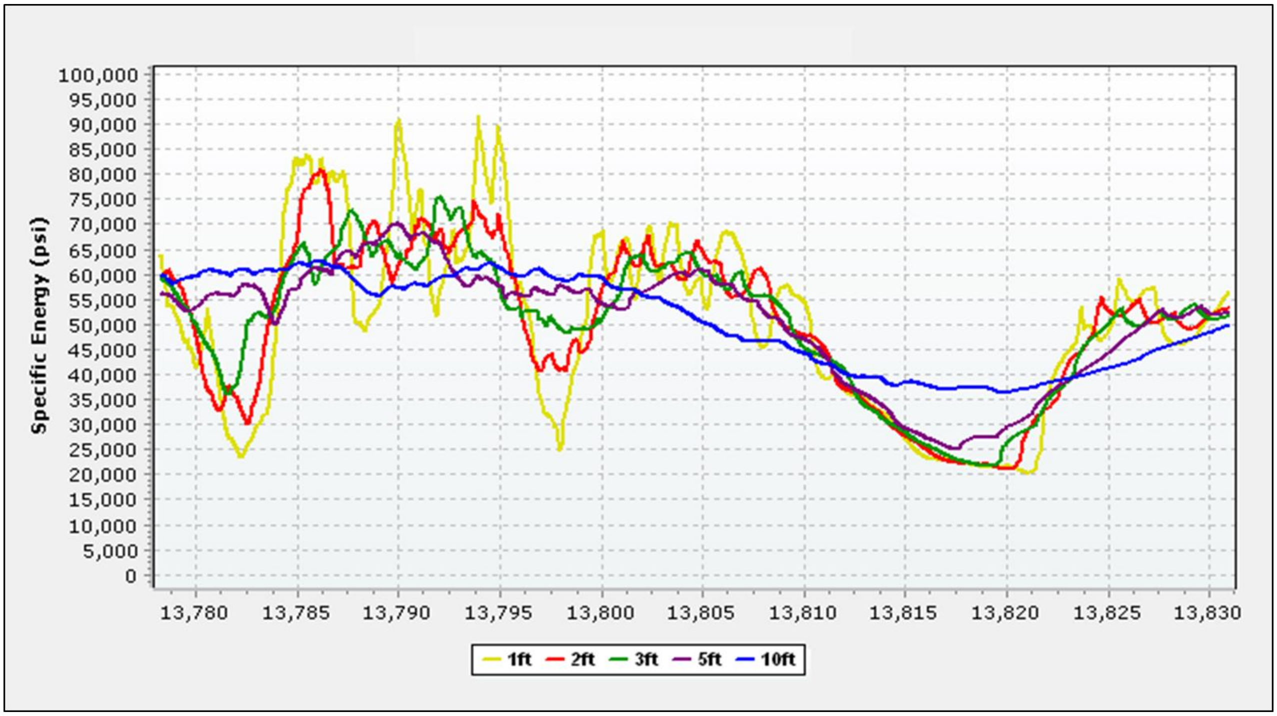

Figure 5: MSE trends with different data density

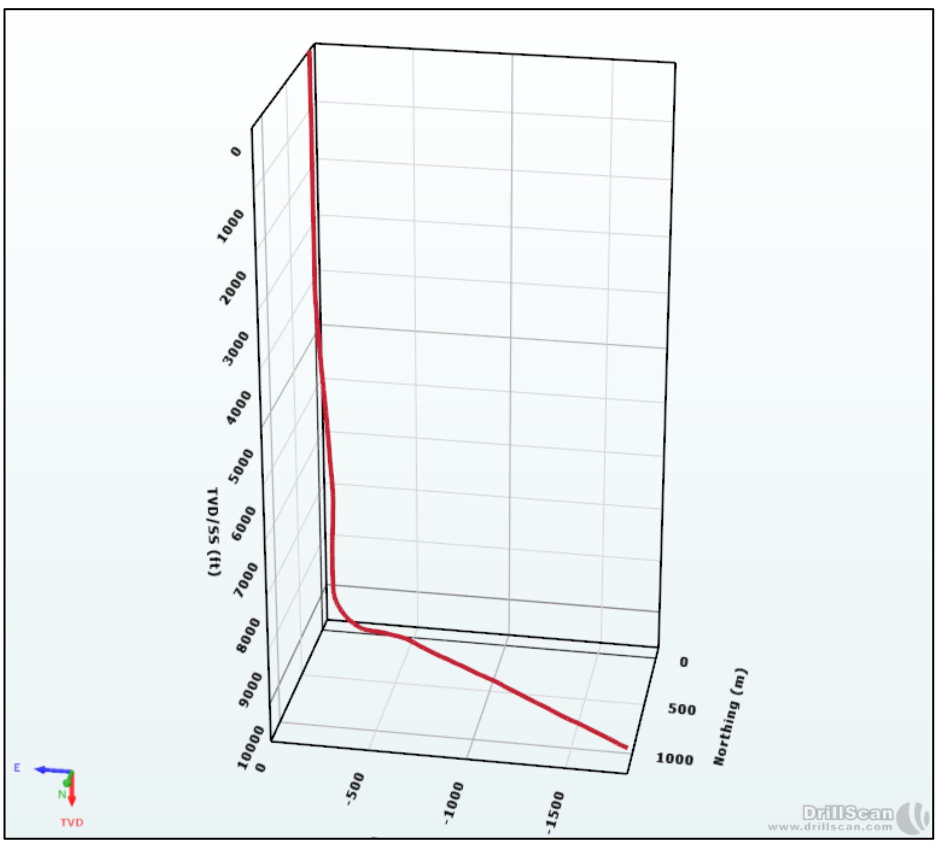

Figure 6: Well 1- 3D Trajectory

Type	Name	Length	OD	ID	Total length	Total mass	Linear mass
		(ft)	*(inch)*	*(inch)*	*(ft)*	*(lb)*	*(lb/ft)*
PDC	8 3/4in PDC Bit	1	-	-	1	100.64	100.64
PDM	2.0 FBH 4/5 7.0 2.0 deg	27.36	6 3/4	2 13/16	28.36	2854.13	100.64
Flex x 1	Pony Collar	8.72	6 3/4	2 13/16	37.08	3731.71	100.64
Sub x 1	UBHO	3.23	6 1/2	2 13/16	40.31	4028.18	91.79
MWD	MWD	29.16	6 3/4	2 13/16	69.47	6962.82	100.64
DC x 1	NM DC	30.66	6 3/4	2 13/16	100.13	10048.43	100.64
DP x 1	5" DP NC50 S-135	31.17	5	4.28	131.3	10777.81	23.4

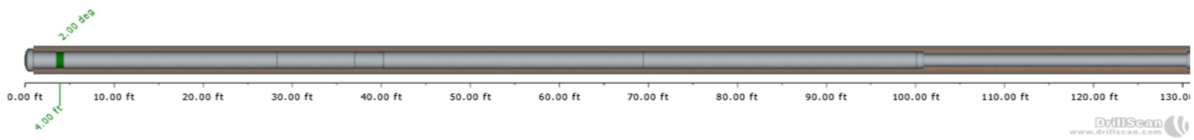

Figure 7: 8 3/4in BHA

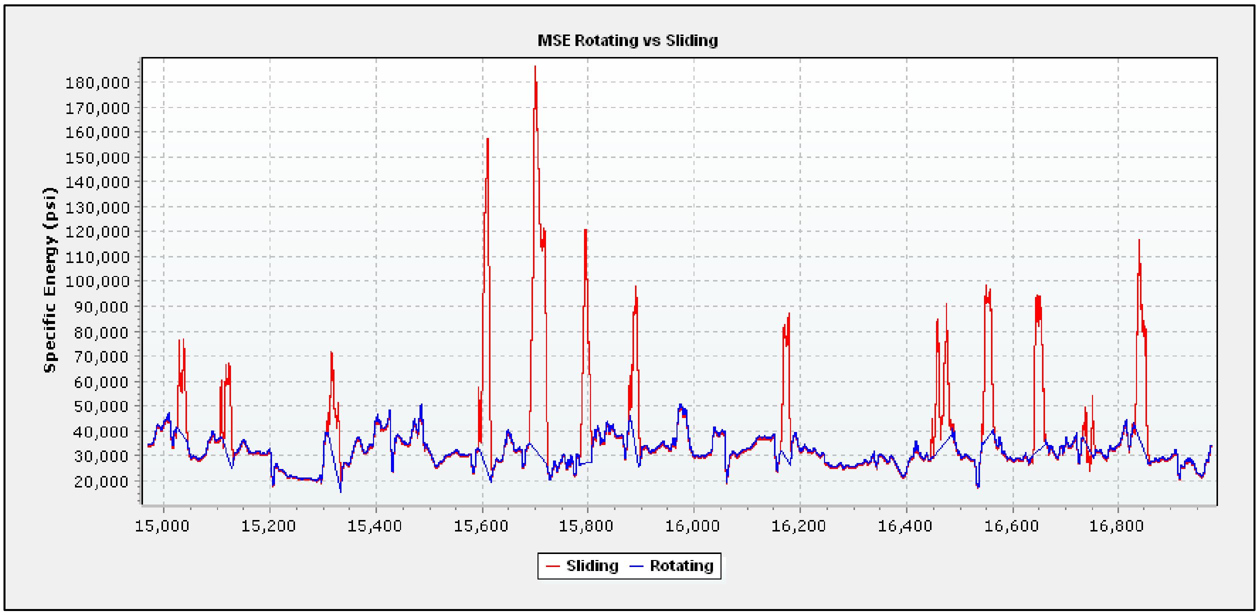

Figure 8: MSE - Sliding vs Rotating

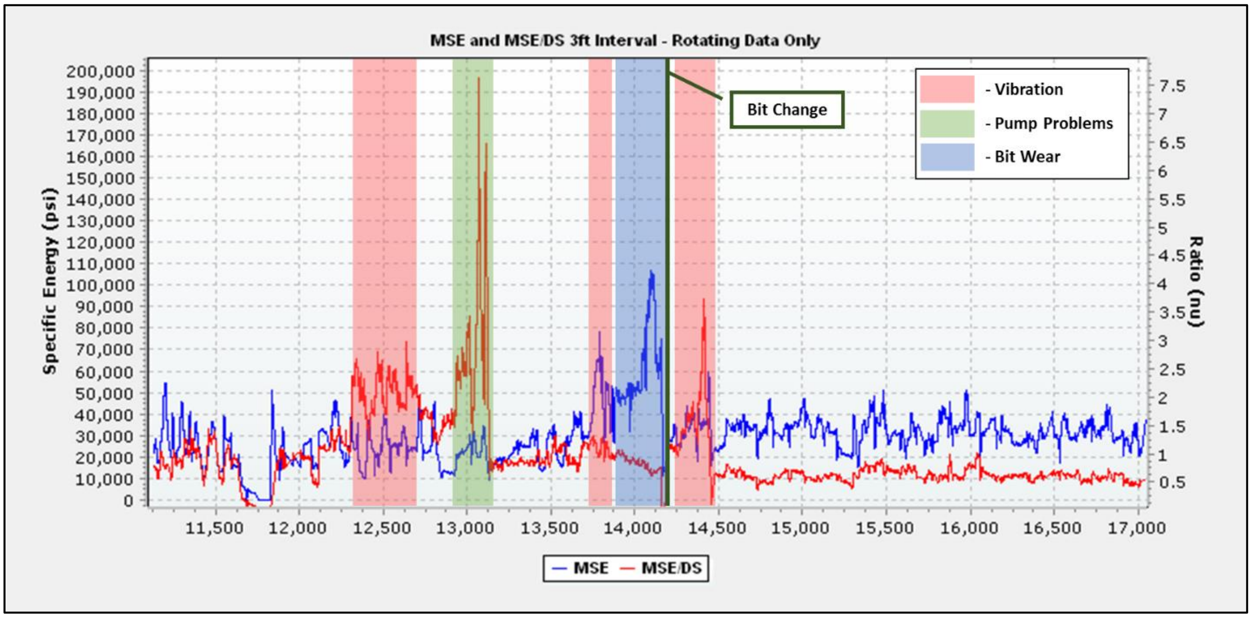

Figure 9: MSE and MSE/DS - Rotating Only

Bit depth (ft)	WOB (klbf)	Overgauge (inch)	Critical speed (rpm)	Type	Mode	Frequency (hz)	Excitation source
14480.00	20.00	0	4.63	Torsion	1	0.15	Mass imbalance
14480.00	20.00	0	12.65	Torsion	2	0.42	Mass imbalance
14480.00	20.00	0	21.81	Torsion	3	0.73	Mass imbalance
14480.00	20.00	0	30.16	Torsion	4	1.01	Mass imbalance
14480.00	20.00	0	39.03	Torsion	5	1.30	Mass imbalance
14480.00	20.00	0	47.91	Torsion	6	1.60	Mass imbalance
14480.00	20.00	0	56.39	Torsion	7	1.88	Mass imbalance
14480.00	20.00	0	65.76	Torsion	8	2.19	Mass imbalance
14480.00	20.00	0	74.00	Torsion	9	2.47	Mass imbalance
14480.00	20.00	0	83.54	Torsion	10	2.78	Mass imbalance
14480.00	20.00	0	91.94	Torsion	11	3.06	Mass imbalance
14480.00	20.00	0	101.18	Torsion	12	3.37	Mass imbalance

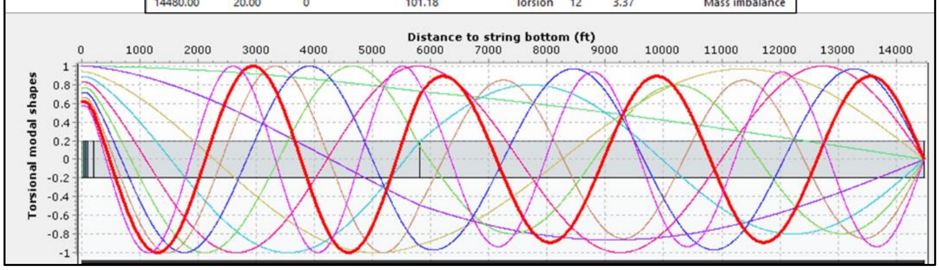

Figure 10: Torsional Modal Analysis at 14,480ft

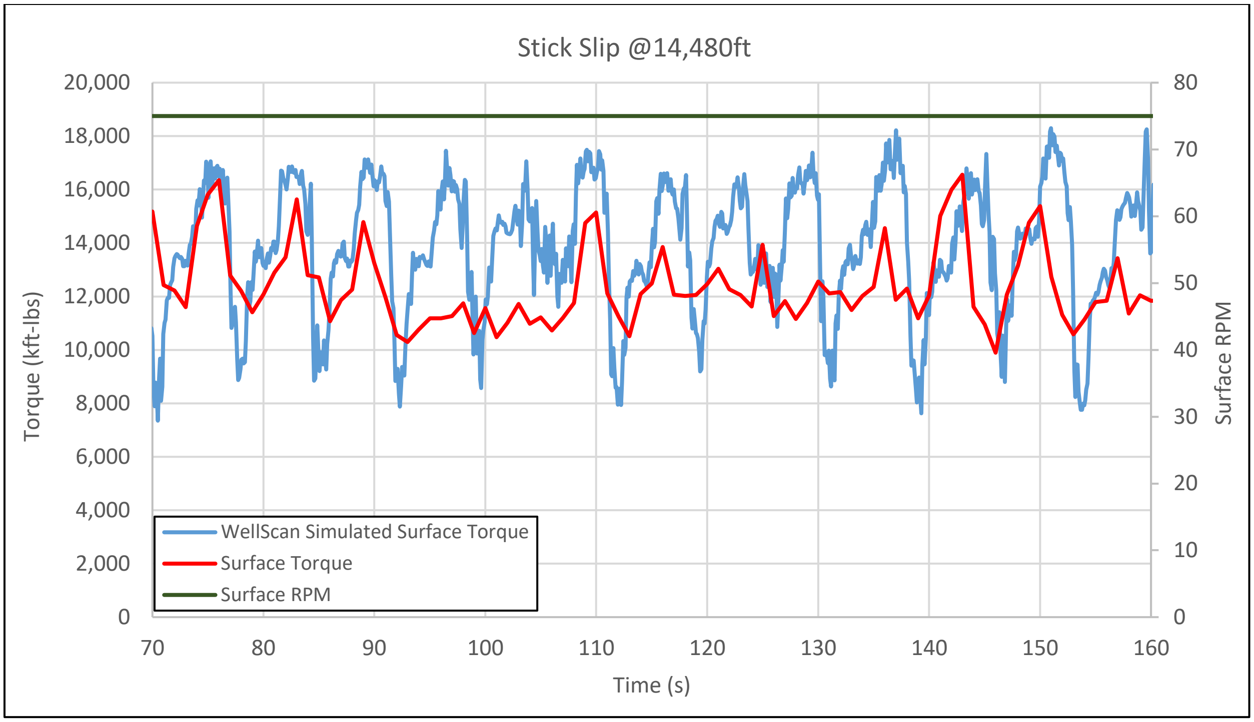

Figure 11:Simulated Stick-Slip vs Measured Surface Torque (1 sec data)

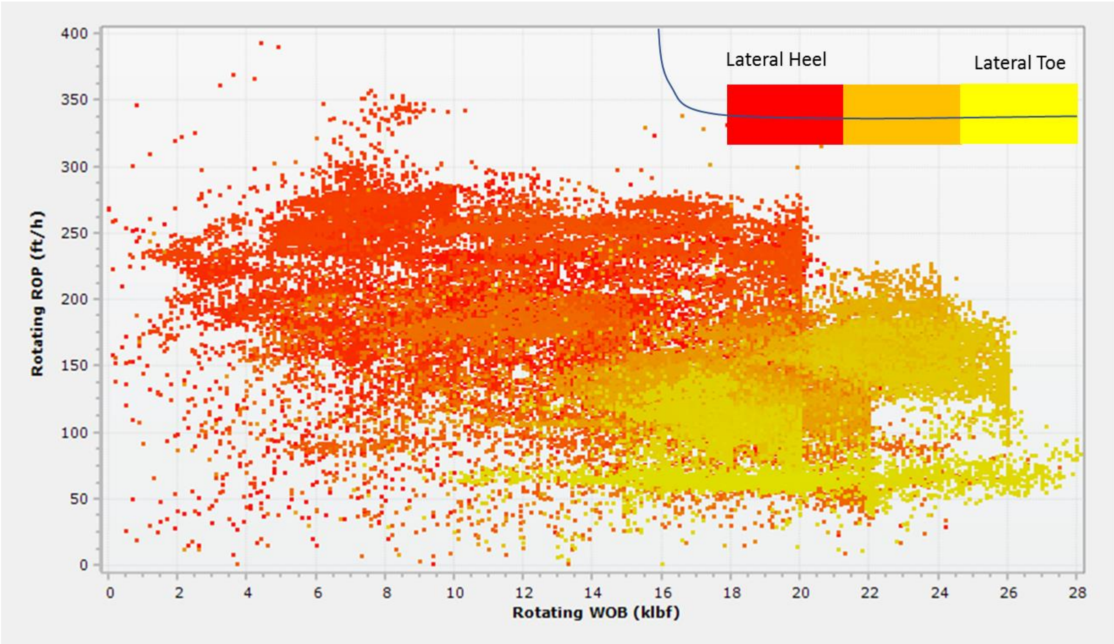

Figure 12: ROP vs WOB along the lateral section (rotating only)

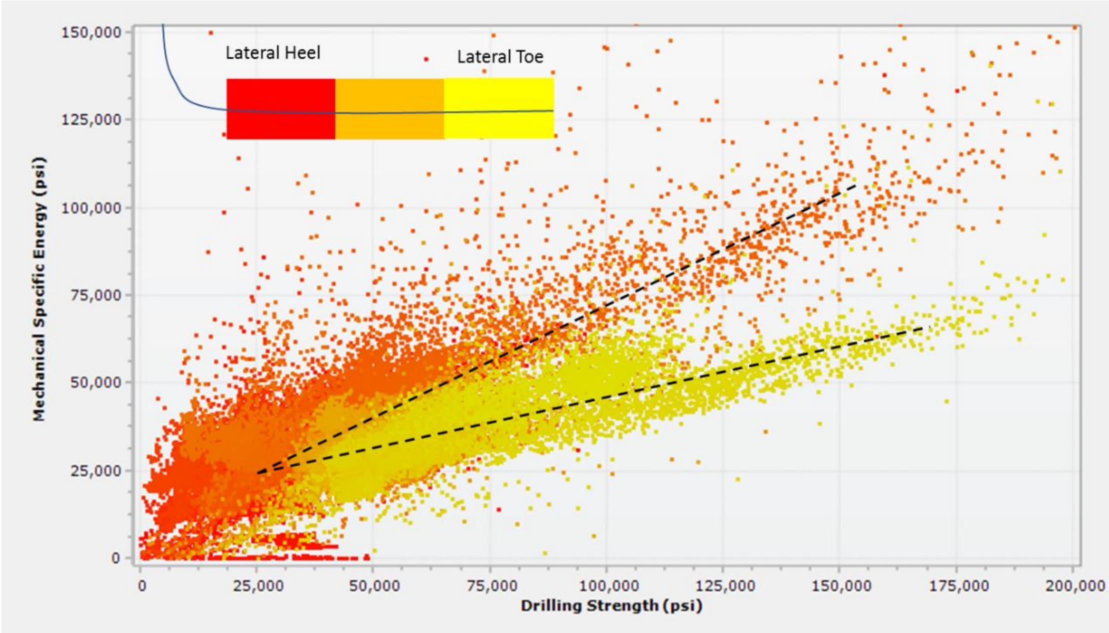

Figure 13: MSE vs DS for Drilling Optimization

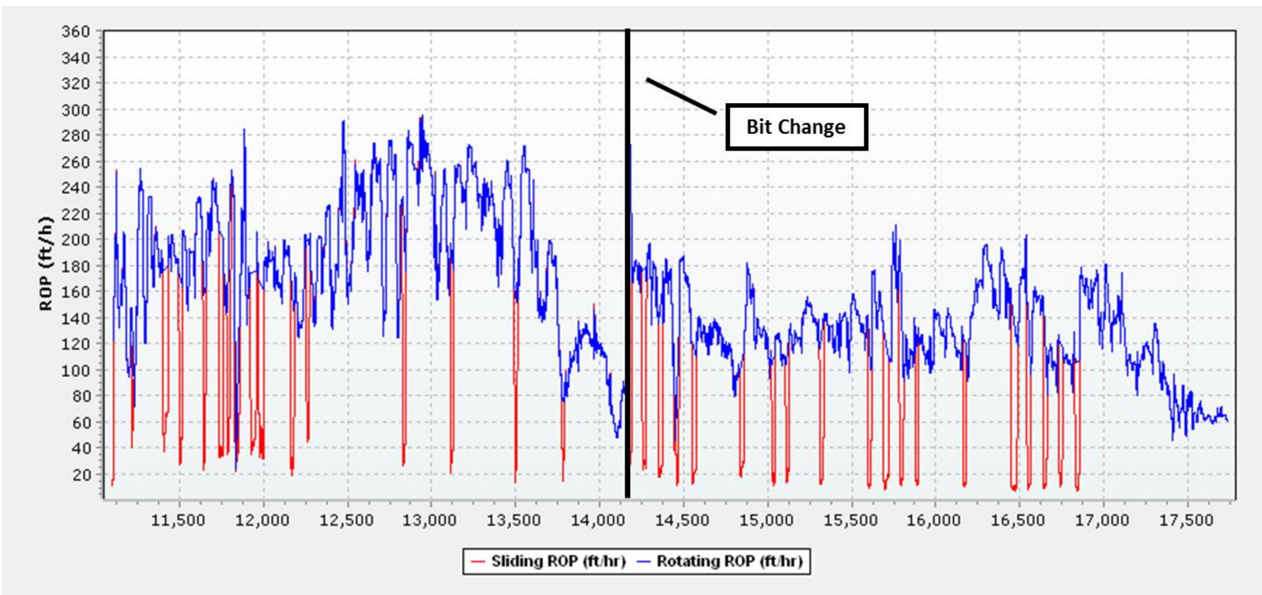

Figure 14: ROP along the lateral section