

**IMPROVING DRILLING PERFORMANCE IN ABRASIVE
SANDSTONE FORMATION BY OPTIMIZING DRILL
STRING AND BHA DESIGN**

BY

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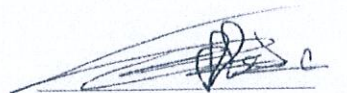
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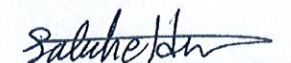
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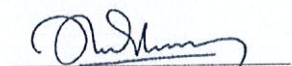

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Dedication

This thesis is dedicated to my Parents, Brothers & Wife

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All praise and thanks are to Almighty Allah, the Most Gracious and the Most Merciful. Peace and mercy be upon His Prophet.

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LIST OF ABBREVIATIONS

ROP	:	Rate of Penetration
RSS	:	Rotatory Steering System
MWD	:	Measurement While Drilling
LWD	:	Logging While Drilling
WOB	:	Weight on Bit
RPM	:	Revolutions Per Minute
MSE	:	Mechanical Specific Energy
BHA	:	Bottom Hole Assembly
MD	:	Measured Depth
HRS	:	Hours
Dull	:	Dull grading
Stab	:	Stabilizers
AFPR	:	Average Footage Per Run
AROP	:	Average Rate Of Penetration
TD	:	Total Depth

ABSTRACT

Full Name : [Abdullateef Ahmed Al-Dahmoush]

Thesis Title : [Improving Drilling Performance in Abrasive Sandstone Formation by Optimizing Drill String and BHA Design]

Major Field : [Drilling]

Date of Degree : [March, 2022]

Zero-emission is our country's 2060 target. There are many ways to achieve our country's target in drilling operations. For example, if we optimize drilling operation, we will be able to drill the well faster with less budget. Optimizing drilling operations means less diesel daily consumption used to operate rig equipment. But the challenges now are greater than before. The formation characteristics are harder and abrasive; the well profile is more complex and requires more HPHT wells on the pipeline to drill it. Avoiding nonproductive time with these challenges is a major contributor to drilling optimization, but this is not easy. This is a highly complex issue as more downhole failures cause us more money and safety hazards, including POOH and changing out downhole tools. The cost of these tools, if they get stuck down a hole, is expensive. It will also raise HSE concerns if it includes radioactive sources. Hence, it is crucial to have a detailed study to know the causes of down-hole tool failures and the performance controllers. This research observed that the most performance controller that makes nonproductive time is the vibration faced while drilling. The vibration consists of lateral, torsional, and axial vibrations. These vibration types limit us from efficiently applying the proper drilling parameters to drill these wells. Vibration can be affected by formation lithology, BHA string design, and drilling

parameters. A detailed literature review was conducted to overcome these vibrations to see what others are doing to solve such issues. The relationship between MSE, formation Geomechanical, BHA design, and drilling parameters combined while drilling an abrasive sandstone formation was not covered until now. In order to find out this relationship, these vibrations causes will be analyzed and consequently reduced or avoided. 5 to 6 bits are required to drill 2000. These are consuming time, cost, nonproductive time, HSE hazards, and other hidden costs. From here, 12 drilled wells were selected to do this research. This research follows 5 phases as follows:

1. Evaluation of historical data.
2. Capturing and analyzing downhole data from RSS and LWD Tools.
3. Selecting optimum drill string and BHA design using frequency and transient models.
4. Selecting optimum real-time drilling parameters to improve drilling efficiency across abrasive sandstone formation.
5. Evaluating the effectiveness of this research success on two new wells for the validation process.

In conclusion, the proposed BHA and parameters represented the effective solution to increase the performance of sandstone formation by improving the average footage per run between 133 – 178% while maintaining the average ROP and having the potential to improve the average ROP by 20% if proper compliance on the drilling parameters guideline is achieved. The transient simulation accurately predicted drilling motion, optimizing BHA design and defining a drilling parameters road map.

ملخص الرسالة

الاسم الكامل: عبد اللطيف أحمد الدهموش

عنوان الرسالة: تحسين أداء الحفر في الصخر الرملي من خلال التصميم المناسب لعامود الحفر

التخصص: الحفر

تاريخ الدرجة العلمية: مارس ٢٠٢٢

إن تحقيق الانبعاثات الصفيرية هي هدف بلدنا لتحقيقه في عام ٢٠٦٠. أثناء عمليات الحفر، هناك العديد من الطرق للمشاركة في تحقيق هذه الرؤية. فعلى سبيل المثال، إذا قمنا بتحسين عملية الحفر، فسنكون قادرين على حفر البئر بشكل أسرع وبميزانية أقل. إن تحسين عمليات الحفر يعني استهلاكاً يومياً أقل للديزل المستخدم لتشغيل معدات الحفر ولكن التحديات الآن أصبحت أكثر تعقيداً حيث أن حفر الصخور القاسية صعب جداً ومما يزيد الأمر صعوبة هو اتجاهات البئر المعقدة ودرجة حرارة باطن الأرض المرتفعة وضغط الأرض المرتفع. إن التصدي لهذه التحديات مع تقليل الوقت الضائع صعب جداً تحقيقه ولكنه من أهم عوامل تحسين أداء حفر الآبار. ولكن ذلك ليس أمراً سهلاً، حيث أنه الأدوات في قاع البئر المتصلة مع عمود الحفر تتعرض للتلف مما يتسبب لنا بخسارة مزيد من المال والمزيد من المخاطر خاصة أثناء إنزال وإخراج المعدات من قاع البئر. إن قيمة هذه الأدوات لو تم فقدانها في قاع البئر باهضه الثمن لاسيما لو كان معها عناصر مشعة فسوف يكون لدينا مخاوف تتعلق بالصحة والسلامة والبيئة. من هنا جاءت أهمية عمل دراسة مفصلة لمعرفة أسباب الفشل وتداركه وماهي العوامل التي تقلل من الاداء النموذجي للحفر. لقد وجدت ان السبب الرئيسي في تقليل الاداء والفشل هو الاهتزازات التي نواجهها خلال الحفر. يتكون الاهتزاز من ثلاثة أنواع هي الاهتزاز الجانبي والالتوائي والمحوري. ان هذه الاهتزازات تمنعنا من تحقيق هدفنا بحفر هذه الآبار بأداء متميز. للتصدي لهذه التحديات لقد قمت بالبحث في المصادر لأرى ما وصل اليه العلم الى اليوم لعلاج هذه المشكلات كي أتعلم منها ولأبني بحثي عليها لأنطلق من حيث ما انتهى اليه الآخرون. ولقد وجدت ان الباحثين الى يومنا هذا لم يجدوا العلاقة المرتبطة بين الطاقة الميكانيكية النوعية أثناء الحفر، علم ميكانيكا الصخور، تصميم عامود الحفر وكذلك القيم التي نحتاج لتطبيقها أثناء الحفر مجتمعة معاً. لكنني أعتقد اعتقاداً جازماً بأنني لو أوجدت هذه العلاقة سوف يكون باستطاعتي معرفة أسباب هذه الاهتزازات وبإذن الله سوف أكون قادراً على منعها أو على الأقل التقليل

منها. حاليا يتطلب حفر ٢٠٠٠ قدم من خمس الى ستة مئاقيب حفر مما ينعكس سلبيا على الوقت المستغرق لحفر البئر، وهدر وقت ضائع كبير وكذلك مبالغ ضائعة ممكن يستفاد منها في تحقيق اهداف أخرى. هذا ايضا يضاف للمخاطر المتعلقة والمبالغ المخفية التي لا يمكن حسابها. من هنا لقد قمت باختيار ١٢ بئر توجد فيها هذه المشكلات واتبعت خمسة مراحل كما يلي:

١-تقييم البيانات التاريخية.

٢- تحليل البيانات التي تم ايجادها أثناء الحفر.

٣- تصميم عمود الحفر باستخدام نماذج ترددية ووقئية.

٤- ايجاد المعطيات المناسبة لاستخدامها أثناء الحفر.

وبعد الانتهاء من بحثي، تم التحقق من صحة ما قمت به على بئرين. وفي الختام وبحمدالله تحقق الهدف

المنشود وذلك بزيادة الأداء أثناء الحفر بين ١٣٣-١٧٨ في المئة مع زيادة معدل الحفر بنسبة ٢٠ في المئة

وهذا يتحقق اذا تم الالتزام بتطبيق المعايير المناسبة.

لقد كان نموذج المحاكاة المتبع دقيقا في التنبؤ مما يسمح بتصميم مناسب لعمود الحفر وتحديد المعايير الواجب الالتزام بها لتحقيق الهدف المطلوب.

CHAPTER 1

INTRODUCTION

Directional drilling activities on HPHT wells have become more complex because of the well profile complexity and drilling through abrasive sandstone formation. Drilling performance optimization is required to drill these wells efficiently. Researchers have the resources and the time needed to develop technologies, processes, and new drilling tools. In some cases, the results have not been sustainable, even achieving the intended performance objectives. Drilling performance must continuously improve to achieve its intended benefits. Drilling Performance is the decisions and actions required to achieve improvements made and driven by relevant data and detailed analysis. Footage drilled per BHA run, several bits were used to complete the section, vibration control, the operational life of drilling tools, ROP, directional effectiveness, and borehole quality are classified as drilling performance measures. Optimizing drilling performance to reduce operating costs requires identifying and analyzing these factors and studying the relationship between each other.

The drilling system and operational environment establish the factors that influence performance factors. These factors include the hardness of different formation types, weight on bit (WOB), rotary speed (RPM), BHA, drilling fluid type and rheology, well profile and drive systems. Vibration is the instability of the drill string on dynamic mode. It can be either axial, torsional, or lateral. Using the optimum WOB & RPM can significantly affect

vibration level. Formation to formation and field to field has a different optimum zone. The high level of shock and vibration experienced while drilling hard and abrasive sandstone formation affects the penetration rate, the bit life, and the reliability of the directional and logging while drilling tools. It is vital to have good shock and vibration prevention and mitigation measure to improve the drilling performance. The vibration level will be increasing while drilling high abrasive index formation, which is required to have close monitoring for dynamic data in parallel to the logging while drilling data to make an effective decision. A real-time drilling parameter guideline involving MSE and logging while drilling data analysis will be defined, increasing the average footage per run and the average penetration rate.

BHA consists of bit, drill collars, stabilizers, LWD, MWD &RSS. Designing the placement of stabilizers can reduce the uncontrolled vibration recorded by the LWD tool.

1.1 Current Challenges

Optimizing footage drilled per BHA, reducing the number of bits to complete the section, vibration control, increasing the operational life of drilling tools, achieving ROP, maintaining directional work effectiveness, and borehole quality are significant challenges.

Proper BHA Design, applying drilling parameters, close monitoring to Mechanical Specific Energy (MSE), and studying wellbore geomechanics will majorly control BHA vibration and drilling with higher ROP, achieving longer footage drilled per bit run and fewer bit numbers to drilled entire lateral.

It is vital to have an effective shock and vibration prevention and mitigation measure to

improve the drilling performance. A detailed study on BHA vibration phenomena was performed. It plays a major role in designing the BHA, selecting proper drilling parameters, and understanding the relationship between formation lithology and BHA vibration. This optimizes drilling performance where higher ROP and longest footage per run can be achieved.

It is important to differentiate between shocks and vibration. Shocks are sudden acceleration or deceleration caused by an impact (considered high energy and low duration). When the bottom hole assembly, bit, or drill string impacts the borehole, it is a sudden input of energy. On the other hand, vibration is a periodic motion of the particles of an elastic body or medium in alternately opposite directions from the equilibrium position when that equilibrium has been disturbed (considered low peak energy and long duration). It is the response of the bit, bottom hole assembly & drill string to the shock. Figure 1 shows the difference between vibration and shocks.



Figure 1 Vibration & Shocks (source: www.slb.com)

1.2 BHA Vibration Types

BHA vibration consists of three types: Axial vibration, Torsional vibration, and Lateral vibration. Figure 2 shows different vibration types on various well profiles design.

1.2.1 Axial Vibration

It is a frequency of motion that harmonically increases and decreases the weight on the bit. It causes bit damage, uncontrolled well trajectory & surface equipment damage.

1.2.2 Torsional Vibration

It is an irregular drill string rotation when rotated from the surface at a constant speed. It causes balled connection, bit damage & a twist-off.

1.2.3 Torsional Vibration

It is the movement of the drill string along its axis of rotation. It causes spiral wellbore profile, bottom hole assembly washout & hard banding or stabilizers worn out.

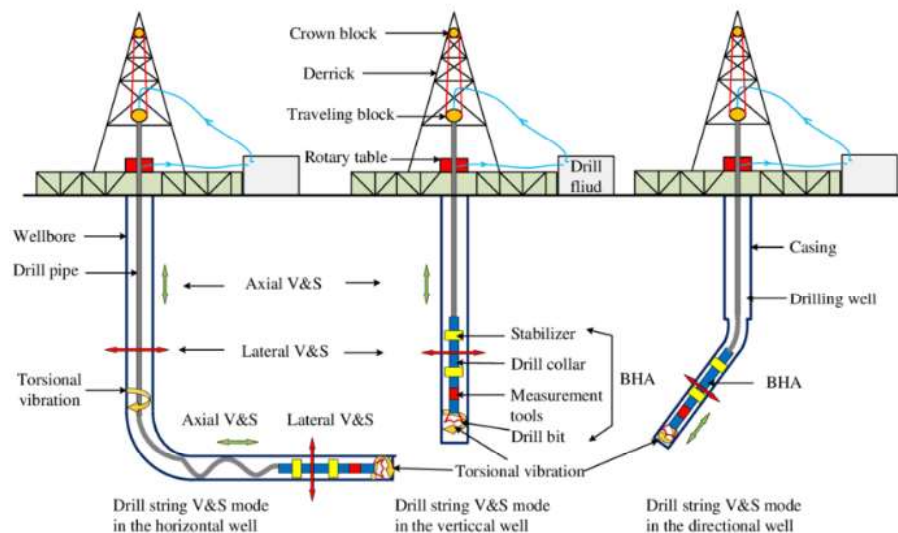


Figure 2 Vibration Types (source: www.researchgate.net/publication/318010391)

1.3 BHA Vibration Factors

The BHA vibration affecting factors are formation lithology, BHA design, and drilling parameters.

1.3.1 Formation Lithology

Formation compressive strength, abrasive formation index, and caliper log are factors to classify BHA vibration types. BHA vibration behavior differs when drilling sandstone formation from drilling across carbonates formation. Abrasive sandstone formation breakout-causing borehole over-gauged, leading to BHA vibrating more than other formation types.

1.3.2 BHA Design

BHA design needs a detailed study analysis. Drilling through abrasive sandstone formation will create a different BHA vibration figure print than other formations. Designing the stabilizer's placement is important as it will reduce BHA vibration.

1.3.3 Drilling Parameters

Designing the required WOB based on formation compressive strength, RPM, and resulting MSE will affect the BHA vibration and its level range.

CHAPTER 2

LITERATURE REVIEW

2.1 Improving Drilling Efficiency by Optimizing MSE

(Abbas et al., 2020) found there will be effective well deliveries when MSE and downhole dynamic data are utilized together. Monitoring MSE will aid in a proper well placement to steer across the high porosity layers. This will optimize the drilling efficiency. This study proves its effectiveness by delivering the longest well in the Middle East and the 4th longest globally in Nov 2019.

(Iftikhar et al.,2019) did a correlation between ROP, drilling difficulty index, azimuth, rock density, MSE, BHA stabilization, S&V, and formation properties using advanced drilling engineering. They concluded that the MSE is getting affected by S&S, formation density, and well trajectory. They proved that stabilized bottom hole assembly would lead to less S&V, ultimately reducing the MSE trends. They also found that using MRSS, vibration isolation tools, or agitators will reduce the S&V.

(Pinto et al.,2019) showed the importance of MSE control to avoid drilling difficulties like S&V, ultimately increasing drilling efficiency.

2.2 Reducing Vibration Effect by Proper Placement of Down Hole

Tools

(Abdelsamad et al., 2018) ensured that using MRSS will reduce S&V. They also showed that placing downhole tools below MRSS will improve drilling performance while drilling hard and abrasive sandstone formation.

2.3 Reducing Vibration Effect by Optimizing Drilling Parameters

(Balka et al., 2018) discussed the importance of applying the proper drilling parameters to mitigate S&V.

(Abdelsamad et al., 2018) identified the improvement of placing MWD & RSS below the mud motor to analyze the vibration data better and act accordingly. Their analysis was based on two significant parts: multiple finite element analysis modeling and RSS & MWD system upgrade to handle excessive vibration forces.

(Christian et al., 2017) highlighted the importance of optimizing drilling parameters to mitigate string vibration.

(Kumar et al., 2017) demonstrated experimentally by monitoring the operation in real-time and comparing it with a simulated model that will help react immediately and work towards the drilling optimization by changing drilling parameters as needed. T&D, S&V, and MSE of several well data were captured & simulated to improve upcoming well performance. This increased the well delivery performance by 30.9%, with a 47% nonproductive time reduction.

(Stefano et al., 2009) analyzed the proper selection of drilling parameters and BHA design to mitigate the drill string vibration.

2.4 Relationship between Formation Geo-mechanical Behavior Vibration

(Sitinjak et al., 2017) demonstrated the relationship between the geological phenomena and drill string vibration, which can be used to steer the horizontal wells.

(Bailey et al., 2018) studied the S&S and showed it varies on every well and field.

(Ahmed et al., 2014) studied formation geo-mechanics to select the proper mud weight. This will reduce formation breakout and also improve BHA stabilization.

(Esmacili et al., 2013) analyzed the relationship between formation compressive strength and drill string vibration.

2.5 Reducing Drill String Vibration by Using Down Hole Tools

(Brown et al., 2018) proved that using two software simulations (finite element simulation and drilling vibration simulator) and adding sections of AL DP with optimum length would reduce torsional and lateral vibration.

(Zhang et al., 2018) studied the effect of using a vibrator above the mud motor will reduce the string vibration as its vibration energy will create waves and overcome it.

(Constantijn et al., 2011) found that vibration in DS is localized and can be anywhere in the string and not always near the bit where MWD can be detected. This phenomenon was

proven by installing a vibration sensor in different string positions.

(Albrecht et al., 2009) performed two-trial tests in Pre-Khuff formation using turbodrill device and showed a good decrease trend in trip frequency, bit, and bottom hole assembly failure.

2.6 Problem Statement and Objectives

As mentioned in the literature review, all were focused on monitoring MSE, proper placement of downhole tools, monitoring drilling parameters, and studying formation Geo-mechanical behavior.

No literature has discussed the relationship between MSE, formation Geo-mechanical formation, BHA design, and drilling parameters while drilling abrasive sandstone formation.

This is the area of research where it needs to design the proper BHA and select the appropriate drilling parameters based on MSE and formation Geo-mechanics to increase drilling performance.

There is a high risk of wellbore instability (formation shear and roof failure) which will lead to several drilling issues because of the high demand for horizontal drilling toward the minimum or maximum stress direction through sandstone formation with a rock compressive strength of more than 20 kips to meet the production objective. The formation shear and roof failure (over-gauged hole) provide an extra annular clearance for the drill string to vibrate. Therefore, it is important to minimize the S&V for the following reasons:

1. A higher level of S&V in front of formation shear/roof failure will increase the borehole deterioration by having a constant impact on the borehole, which at the same time brings the following problems:
 - ✓ Hole cleaning issue is higher cutting/caving annular loading with a lower annular fluid velocity (lower fluid carry capacity).
 - ✓ Higher risk of stuck pipe (mechanical and pack off).
 - ✓ Increasing downhole circulation temperature due to a higher frictional temperature reduces directional tool life.
 - ✓ Limitation to run Multistage Fracturing (MSF) completion by exceeding the top packer out diameter affects final well production.
2. A higher level of S&V represents a higher risk of directional and LWD tools failure and damage to the bit, maximizing the number of trips and days required to accomplish the planned reservoir exposure.
3. S&V represents a loss of the energy used to drill the borehole, affecting ROP and increasing the days required to accomplish the planned footage.

Under this complex drilling environment, low ROP and low average footage per run have been observed, requiring 5 up to 6 runs to accomplish 2000 ft of lateral exposure. Multiple ideas for drilling optimization have been applied without success-focused mainly on directional tools and bit or BHA design, excluding the drilling dynamic in conjunction with logging while drilling data.

CHAPTER 3

METHODOLOGY

3.1 Methodology

A complete analysis of the downhole drilling motion was performed using RSS, Drilling Dynamic Data, and LWD to understand the main contributing factors of the low ROP and average footage per run observed while drilling hard and abrasive sandstone formation. 12 wells with 51-bit runs were selected to perform this research to do the analysis. The following processes were divided into five phases, as shown in the chart in Figure 3.

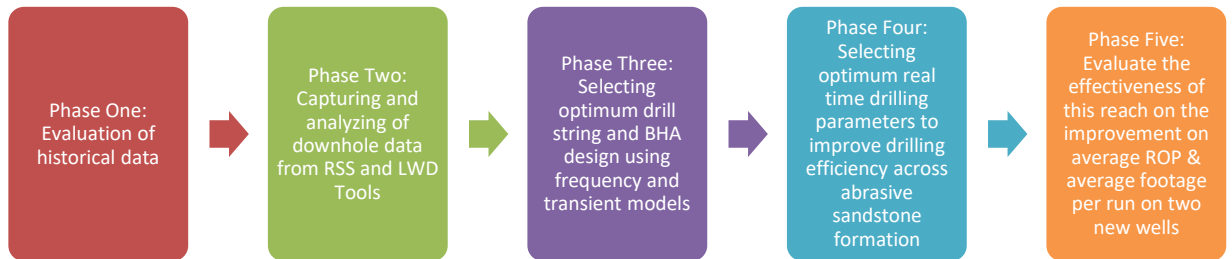


Figure 3 Thesis Work Methodology

3.2 Shock and Vibration Modelling

Vibration models in use today may be divided into two primary categories:

- Time-domain models that run simulations (transient models).
- Frequency-domain models

Models in the frequency domain are often simpler and quicker to perform. Analyses that employ units of time like seconds or their multiples (such as minutes or hours) as units of

measurement to quantify their results, these units are often considered in the time domain. On the other hand, the frequency domain involves units such as Hertz for analyzing data in terms of units.

3.2.1 Transient model

The computations continue in time from a starting point and analyze the influence of wellbore excitation forces and constraints on the BHA or drill string. While multiple methodologies (i.e., FEA at each step or finite difference in space and time) may be used, the calculations normally take place with tiny time steps to capture the movement of axial and torsional waves through the BHA/drill string components.

The BHA/drill string is split into pieces and put in a three-dimensional trajectory.

A visco-elastic boundary technique with Hertzian contact may be used to represent the borehole's interaction.

Capabilities:

1. Drilling process analysis in real-time (the model simulates a short period where the assembly drills forwards).
2. The model can mimic a whirl because it takes into account the effects of contact with the borehole wall and friction.
3. Presents models of excitation factors (stabilizers, bits, reamers, bends, motors, etc.).
4. Capture the influence of components in the BHA, such as flex joints, and offer insight into complicated assemblies, such as vortex and rotating bends.
5. Capability to record the effect of buckling on shock and vibration.

Limitations

1. Performing an analysis using a completely transient model generally takes a long time.
2. The model has inputs that are generally unknown, thus assumptions must be made:
 - a. the precise diameter/shape of the hole
 - b. the friction factor at the contact locations
 - c. downhole damping levels
 - d. real component imbalance

3.2.2 Frequency model

This method implies that vibration-induced displacements and stresses are small until the system is activated by a signal at one of its natural frequencies, which may cause the string to resonate.

Although the lateral natural frequencies of the BHA are often of most relevance, this method may also be used to calculate the axial and torsional natural frequencies of the complete drill string.

A three-dimensional finite element analysis model is utilized to identify the contact sites inside the BHA and to generate a mass and stiffness matrix for the components. Contact points are defined by side-forces that exceed a certain threshold. The contact points take into account the BHA in a 3D trajectory (some models may be 2D).

The distance between the bit and the "tangency" point, where the drill collars contact the wellbore above the final stabilizer, determines the length of the vibrating BHA. The top touch point is set to be at the top of the BHA if it does not occur within the length of the BHA (defined as the distance from the first HWDP or DP component).

The system's natural frequencies and mode shapes are computed using a modal eigenvector analysis. (Natural frequencies are the vibrational frequencies that the system prefers to use.) The forms of the deflections at each natural frequency are known as mode shapes).

Critical rpms are derived by selecting excitation factors based on the estimated natural frequencies. When the frequency of an excitation factor equals one of the BHA's inherent frequencies, a critical rpm occurs. The majority of excitation factors are forces that occur X times every rotation of the drill string. (A mud motor that excites at a frequency determined by the rotor's rpm is an exception).

The magnitude (forces) caused by these excitation sources are then estimated using models of excitation factors such as the bit and stabilizers.

The response of the BHA may thus be observed in terms of displacements, bending stresses, and side forces as a function of rpm and distance along with the BHA. Because damping is a significant issue, these magnitudes are qualitative and may be used to compare various BHA designs.

Capabilities

This can be used to compare BHA designs by investigating the number of natural frequencies within the projected 0-XXX rpm working range may be utilized.

Critical rpms may be defined as a starting guideline for field operations by carefully considering the potential excitation factors.

Allows the user to compare various BHA designs by comparing:

- The number of critical rpms within the projected operating window.
- Estimating the displacement, bending stress, and side force that might be present inside the BHA as a function of rpm and distance along with the BHA.

Limitations

1. Assumes that the static FEA model's contact points stay fixed throughout vibration. The location of the top node in the analysis is really important (tangency point). This determines the vibrating system's length (weak assumption at low inclinations). This is most likely true for traditional BHAs in inclined wellbores with hefty drill collars. Nonetheless, the assumption is weak for BHAs at low slopes or BHAs for ERD applications when the drillpipe is operated under compression.
2. In a limited design, frequency analysis might be deceiving. The invariance of touch points derived from a static analysis is not guaranteed when the instrument spins and slides.
3. Mechanisms, such as swirl, are not captured.
4. Excitation caused by friction between the wellbore wall and contact points is not taken into consideration. (The revolving string and the borehole are not in contact).

CHAPTER 4

Results and Discussions

4.1 Phase One: Evaluation of Historical Data

Evaluation of historical data covered defining the benchmark to measure the improvement after completing the research, evaluating bit dull grading, stabilizers worn-out condition, and MSE. The common characteristics of these wells are shown in table 1. The standard BHA for the selected wells is shown in table 2.

Table 1 Wells Data

Hole Size	5 7/8"
Inclination	87-90 degree
Lateral Length	2000'
Formation	Abrasive sandstone formation (70% quartz and 25-30 kips Unconfined compressive Strength (UCS))
Mud Type & MW	OBM (95-100 PCF)
Bit Characteristics	6 blades with 13 mm cutters

Table 2 Wells BHA

Description	Outer Diameter	Length
Bit	5.875	0.69
RSS Stabilizer	5.750	18.10
MWD	5.250	33.55
5 ¾" ILS	5.750	2.50
LWD Stabilizer	5.750	25.50
Pony NMDC	4.750	15.00
4" HWDP	4.000	91.60
Jar	4.750	30.90
4" HWDP	4.000	61.64
4" DP	4.000	7974.11
5 ½" DP	5.500	Surface

4.1.1 Evaluating the Main Performance Controller

The two main performance controllers are the average rate of penetration & the average footage achieved per run. This research aims to improve these controllers to be drill faster by improving the average penetration rate and drilling more footage, meaning avoiding unnecessary tripping and saving bit costs. Table 3 shows the drilling data for the selected wells.

Table 3 Wells Drilling Data

Well Number	Depth In	Depth Out	Drilled Footages ft	Total Hours While Drilling	ROP ft/hr	Bit Dull Grading	Stabilizers Evaluation	Average Footage ft	Average Rate of penetration ft/hr
Well 1	xx716	xx856	140	42.2	3.32	1-2-WT-PR	1/16 UG	290	4.91
	xx856	xx937	81	25.0	3.24	1-2-WT-PR	1/16 UG		
	xx937	xx273	336	65.7	5.11	1-3-WT-PR	1/16 UG		
	xx273	xx836	563	86.5	6.51	2-6-WT-PR	1/8 UG		
	xx836	xx165	329	75.5	4.36	3-7-RO-PR/TD	1/16 UG		
Well 2	xx162	xx447	284	59.8	4.75	2-4-WT-PR	1/16 UG	393	5.57
	xx447	xx856	409	73.5	5.56	2-3-WT-PR	1/8 UG		
	xx856	xx161	305	68.5	4.45	2-3-WT-PR	1/16 UG		
	xx161	xx481	320	56.5	5.66	1-3-WT-PR	1/16 UG		
	xx481	xx126	645	94.0	6.86	1-3-WT-TD	1/8 UG		
Well 3	xx513	xx818	305	41.5	7.35	1-4-WT-PR	1/16 UG	374	7.98
	xx818	xx359	541	59.8	9.05	1-2-WT-PR	1/8 UG		
	xx359	xx527	168	18.5	9.08	1-2-WT-HP	1/16 UG		
	xx527	xx010	483	67.8	7.13	2-4-WT-PR/TD	1/8 UG		
Well 4	xx011	xx580	569	64.0	8.89	3-5-WT-PR	1/8 UG	490	9.05
	xx580	xx256	676	78.0	8.67	3-3-WT-PR	1/16 UG		
	xx256	xx481	225	20.5	10.98	1-1-WT-TD	1/16 UG		
Well 5	xx302	xx650	348	73.5	4.73	1-2-WT-BHA	1/16 UG	448	6.59
	xx650	xx045	395	56.5	6.99	1-1-WT-PR	1/8 UG		
	xx045	xx613	568	90.5	6.28	2-1-WT-PR	1/8 UG		
	xx613	xx092	479	51.3	9.35	1-2-WT-BHA/TD	1/8 UG		
Well 6	xx090	xx449	359	43.0	8.35	1-1-WT-BOP	1/16 UG	320	4.48

Well Number	Depth In	Depth Out	Drilled Footages ft	Total Hours While Drilling	ROP ft/hr	Bit Dull Grading	Stabilizers Evaluation	Average Footage ft	Average Rate of penetration ft/hr
	xx449	xx665	216	63.8	3.39	1-3-CT-BHA	1/16 UG		
	xx665	xx993	328	98.5	3.33	1-1-WT-PR	1/8 UG		
	xx993	xx369	376	80.3	4.69	1-1-WT-TD	1/8 UG		
Well 7	xx319	xx601	282	40.5	6.96	2-1-WT-DTF	1/16 UG	319	6.74
	xx601	xx050	449	73.8	6.09	1-2-WT-PR	1/8 UG		
	xx050	xx602	552	70.8	7.80	1-1-WT-BOP	1/8 UG		
	xx602	xx835	233	37.3	6.26	1-1-WT-PR	1/16 UG		
	xx835	xx164	329	51.0	6.45	1-1-WT-DTF	1/8 UG		
	xx164	xx232	68	10.8	6.33	1-1-BT-DTF/TD	Full Gauge		
Well 8	xx231	xx735	504	90.3	5.58	1-3-WT-HRS	1/8 UG	387	5.13
	xx735	xx903	168	30.3	5.55	1-2-BT-PR	1/16 UG		
	xx903	xx010	107	32.8	3.27	1-1-WT-DTF	1/16 UG		
	xx010	xx725	715	128.0	5.59	2-1-WT-BOP	1/8 UG		
	xx725	xx167	442	96.5	4.58	2-1-WT-TD	1/8 UG		
Well 9	xx628	xx047	419	63.3	6.62	1-2-WT-BOP	1/8 UG	479	5.99
	xx047	xx631	584	107.3	5.45	1-3-WT-HRS	1/8 UG		
	xx631	xx065	434	69.3	6.27	1-3-WT-DTF/TD	1/8 UG		
Well 10	xx067	xx528	461	99.0	4.66	3-1-WT-BOP	1/8 UG	325	4.11
	xx528	xx904	376	95.0	3.96	1-2-WT-DTF	1/8 UG		

Well Number	Depth In	Depth Out	Drilled Footages ft	Total Hours While Drilling	ROP ft/hr	Bit Dull Grading	Stabilizers Evaluation	Average Footage ft	Average Rate of penetration ft/hr
	xx904	xx254	350	86.0	4.07	1-2-WT-HRS	1/8 UG		
	xx254	xx368	114	36.5	3.12	1-2-WT-TD	1/16 UG		
Well 11	xx870	xx253	383	85.0	4.51	1-4-FC-PR	1/8 UG	419	4.31
	xx253	xx587	334	90.0	3.71	1-4-WT-PR	1/8 UG		
	xx587	xx067	480	99.0	4.85	6-2-WT-PR	1/8 UG		
	xx067	xx544	477	114.5	4.17	6-2-WT-PR/TD	1/8 UG		
Well 12	xx545	xx309	764	114.0	6.70	6-2-WT-PR	1/8 UG	447	5.27
	xx309	xx717	408	92.8	4.40	5-2-WT-PR	1/8 UG		
	xx717	xx137	420	97.5	4.31	6-2-WT-PR	1/8 UG		
	xx137	xx333	196	35.0	5.60	2-2-WT-TD	1/16 UG		

Mean, and standard deviation were calculated from the average values per well, as shown in Table 4, Figure 4 & Figure 5. They were used for expected ROP and average footage per run benchmarking.

Table 4 Average Footage per run & Average ROP

Average Footage Per Run	Mean	391 ft
	Standard Deviation	67
Average ROP	Mean	5.84 ft/hr
	Standard Deviation	1.51

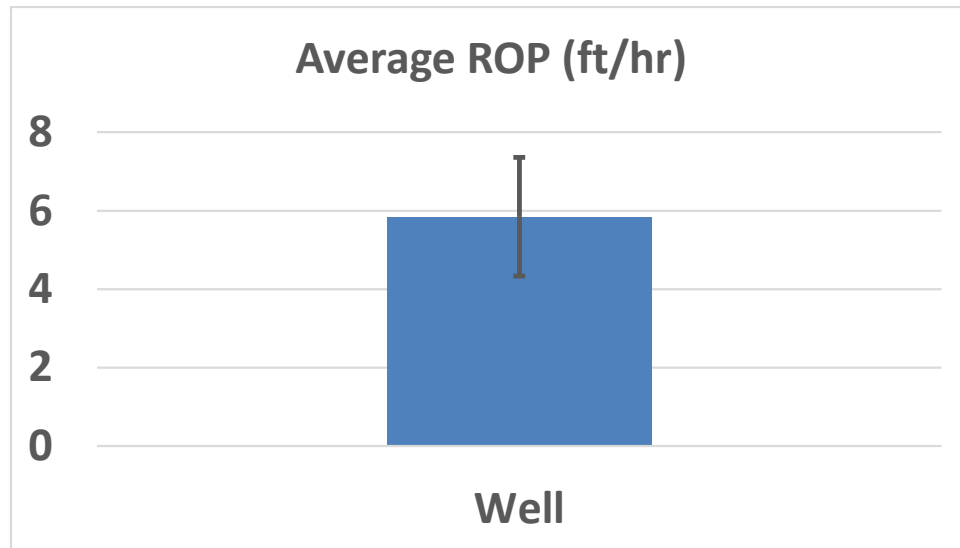


Figure 4 Average ROP Chart

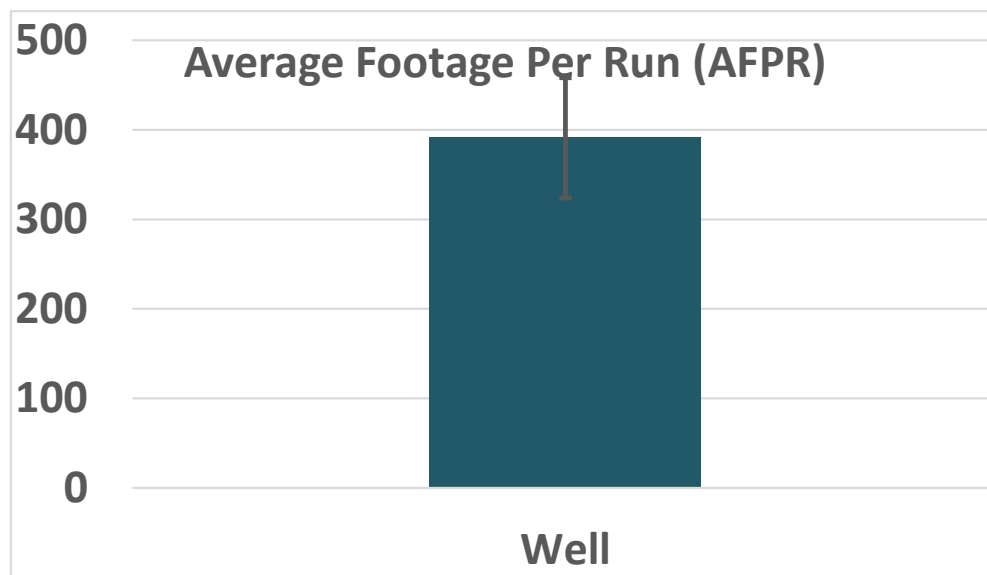


Figure 5 Average Footage Per Run Chart

4.1.2 Evaluating Bit Dull Grading

This process determined the main dull grading characteristic for each bit used. The bit dull grading mainly describes the inner row condition, outer row condition, main dull characteristic, and the reason for pulling out the hole. Below is PDC dull grading guide.

IADC DULL GRADING SYSTEM

CUTTING STRUCTURE				BEARINGS/ SEALS	GAUGE	OTHER DULL CHAR.	REASON PULLED
INNER	OUTER	DULL CHAR.	LOCATION				
I	O	D	L	B	G	O	R

I — INNER CUTTING STRUCTURE (All inner rows)

O — OUTER CUTTING STRUCTURE (Gauge row only)
In columns 1 and 2 a linear scale from 0 to 8 is used to describe the condition of the cutting structure according to the following:

STEEL TOOTH BITS
A measure of lost tooth height due to abrasion and / or damage.
0 — NO LOSS OF TOOTH HEIGHT
8 — TOTAL LOSS OF TOOTH HEIGHT

INSERT BITS
A measure of total cutting structure reduction due to lost, worn and / or broken inserts.
0 — NO LOST, WORN AND / OR BROKEN INSERTS
8 — ALL INSERTS LOST, WORN AND / OR BROKEN

FIXED CUTTER BITS
A measure of lost, worn and / or broken cutting structure
0 — NO LOST, WORN AND / OR BROKEN CUTTING STRUCTURE
8 — ALL OF CUTTING STRUCTURE LOST, WORN AND / OR BROKEN

D — DULL CHARACTERISTICS
(Use only cutting structure related codes)

*BC — Broken Cone	LT — Lost Teeth / Cutters
BF — Bond Failure	OC — Off-Center Wear
BT — Broken Teeth / Cutters	PB — Pinched Bit
BU — Balled Up Bit	PN — Plugged Nozzle / Flow Passage
*CC — Cracked Cone	RG — Rounded Gauge
*CD — Cone Dragged	RO — Ring Out
CI — Cone Interference	SD — Shirltail Damage
CR — Cored	SS — Self-Sharpening Wear
CT — Chipped Teeth / Cutters	TR — Tracking
ER — Erosion	WD — Washed Out Bit
FC — Flat Crested Wear	WT — Worn Teeth / Cutters
HC — Heat Checking	WQ — No Dull Characteristics
JD — Junk Damage	
*LC — Lost Cone	
LN — Lost Nozzle	

*Show cone # or #'s under location 4.

L — LOCATION

ROLLER CONE	
N — Nose Row	Cone # 1
M — Middle Row	2
G — Gauge Row	3
A — All Rows	

B — BEARING SEALS

NON SEALED BEARINGS	SEALED BEARINGS
A linear scale estimating bearing life used; (0 - No life used, 8 - All life used, ie. no bearing life remaining.)	E — seals effective
	F — seals failed
	N — not able to grade
	X — fixed cutter bit (www.iadc.org)

G — GAUGE

1 — in gauge
1/16 — 1/16" out of gauge
2/16 — 1/8" out of gauge
4/16 — 1/4" out of gauge

O — OTHER DULL CHARACTERISTIC
Refer to column 3 codes

R — REASON PULLED OR RUN TERMINATED

BHA — Change Bottom Hole Assembly	LH — Left in Hole
CM — Condition Mud	LOG — Run Logs
DMF — Downhole Motor Failure	PP — Pump Pressure
DP — Drill Plug	RIG — Rig Repair
DSF — Drill String Failure	TD — Total Depth / Casing Depth
DST — Drill Stem Testing	TQ — Torque
DTF — Downhole Tool Failure	TW — Twist Off
FM — Formation Change	WC — Weather Conditions
HP — Hole Problems	
HR — Hours on Bit	

Figure 6 IADC Dull Grading System

The bit dull grading analysis is shown in Figures 7, 8 & 9.

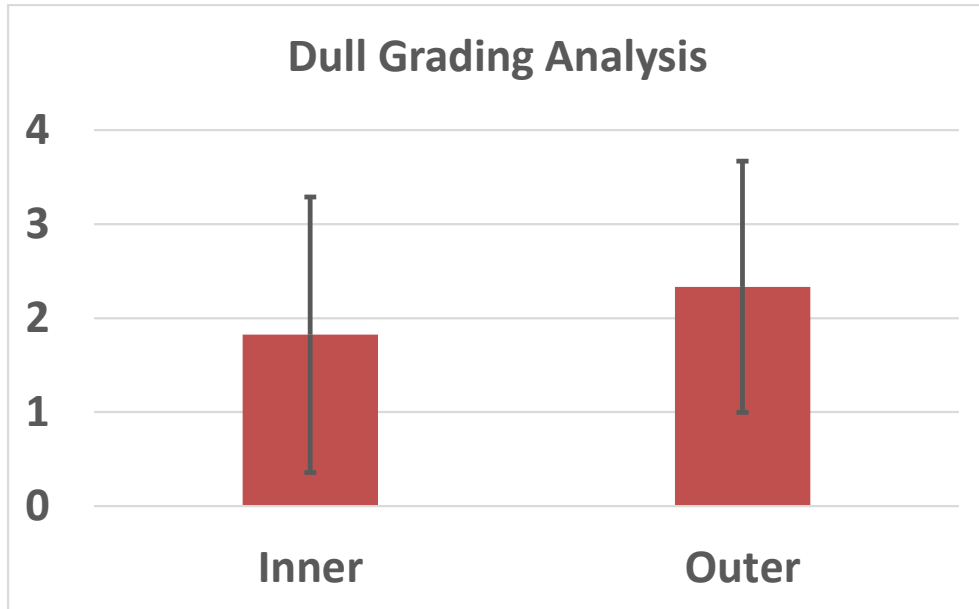


Figure 7 Bits Dull Gradings (inner & outer cutters)

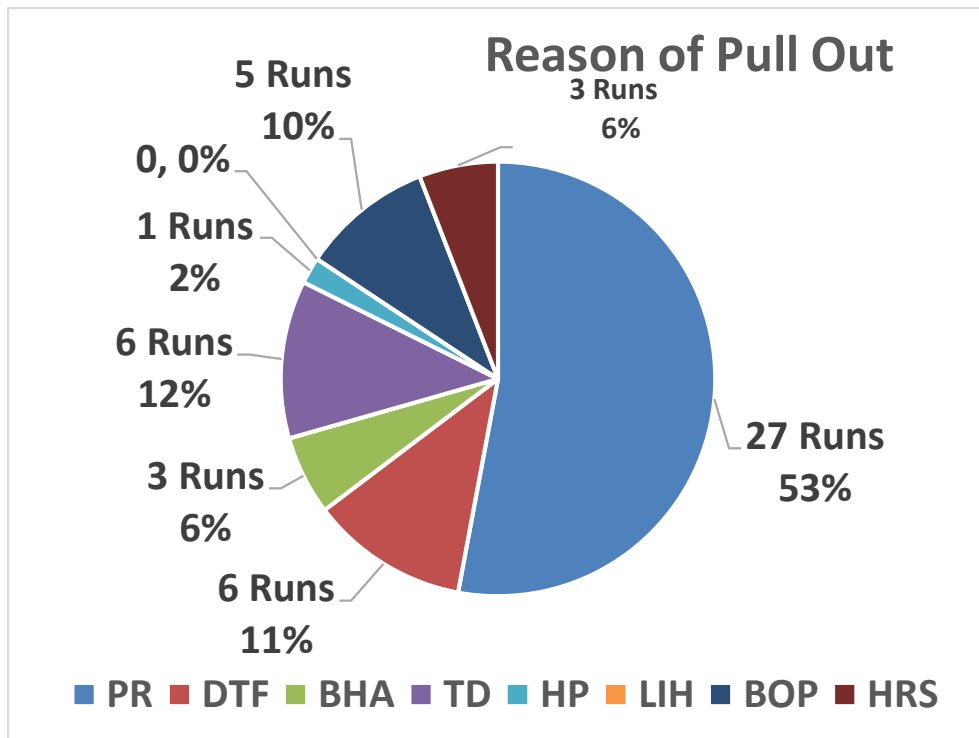


Figure 8 Bits Dull Gradings (reasons for POOH)

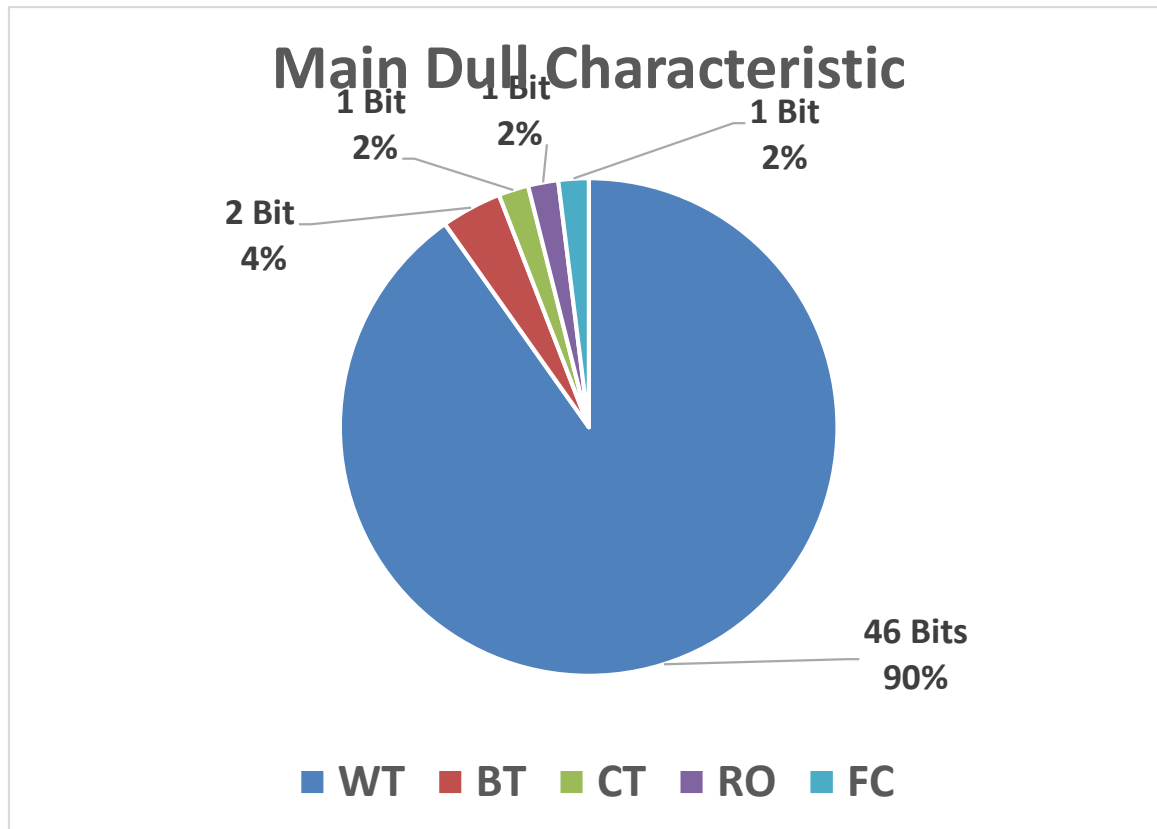


Figure 9 Bits Dull Gradings (Main Dull Characteristics)

From the above charts, we can conclude the followings:

1. Outer cutters showed a higher level of damage than inner cutters related to the higher demand for steering action.
2. Worn teeth (WT) showed the higher percentage representing 90%.
3. Penetration rate (PR) represented 53% as the main reason for pulling out of the hole, followed by downhole tool failures (TF), representing 11%. This indicated the complex drilling environment.

4.1.3 Evaluating Stabilizers Worn-Out Condition

For the worn-out stabilizer condition, the following was observed:

1. 1 out of 51 runs (2%), the stabilizer was coming out full gauge
2. 20 out of 51 runs (39%), the stabilizer was coming out 1/16 under gauge
3. 30 out of 51 runs (59%), the stabilizer was coming out 1/8 under gauge
4. Run below 100 ft (50% was coming full gauge & 50% was coming to 1/16 UG)
5. Run higher than 100 ft but below 350 ft (81% was coming to 1/16 UG & 19% was coming to 1/8 UG)
6. Run higher than 350 ft (7% was coming to 1/16 UG & 93% was coming to 1/8 UG)

The above analysis showed that the stabilizers' worn-out condition is directly linked to the footage drilled, and under gauge stabilizers condition is linked to drilling in abrasive formation. The highest worn-out occurred on upper stabilizers because of the higher level of S&V that was happening between 60 ft to 100 ft away from the bit. Some of the bit runs were showed a severe hard banding worn out on HWDP because of drill string whirl. The bit dull grading and drill string wear condition analysis indicate the complex drilling environment. The surface drilling parameters observed while drilling needed to be evaluated to have a clear analysis. For this reason, the Mechanical Specific Energy (MSE) idea was used as it contains all the surface parameters.

4.1.4 Evaluating MSE

MSE is the energy used to destroy or remove a unit volume of rock. It can be calculated from the surface (SMSE) and downhole parameters (DMSE). It is an energy unit input divided by volume removed.

$$MSE \approx \frac{\text{Input Energy}}{\text{Output ROP}}$$

$$SMSE = \left(\frac{480 \times STOR \times Bit \ RPM}{Bit \ Dia^2 \times ROP} \right) + \left(\frac{4 \times SWOB}{Bit \ Dia^2 \times \pi} \right)$$

$$DMSE = \left(\frac{480 \times DTOR \times Bit \ RPM}{Bit \ Dia^2 \times ROP} \right) + \left(\frac{4 \times DWOB}{Bit \ Dia^2 \times \pi} \right)$$

Where:

- STOR and DTOR are the surface and downhole torque, respectively. These are measured by Klbf-ft.
- SWOB and DWOB are the bit's surface and downhole weight, respectively. These are measured by Klbf.
- ROP is the rate of penetration. It is measured by ft/hr.
- Bit Diameter measured by in.
- SMSE and DMSE are the surface and downhole mechanical specific energy. These are measured by Kpsi.

Theoretically, the required energy to remove or destroy a unit volume of rock should equal the rock's Confined Compressive Strength (CCS). SMSE trend lines showed a normal trend if the required energy is fully utilized; however, the trend line will show a sudden increase if there is a waste of energy, and this can happen for many reasons; one of them is bit cutters worn out.

On the normal SMSE trend line interval, if torque and WOB graph is generated, it will show a linear relationship, and the slope will start from the origin. But when SMSE has a sudden increase, the slope of torque and WOB slope will be shifted as more WOB is required to see the effect on torque.

On these 12 wells, SMSE was illustrated, and the relationship between torque and WOB was generated.

For Well#1

Figure 10 & Figure 11 show the well#1 drilling and MSE charts; there is an increasing trend in MSE due to bit wearing condition. The sudden increase in MSE events indicates the possibility of having shock and vibration. From MSE deterioration versus depth higher than the extra torque impact indicating bit wearing condition, this condition was also confirmed on the surface, observing bit worn out condition coming at least 1-2 with the higher effect on the outer structure.

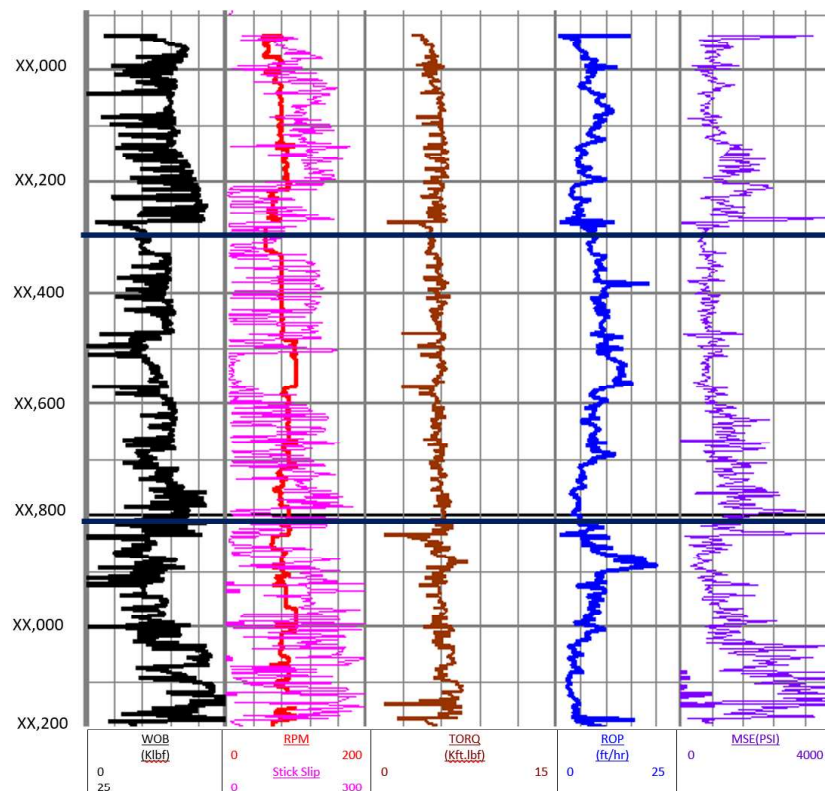


Figure 10 Well#1 Drilling Chart

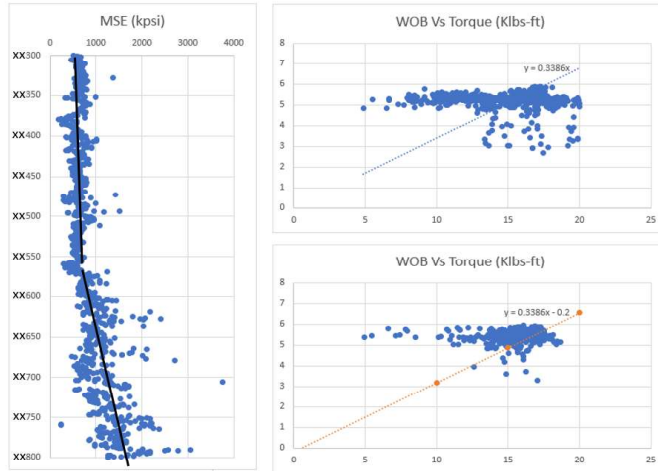


Figure 11 Well#1 MSE Analysis

For Well#2

Figures 12 & 13 show the well#2 drilling and MSE charts, observing the same phenomena on well#1, which happened again on well#2 but with more severity. A significant increase in the MSE trend due to excessive bit wearing conditions was observed. A sudden increase in MSE events indicates possible shock and vibration, negatively impacting ROP.

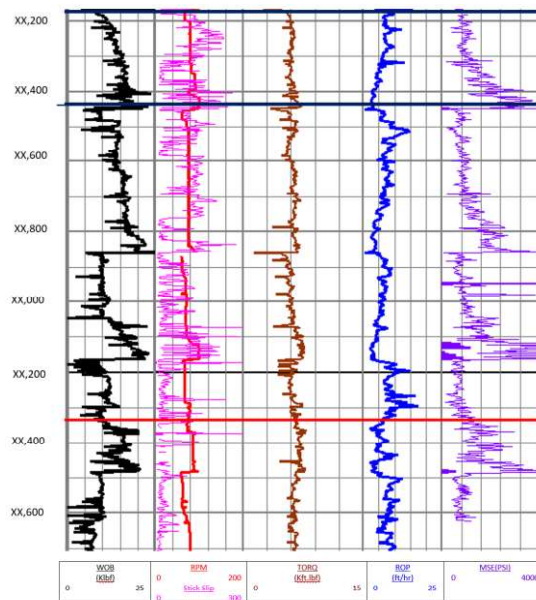


Figure 12 Well#2 Drilling Chart

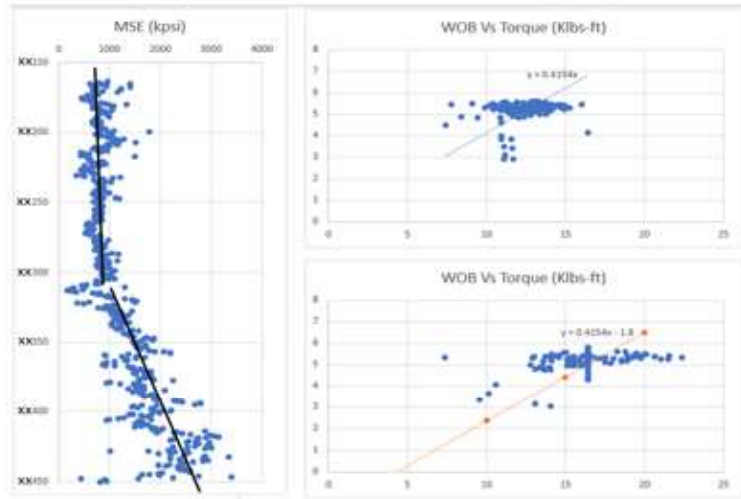


Figure 13 Well#2 MSE Analysis

For Well#3

Figures 14 & 15 show the well#3 drilling and MSE charts, observing MSE following the same behavior as previous wells.

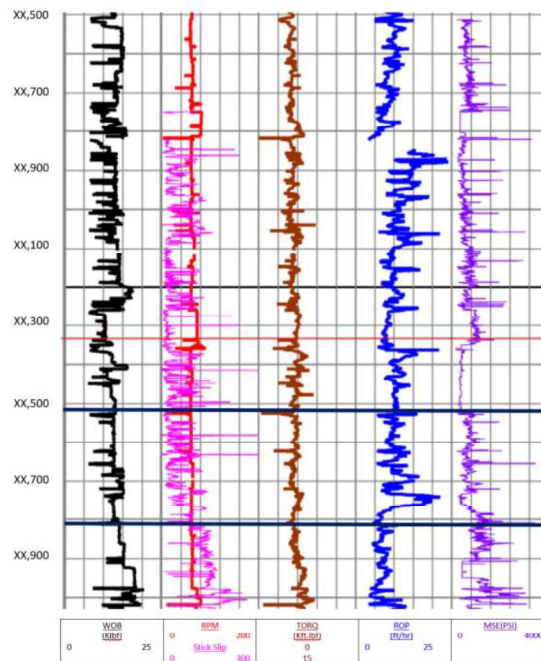


Figure 14 Well#3 Drilling Chart

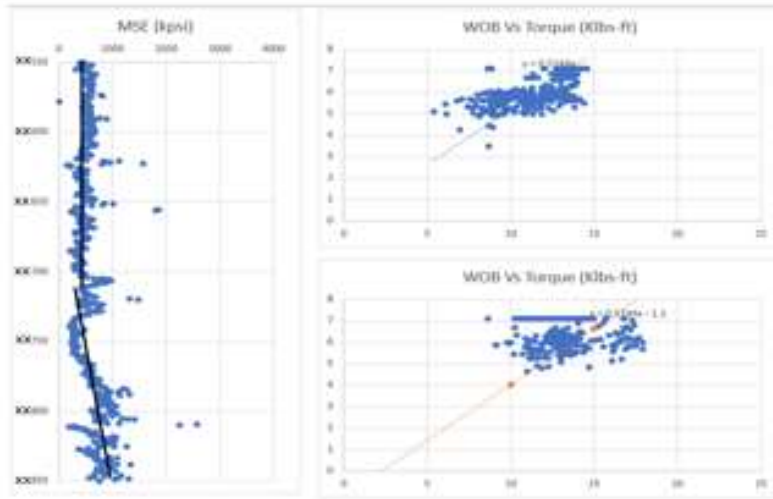


Figure 15 Well#3 MSE Analysis

For Well#4

Figures 16 & 17 show the well#4 drilling and MSE charts, illustrating multiple increasing trends on MSE due to bit wearing conditions. The sudden increase in MSE has indicated the possibility of shock & vibration events.

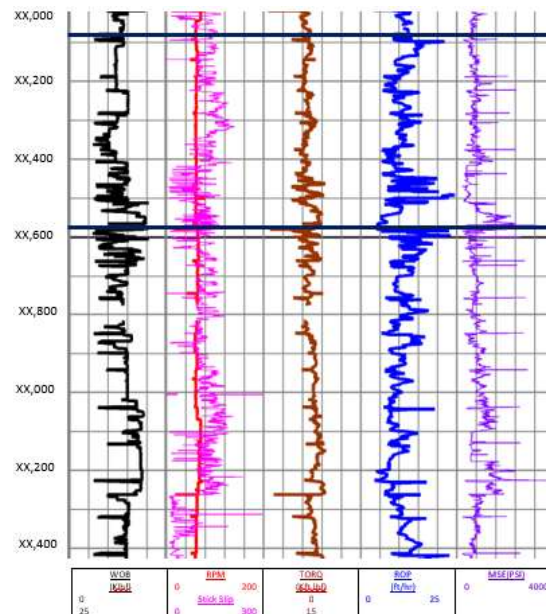


Figure 16 Well#4 Drilling Chart

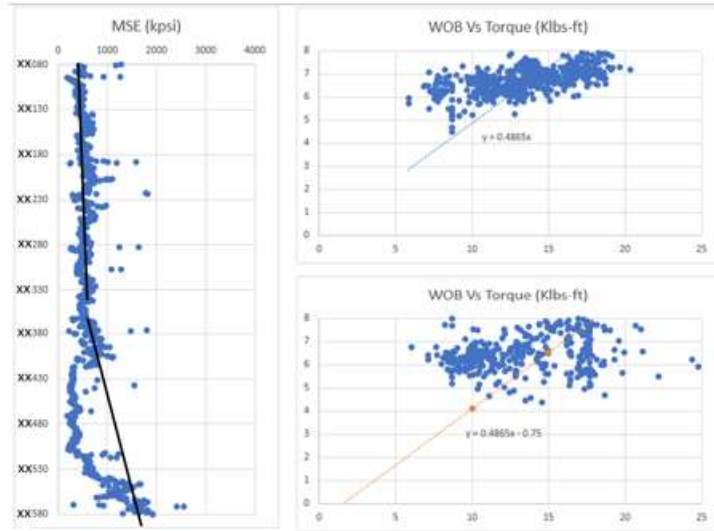


Figure 17 Well#4 MSE Analysis

For Well#5

Figures 18 & 19 show the well#5 drilling and MSE charts, depicting multiple increasing trends on MSE due to bit wearing conditions. The sudden increase in MSE has indicated the possibility of shock & vibration events.

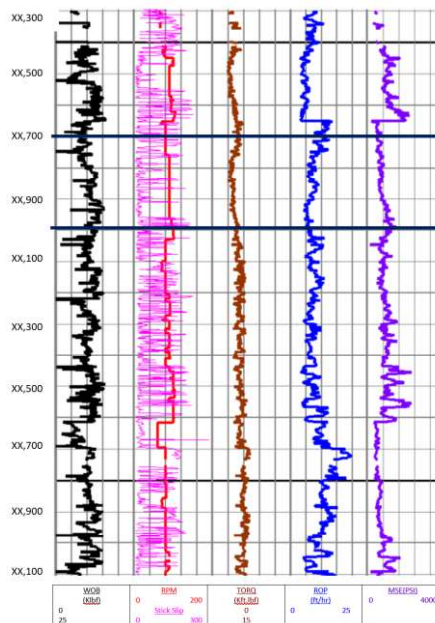


Figure 18 Well#5 Drilling Chart

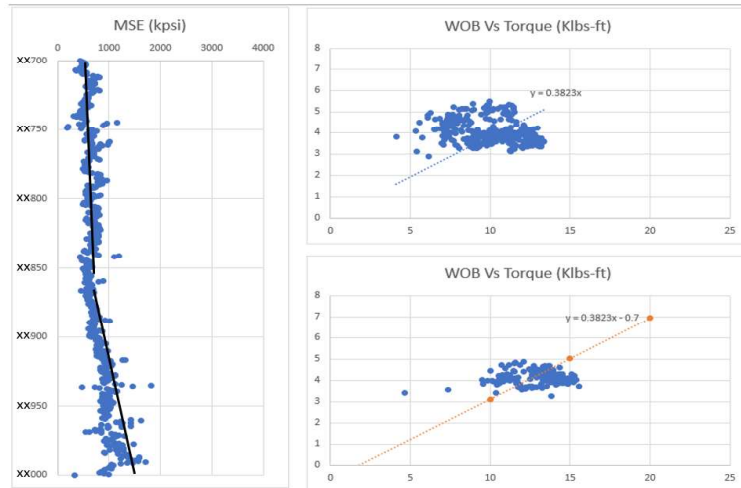


Figure 19 Well# 5 MSE Analysis

For Well#6

Figures 20 & 21 show the well#6 drilling and MSE charts, observing multiple increasing trends on MSE due to bit wearing conditions. The sudden increase in MSE has indicated the possibility of shock & vibration events.

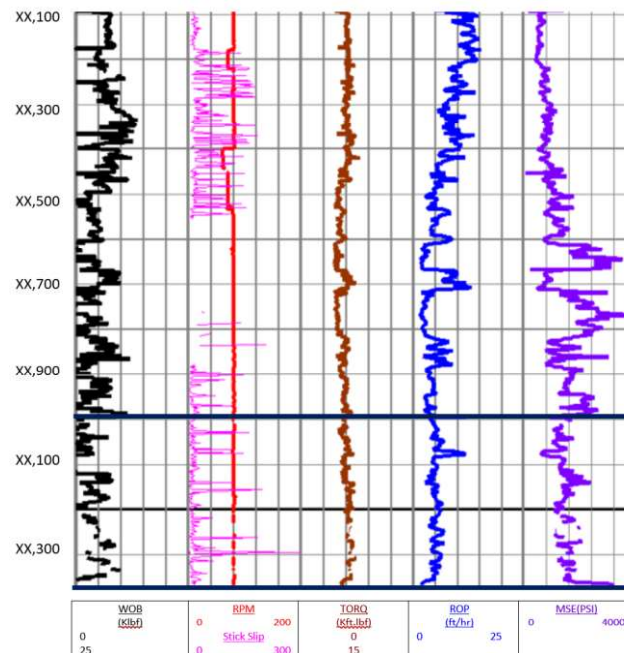


Figure 20 Well#6 Drilling Chart

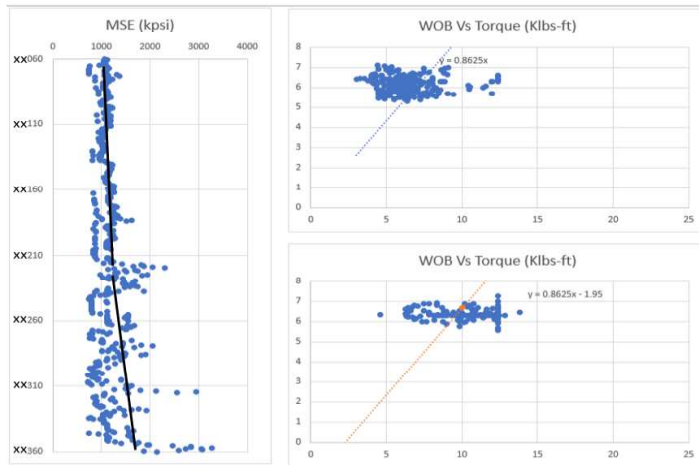


Figure 21 Well#6 MSE Analysis

For Well#7

Figures 22 & 23 show the well#7 drilling and MSE charts, observing multiple increasing trends on MSE due to bit wearing conditions. The sudden increase in MSE has indicated the possibility of shock & vibration events.

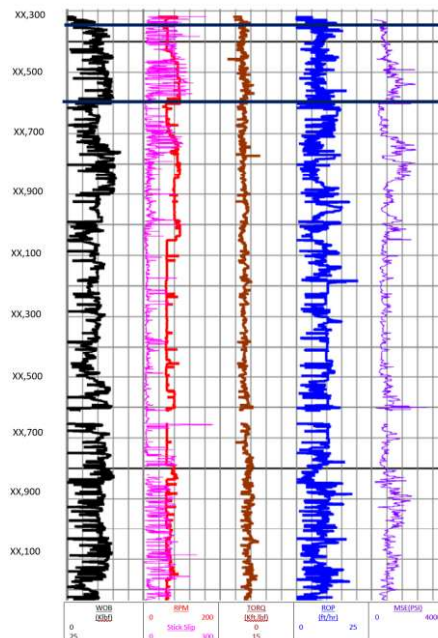


Figure 22 Well#7 Drilling Chart

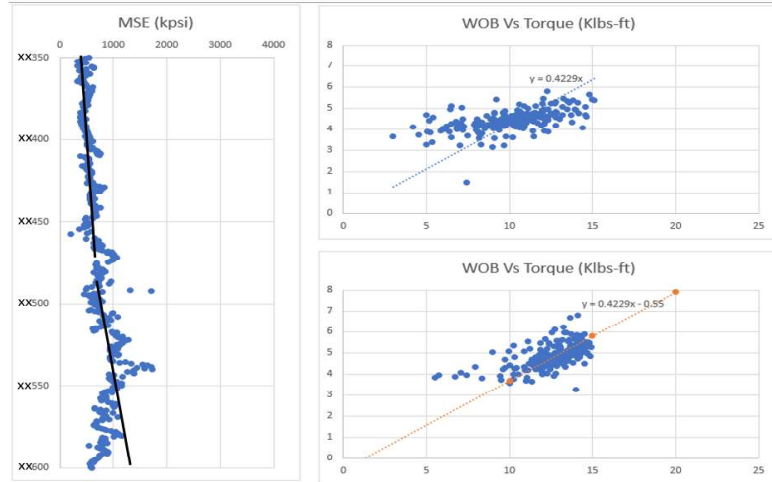


Figure 23 Well#7 MSE Chart

For Well#8

Figures 24 & 25 show the well#8 drilling and MSE charts, illustrating multiple increasing trends on MSE due to bit wearing conditions. The sudden increase in MSE has indicated the possibility of shock & vibration events. Bit deterioration was observed, which was controlled by reducing RPM.

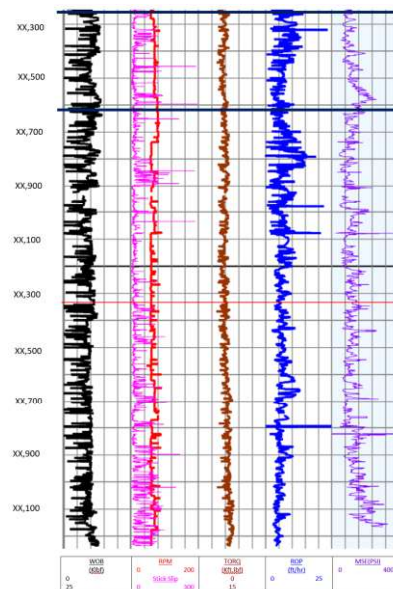


Figure 24 Well#8 Drilling Chart

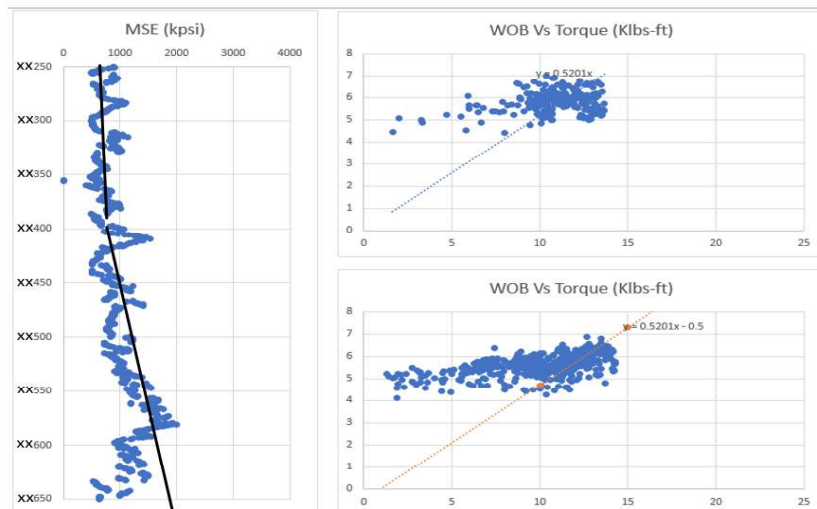


Figure 25 Well#8 MSE Analysis

For Well#9

Figures 26 & 27 show the well#9 drilling and MSE charts, depicting multiple increasing trends on MSE due to bit wearing conditions. The sudden increase in MSE has indicated the possibility of shock & vibration events. Bit deterioration was observed to increase with increased RPM.

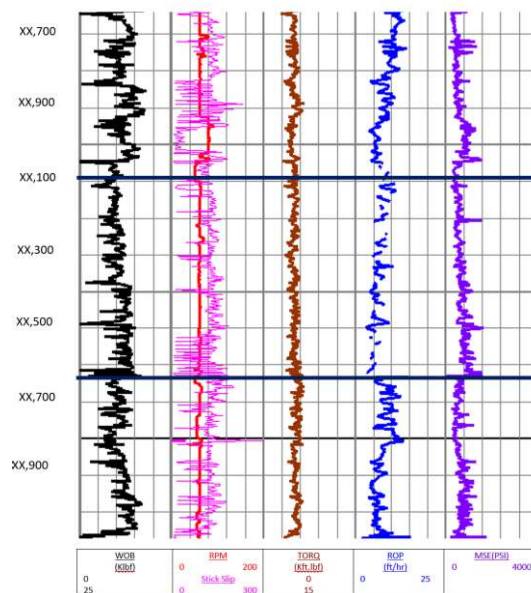


Figure 26 Well#9 Drilling Chart

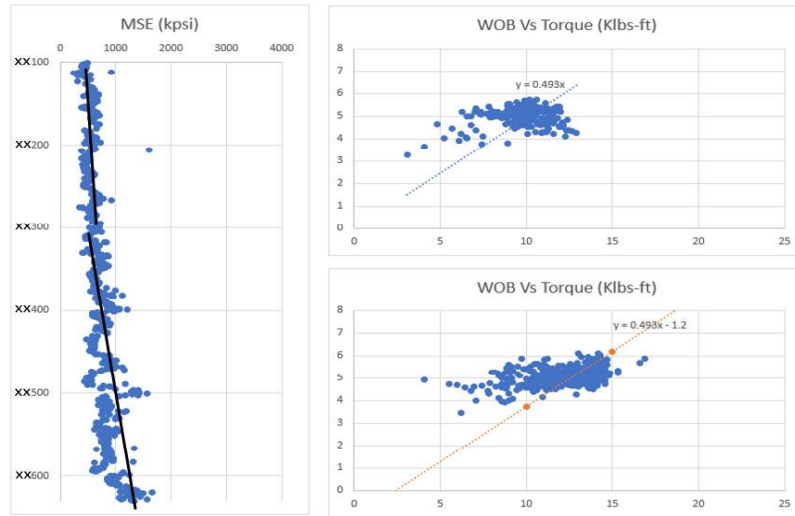


Figure 27 Well#9 MSE Analysis

For Well#10

Figures 28 & 29 show the well#10 drilling and MSE charts, observing multiple increasing trends on MSE due to bit wearing conditions. The sudden increase in MSE has indicated the possibility of shock & vibration events.

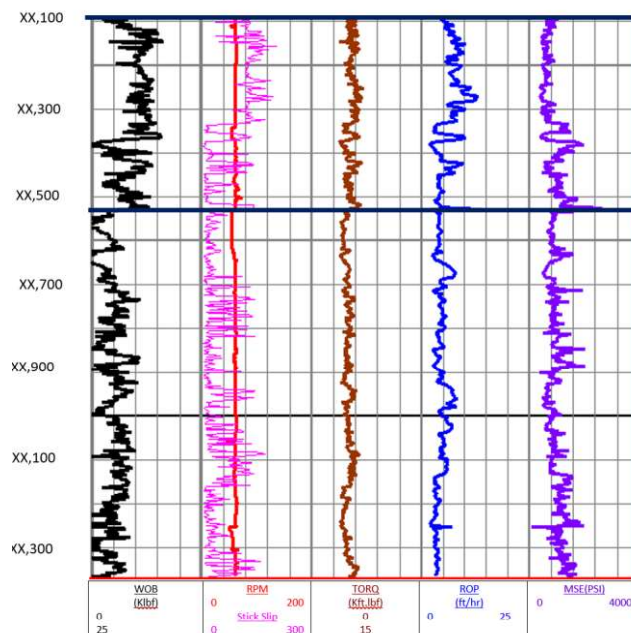


Figure 28 Well#10 Drilling Chart

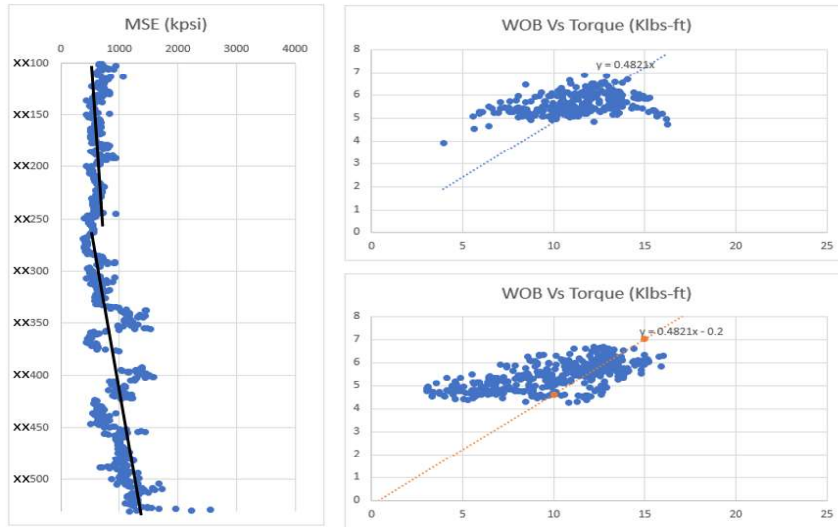


Figure 29 Well#10 MSE Analysis

For Well#11

Figures 30 & 31 show the well#11 drilling and MSE charts, observing multiple increasing trends on MSE due to bit wearing conditions. The sudden increase in MSE has indicated the possibility of shock & vibration events. Some erratic torque happened on the last run bit with a steady MSE level.

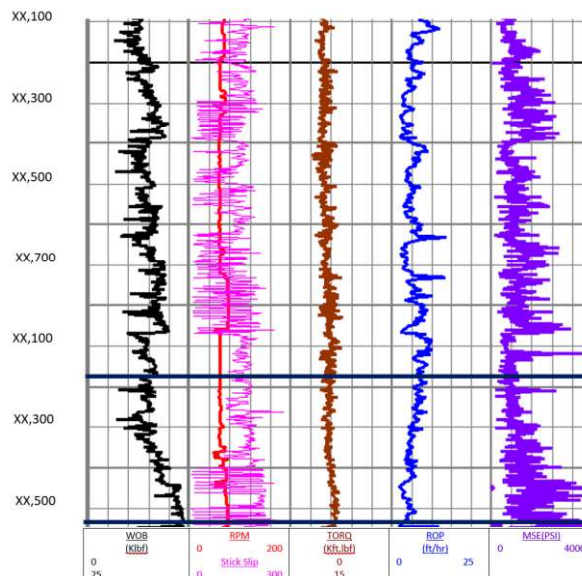


Figure 30 Well#11 Drilling Chart

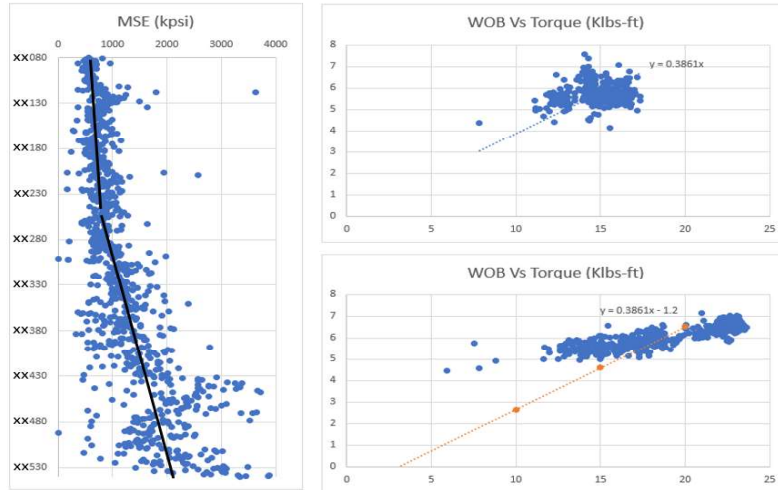


Figure 31 Well#11 MSE Analysis

For Well#12

Figures 32 & 33 show well#12 drilling and MSE charts, depicting multiple increasing trends on MSE due to bit wearing conditions. The sudden increase in MSE has indicated the possibility of shock & vibration events. Torque behavior was improved with mud properties adjustment.

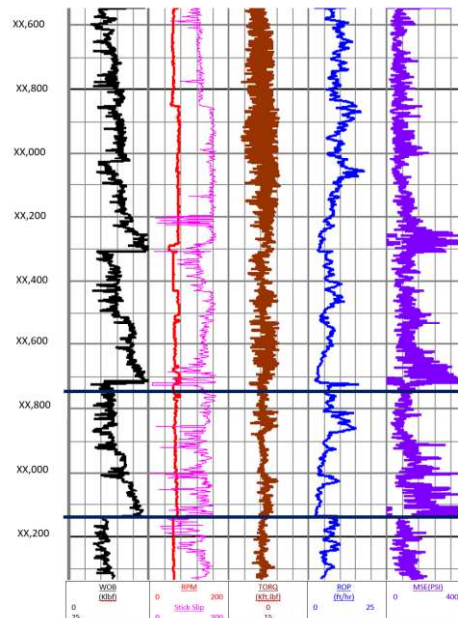


Figure 32 Well#12 Drilling Chart

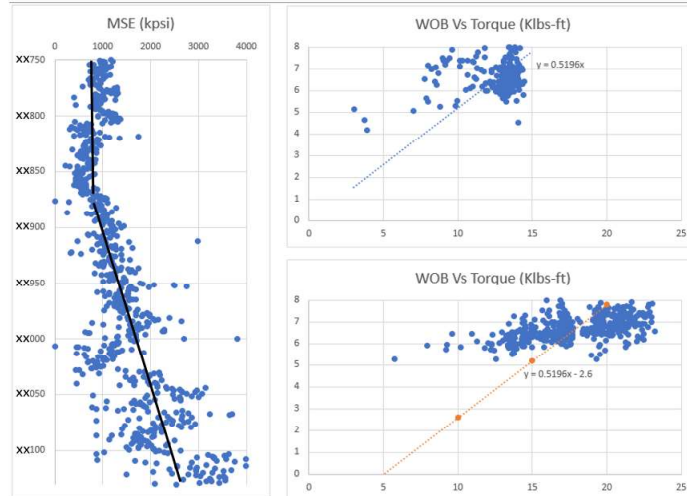


Figure 33 Well#12 MSE Analysis

The evaluation of the historical data allowed us to determine:

1. The average footage per run and average ROP to be used as benchmarking will be 391 ft and 5.84 ft/hr, respectively.
2. The higher bit deterioration occurs in the outer cutters, indicating that the borehole steering action considerably impacts bit durability.
3. The main cutter damage came from bit wear on abrasive formation.
4. The main reasons for pulling out of the hole are penetration rate and downhole tool failure; the key action to improve the performance is to extend the bit life and improve the downhole drilling dynamic environment to improve the directional tool's reliability.
5. The drill string wear condition analysis indicates great shock and vibration across the MWD and LWD tools with a possible drill string whirl condition.
6. The MSE analysis confirmed the complex drilling dynamic environment in terms of shock and vibration by observing a sudden ramp-up in the MSE behavior. At the same time, the MSE trend analysis can be used to determine bit worn conditions.

It is required to collect downhole drilling dynamic data to understand the primary sources of the shock and vibration, which will be the second phase of this research.

4.2 Phase Two: Capturing and Analyzing Down Hole Data from RSS and LWD Tools

The downhole drilling dynamic data was collected and combined with LWD (Logging While Drilling) data in each well described above, getting the following results:

For Well#1:

In this well, as we can see in Figure 34, LWD tools were not planned to be run as well#1 was at the early stage of the project, and therefore no correlation is made between the drilling dynamics and the hole caliper. Figure 34 shows well#2 downhole dynamic data. GR was available for correlation of shock and vibration data.

The rotary steerable's real-time shock and vibration data, presented as SHK Peak (G), indicated that medium-to-high shocks were present during the run. The severity was increasing, correlating with increasing surface WOB to increase the ROP observing an increase in the MSE simultaneously. The sensor to measure the axial shock was not available for this well.

6Stick slip remains high while drilling with an occasional interval of low severity where the low surface parameters were used. Towards the end of the well-observed extremely high MSE and high shock peaks, the ROP was exceptionally low even with the high application WOB reaching up to 25 klpf, indicating tough formation. Finally, the well TD was called.

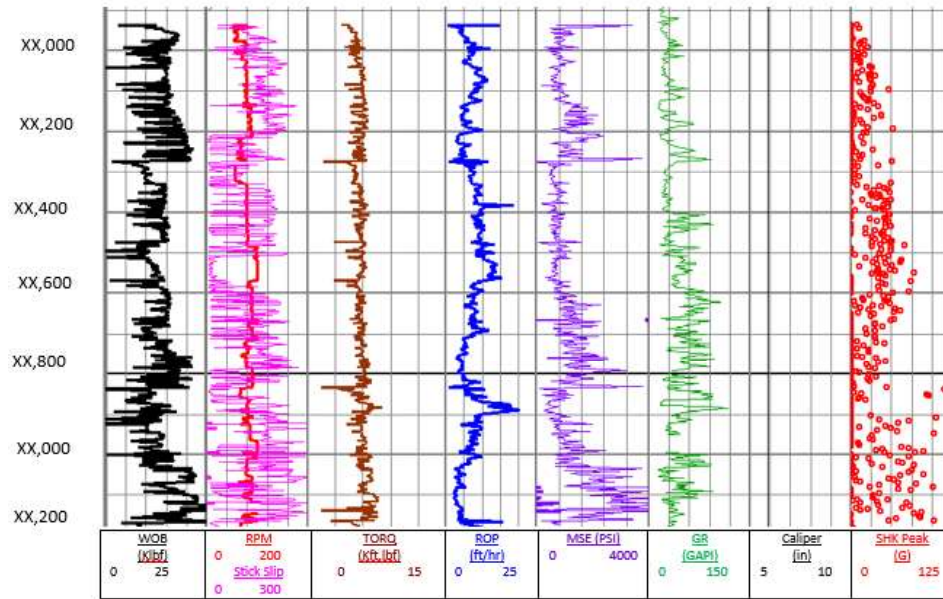


Figure 34 Well#1 Downhole Dynamic Data

For Well#2:

In this well, LWD tools were not planned to be run as well#2 was at the early stage of the project, and therefore no correlation is made between the drilling dynamics and the hole caliper. Figure 35 shows well#2 downhole dynamic data. In this well, high stick slip was seen during the initial interval drilled with the first two runs; stick slip severity was reduced in the 3rd run. While drilling, runs 4 & 5 recorded a low level of stick slip. No abnormal torque fluctuations were recorded.

Shock peaks on the rotary steerable follow the stick slip and remain at a medium level during the first two runs and were low for runs 3, 4, and 5. Still, we can see an increase in the shock peaks towards the end of each run where the WOB was high before a bit trip, having a significant increasing trend on the MSE. The sensor to measure the axial shock was not available for this well.

The drastic decrease in ROP and increase of the MSE at the end of each run combined with

a sudden shock peak demonstrated that LWD data was required to analyze the source of vibration properly; for that reason, all the upcoming wells' LWD data was included.

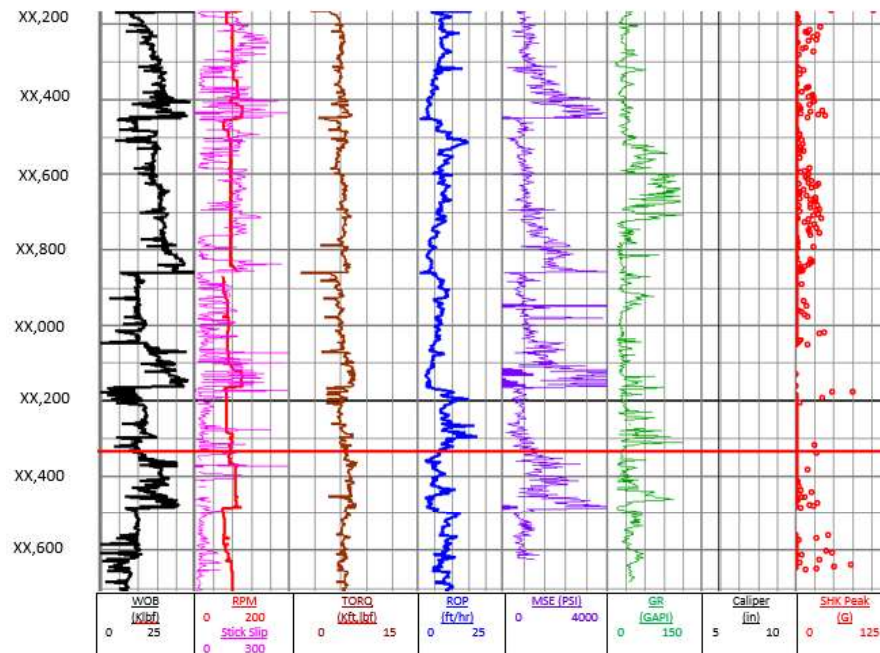


Figure 35 Well#2 Downhole Dynamic Data

For Well#3:

The homogeneous formation was mostly seen while drilling this well; whoever observed some increase in GR on some intervals, as shown in Figure 35. During drilling this well, the stick slip severity was low.

Steady WOB was applied on this well during drilling. On this well, LWD data was available. LWD, image data, and hole caliper correlate with the drilling dynamics. The hole was mostly enlarged for the first 2/3rd of the interval, and shock peak correlation can be seen across the transition zones and around the breakout area confirmed in the image log. Axial shock peaks were also recorded at the interval where lateral shocks were seen, along

with intermittent stick slip peaks recorded by the MWD tool.

No shocks were recorded by the rotary steerable system across the in-gauge hole towards the TD of the well.

A clear relation between formation breaks out and lateral shock peak increase is visible in this well. However, it does not impact MSE, being the most significant contributor to MSE increase the bit worn-out condition.

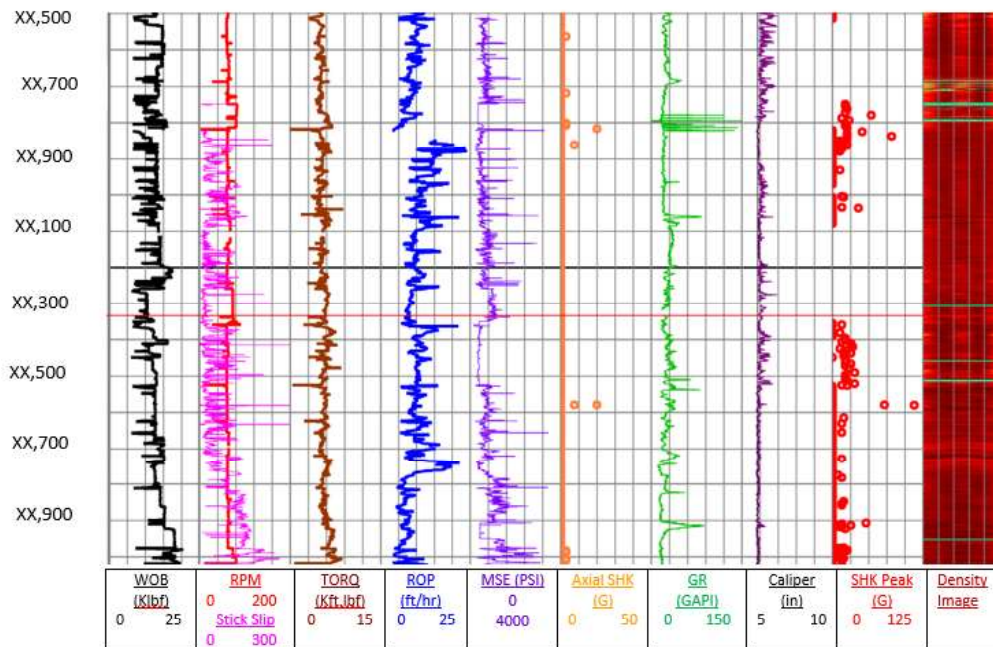


Figure 36 well#3 Downhole Dynamic Data

For Well#4:

Three BHA runs were used to drill this well. Figure 37 shows high to medium level stick slip being recorded throughout drilling. A normal torque trend was observed.

WOB for all drilling runs was started low; an increase in the WOB was observed before the BHA was pulled for the change-out bit. In the current well, there is a correlation between the increase in WOB and the shock peaks to some extent but not throughout the

well, as WOB was high in the interval where the breakout is seen.

The shock peaks have a clear correlation with the increase in the hole caliper, which is seen in the image log due to formation failure. There is also variation in the GR in the same interval indicating a transition zone. The severity of shock peaks goes very low across the gauge hole and in the homogenous layer.

A low level of axial shock peaks was recorded during this well.

In this well, the relation between WOB, MSE, and shocks is visible, proportional to each other.

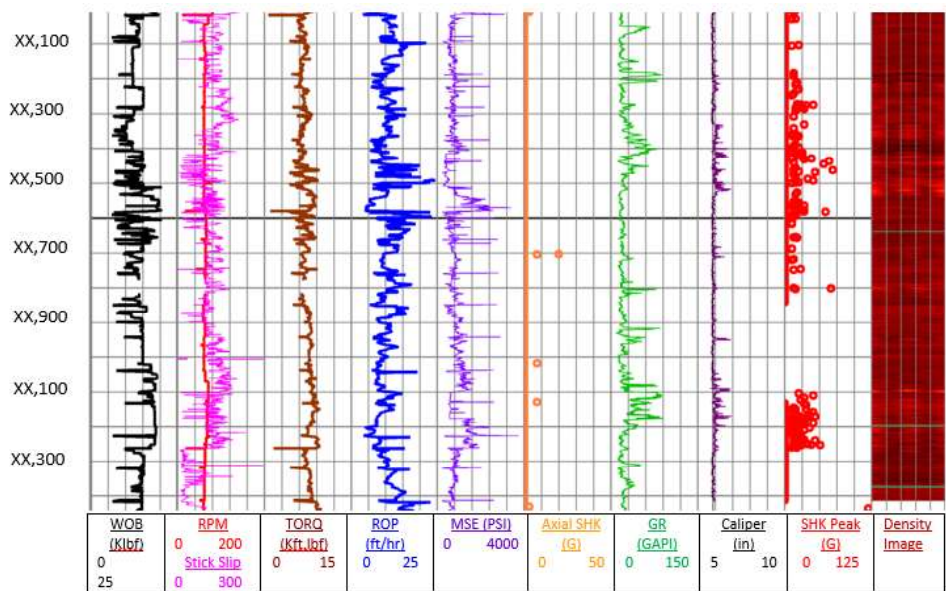


Figure 37 well#4 Downhole Dynamic Data

For Well#5:

While drilling this well, as shown in Figure 38, the stick slip had a varying behavior and did not correlate with the drilling parameters or the GR. This indicates the lithological changes which GR can not identify. The stick slip severity varies from low to medium in

the well and across certain intervals from medium to high.

Variation in the drilling parameters WOB and RPM indicates that the mitigation was done to reduce the severity of the stick slip and reduce the shocks as recorded by the rotary steerable system.

The Shock peaks correlate with the hole caliper and hole breakouts, as identified by the image data. We can see an increase in the shock peak registered by the rotary steerable system across depth intervals where breakouts are seen and no shock peaks across the in-gauge hole where the image data shows a good hole. No Axial shock peaks were recorded during this well.

Related to MSE, there is a clear relationship between formation break out, MSE, and shock and vibration increase.

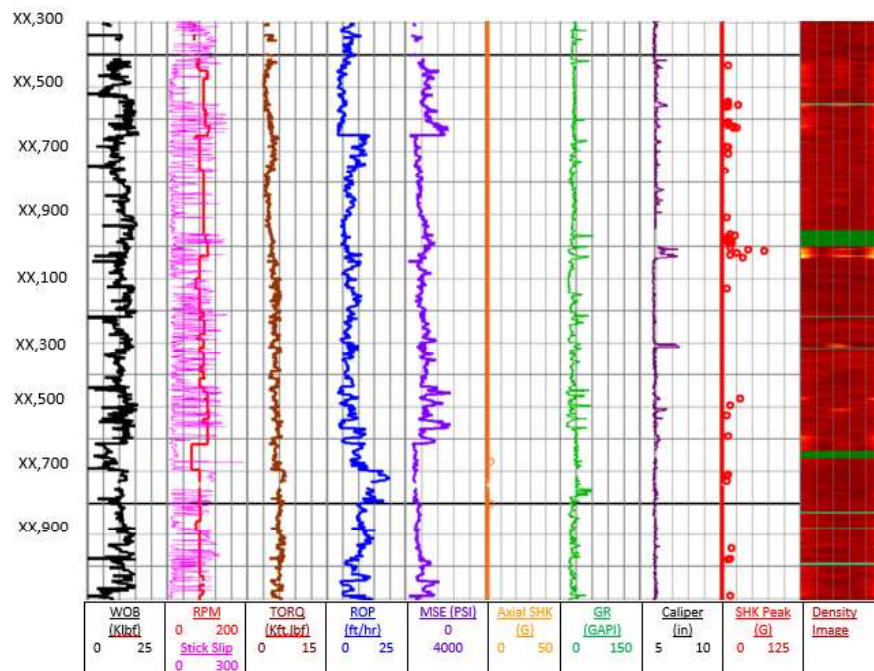


Figure 38 well#5 Downhole Dynamic Data

For Well#6:

At the beginning of the drilling of this well lateral, as per Figure 39, we can see a gauge hole with no indication of hole breakouts, where maximum drilling parameters were applied to achieve good ROP. Then the ROP started to drop, getting close to a transition zone based on the roof failure, which was observed on the density image. After that, for some unknown reasons, image data is not available.

While drilling almost halfway, an increase in hole caliper can be seen. Also, image data shows breakouts which resulted in shock peaks as recorded by the rotary steerable system. This phenomenon can be seen almost till the end of the well. During this interval, drilling parameters were controlled for drilling dynamics mitigation, which was very effective. However, this resulted in an overall ROP reduction.

There is only one interval where the axial shock peaks were recorded; the rest of the well drilling dynamics were low.

Stick slip varied between high and low during the first half of the well and was low for the rest of the section. In the end, the hole becomes in the gauge, and the shock and vibration reduction in this interval can be seen.

Related to MSE, there is considerable footage drilled in the middle of the lateral with high MSE, where a high lateral shock peak is observed.

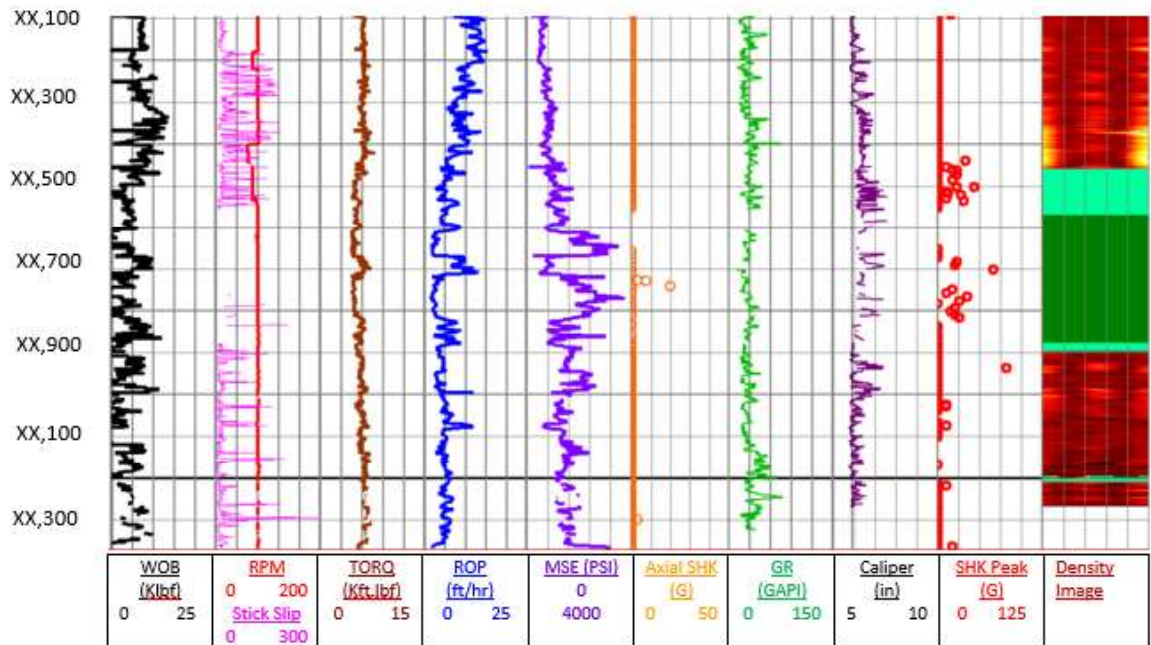


Figure 39 well#6 Downhole Dynamic Data

For Well#7:

This well as evident in Figure 40, showed medium to high stick slip and no shocks with the increase in WOB; a recording of the shock peaks by the rotary steerable tool can be seen.

Afterwards, with changes in the formation as indicated by the GR, observed a reduction in S&V level. The middle part of this section shows breakouts in image data and an over-gauge hole as indicated by the caliper, where the shock peaks increase.

There was only a single event of axial shock peak throughout this well, even with multiple BHA runs.

The last 1/3rd of the whole section was drilled with the low stick slip and with low shock peaks where no over-gauge hole or breakouts on the image data was recorded.

The relationship between lateral shock peak, increase in MSE, and formation break out is

remarkable in this well.

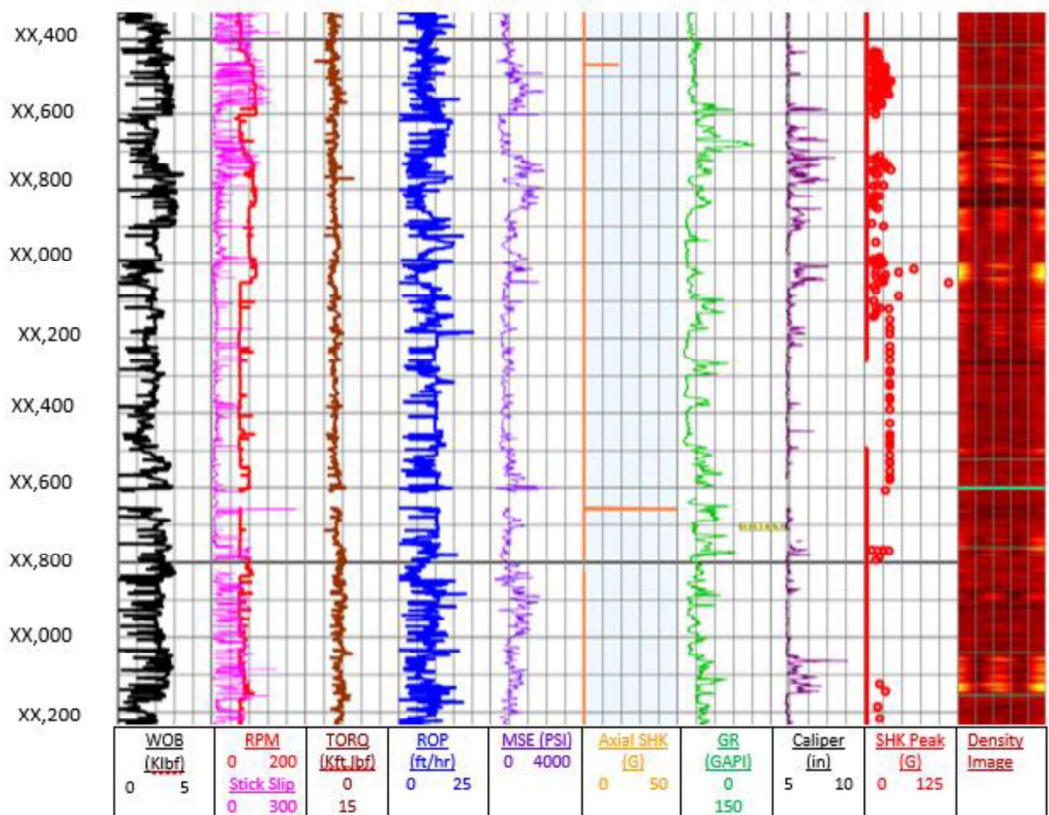


Figure 40 Well#7 Downhole Dynamic Data

For Well#8:

The observed stick & slip are low to medium level in this well, as shown in Figure 41. The drilling parameters were consistent with optimizing the ROP. WOB was varying following the GR variation.

Shock peaks recorded were of low level and followed the hole enlargement as indicated by the increased hole caliper and borehole breakouts as seen in the image data. This correlation is like wells, confirming that the borehole deterioration related to breakout or roof failure has a considerable impact on the drilling dynamic. A low level of axial shock peaks was recorded during this well.

There is no clear relationship between lateral shock peak, break out, and MSE as observed in other wells; the MSE increase looks mainly related to bit deterioration.

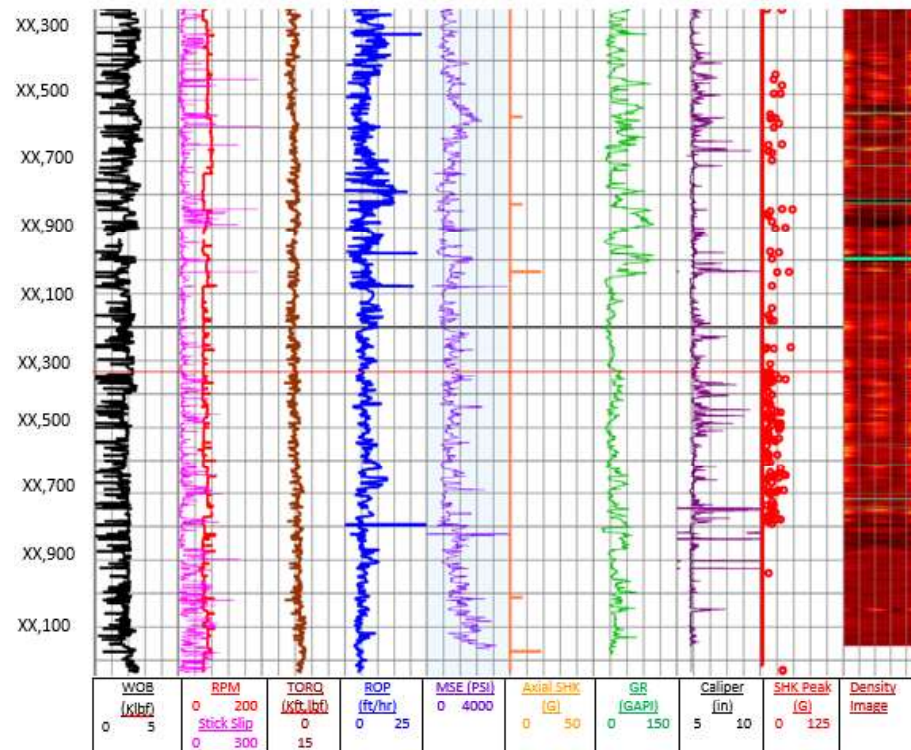


Figure 41 Well#8 Downhole Dynamic Data

For Well#9:

This well in Figure 42 showed severe stick slip during almost all the sections, and GR was at a low level, mainly indicating homogenous layers were drilled. The parameters were applied varied to mitigate the stick slip severity. No Axial shock peaks were recorded during drilling. Observed fewer breakouts or hole enlargement. Shock peaks follow the same trend; they appear where certain levels of breakouts are recorded as per image data. Towards the end of the well, continuous shocks were recorded in a gauge hole; however, high WOB application and low ROP indicated tough formation. There is no relationship between lateral shock peak and MSE for this well; the MSE increase is mainly associated

with bit deterioration.

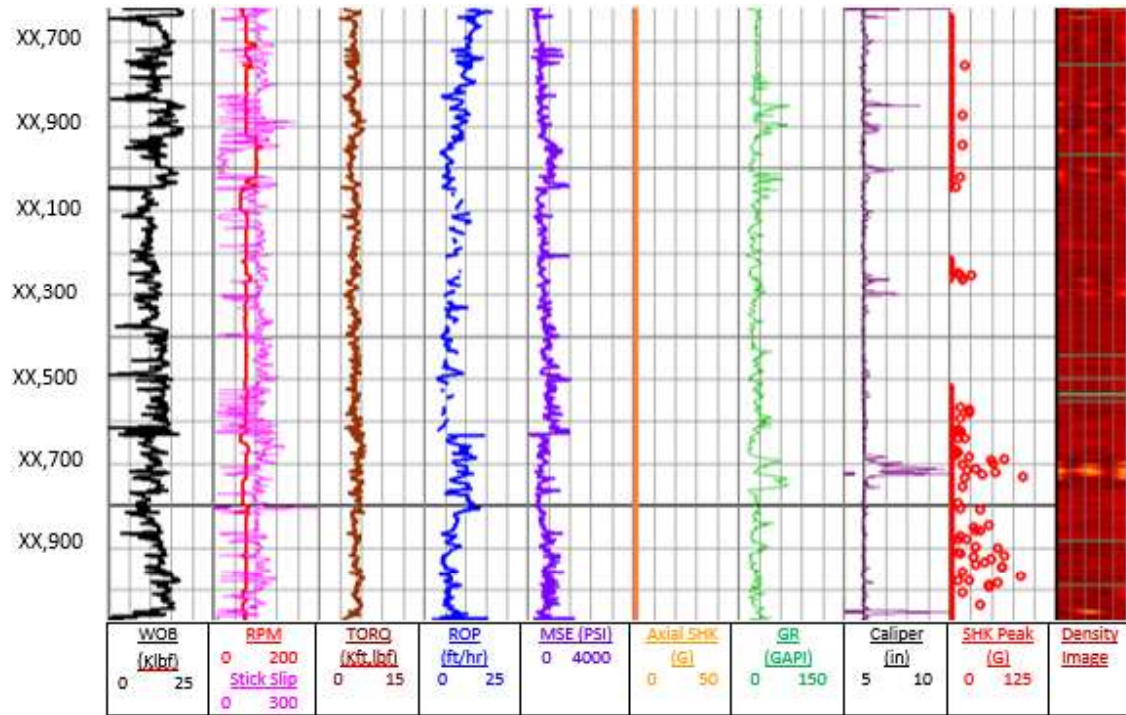


Figure 42 Well#9 Downhole Dynamic Data

For Well#10:

While drilling this well, as shown in Figure 43, a high stick slip was observed, and later in this section, the stick slip was reduced and was at a low to medium level.

The shock peaks as recorded on the rotary steerable system were extremely low. They were only recorded across the enlarges interval as seen in caliper data or across the hole breakout interval on the image log.

Throughout this section, overall, shallow drilling dynamics were seen. One reason was that no hole enlargement was seen during this well and only at the end of the well where a small breakout zone was observed. The drilling parameters were optimized, having the shock and vibration within an acceptable level

It can be observed a relationship between formation break out, lateral shock peak, and MSE.

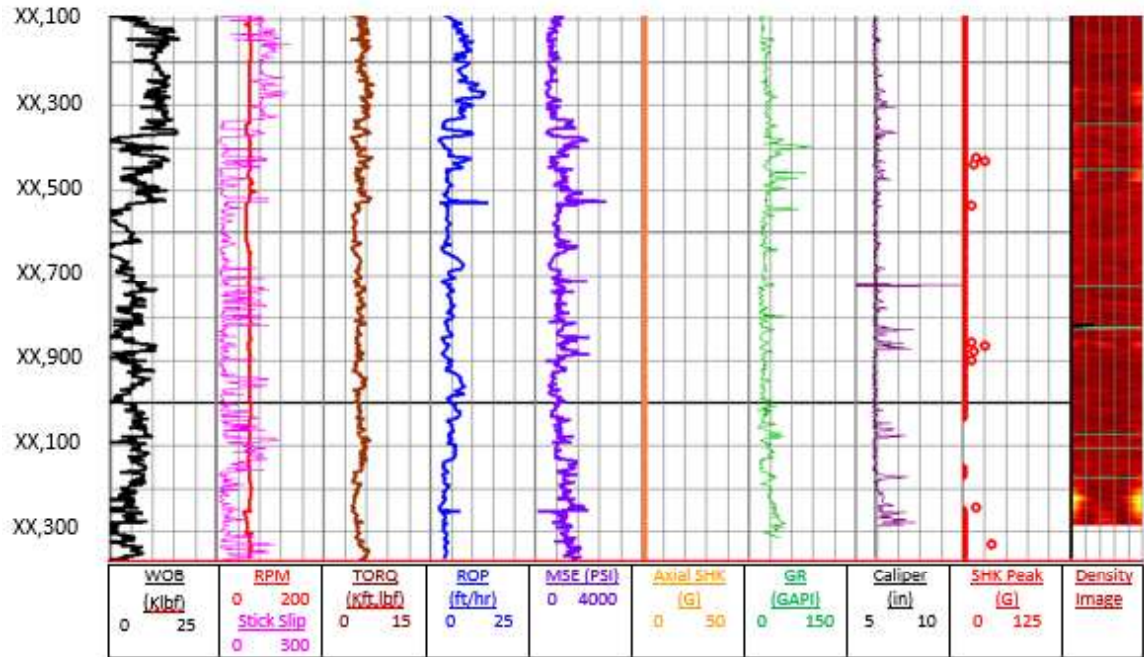


Figure 43 Well#10 Downhole Dynamic Data

For Well#11:

While drilling this well, as shown in Figure 44, recorded very high stick slip regardless of varying the WOB or RPM. ROP was very low on this well.

GR shows primarily flat with minor variation, potentially indicating some transition within the formation. Caliper data indicates that mostly the section was in gauge, with minor enlargement across the GR peaks. Image data shows little breakouts, and the rotary steerable system recorded shock peaks across this interval. The density data showed a high-density formation drilled in this well compared to the offset wells. This indicates the onset of vibration in high-density formation even with minor breakouts across the formation drilled.

Axial shocks were seen during this well, potentially correlating with the bed boundaries indicated in the image log.

Related to MSE behavior, only a relationship with the bit deterioration requiring an increase on the WOB can be observed. There is no clear impact of the lateral shock peak on the MSE.

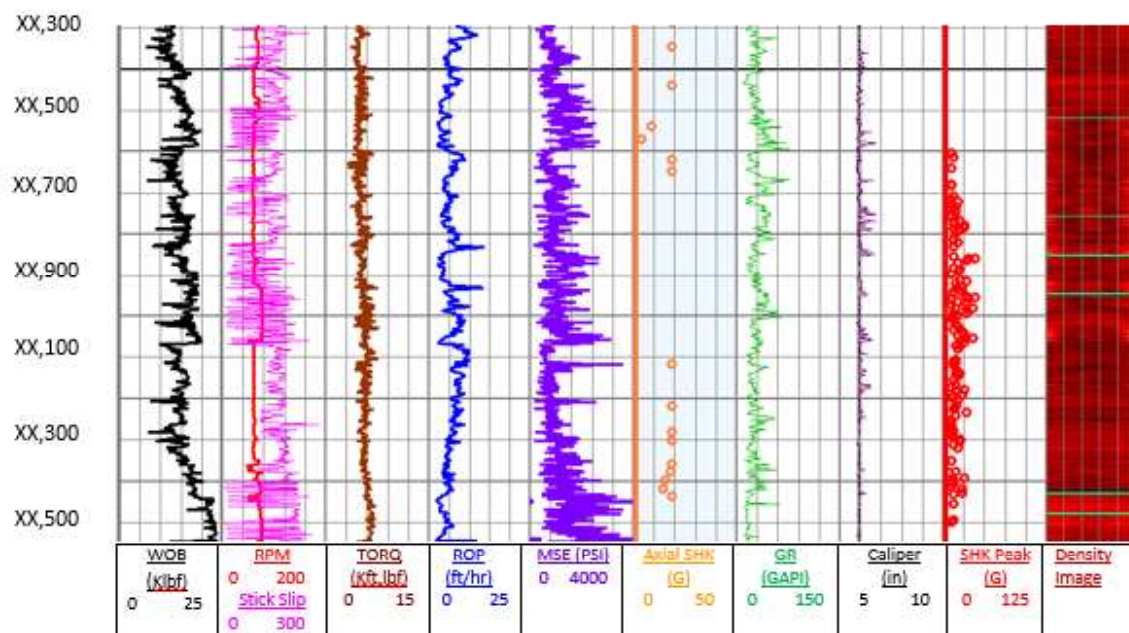


Figure 44 Well#11 Downhole Dynamic Data

For Well#12:

This well was showed high stick slip and very high torque fluctuation, as shown in Figure 45. Caliper showed in gauge hole with almost no hole enlargement. We can see a correlation between shock peaks across transition within the density image data.

Comparing the increased WOB with the image data and shock peaks shows a fair correlation with the onset of shocks while drilling with the high WOB, specifically due to a reduction in the ROP.

The main contribution of the bit deterioration requires a higher WOB on the MSE increasing trend behavior.

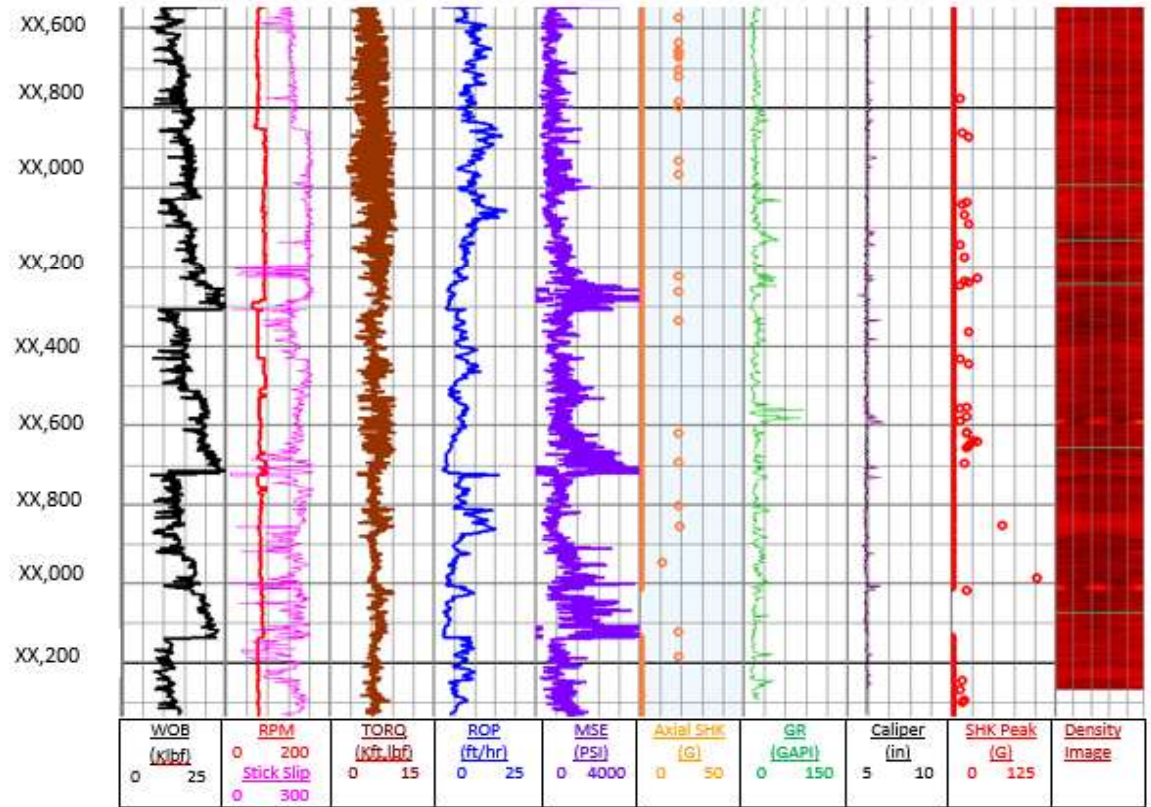


Figure 45 Well#12 Downhole Dynamic Data

4.3 Phase Three: Selecting Optimum Drill String and BHA Design Using Frequency and Transient Models

To understand the primary drilling dynamic environment faced while drilling, transient simulation was used. It was calibrated using vibration data which was obtained on these 12 wells.

4.3.1 Transient Simulation

A transient simulation is a finite element analysis. It was used to understand the complete drilling dynamic environment encountered while drilling to determine the best BHA design

to minimize shock and vibration risk across the entire BHA. The environmental conditions used for the simulation are described below in table 5.

Table 5 Wells Data

Formation characteristics	Abrasive sandstone formation with more than 70% quartz, high abrasive strength, and 25-30 kips unconfined compressive strength (UCS).
Wellbore geometry consideration	It is based on caliper data obtained from previous wells drilled.
Mud type	Oil Base Mud (OBM) with MW between 95-100 PCF
Lateral length	2000 ft lateral measured depth length
Inclination	87-90 degree
Flow rate	200 – 250 gpm
WOB	5 – 20 Klbs
RPM	60 – 140 rpm
Bit characteristics	PDC, 6 blades with 13 mm cutter having 3 nozzles of 13
Friction factor	0.22 for cased hole condition and 0.33 for open-hole condition
Stabilizer configuration	loaded considering standard industry-recognized size for the three types of stabilizers which are: String stabilizer (Normal integral steel stabilizer) In-line stabilizer called ILS (Non-mag stabilizer with extender connection placed between tools) LWD stabilizer (Non-mag stabilized incorporated on directional tools)

The standard BHA, which has been used on 12 historical wells, is described in table 6:

Table 6 Standard BHA

Description	OD	Length
Bit	5.875	0.69
RSS Stab	5.750	18.10
MWD	5.250	33.55
5 ¾" ILS	5.750	2.50

LWD Stab	5.750	25.50
Pony NMDC	4.750	15.00
4" HWDP	4.000	91.60
Jar	4.750	30.90
4" HWDP	4.000	61.64
4" DP	4.000	7974.11
5 ½" DP	5.500	Surface

The steps were followed as follows:

1. Basic Model Simulation (Simulation input & output):

- ✓ Load the BHA, wellbore geometry, survey, mud properties, and select the generic rock characteristic based on petrophysical data provided.
- ✓ Run the simulation using the average values from the 12 wells' historical data for WOB, RPM & flow rate. Average WOB (16 klbs), RPM (80 rpm) & flow (240 GPM).
- ✓ The simulation output will give the ROP & shocks vibration data.

2. Model Calibration (Simulation new input & target output):

- ✓ Compare the basic model simulation results with the shocks and ROP observed on historical data.
- ✓ Adjust the rock properties to get simulation output ROP(7ft/hr), shock behavior (25 G's), and S&S (30%) similar to the historical data.

3. Determine the optimum parameter for historical wells BHA

- ✓ Run using the calibrated model, a sensitivity analysis considering a range of WOB and RPM. WOB ranges (5-20 klbs), RPM ranges (60-140 rpm),

and flow rate ranges (200-250 GPM)

- ✓ Determine the optimum parameters (best WOB and RPM combination; 18 klbs WOB & 120 RPM this is will give the following 10 - 25 G's lateral vibration & 31-37% S&S)
- ✓ Plot the BHA behavior using the best parameters.

4. BHA Optimization:

- ✓ Modify the BHA by adding a stabilizer at the high lateral vibration position (+/- 100 ft from bit depth)
- ✓ Run using the calibrated model, a sensitivity analysis considering a range of WOB and RPM. WOB ranges (5-20 klbs), RPM ranges (60-140 rpm), and flow rate ranges (200-250 GPM)
- ✓ Determine the optimum parameters (best WOB and RPM combination; 18 klbs WOB & 80 RPM this is will give the following 8 - 16 G's lateral vibration & 18-19% S&S).
- ✓ Plot the BHA behavior using the best parameters.

Results:

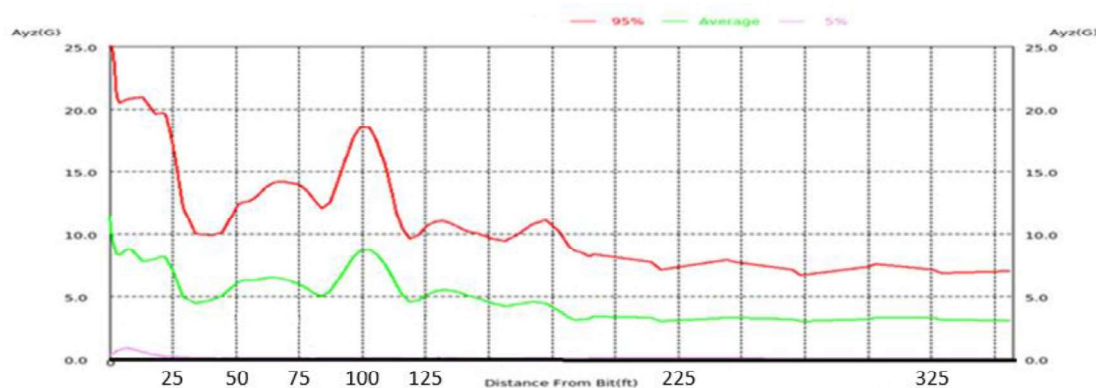


Figure 46 Lateral Vibration With Standard BHA

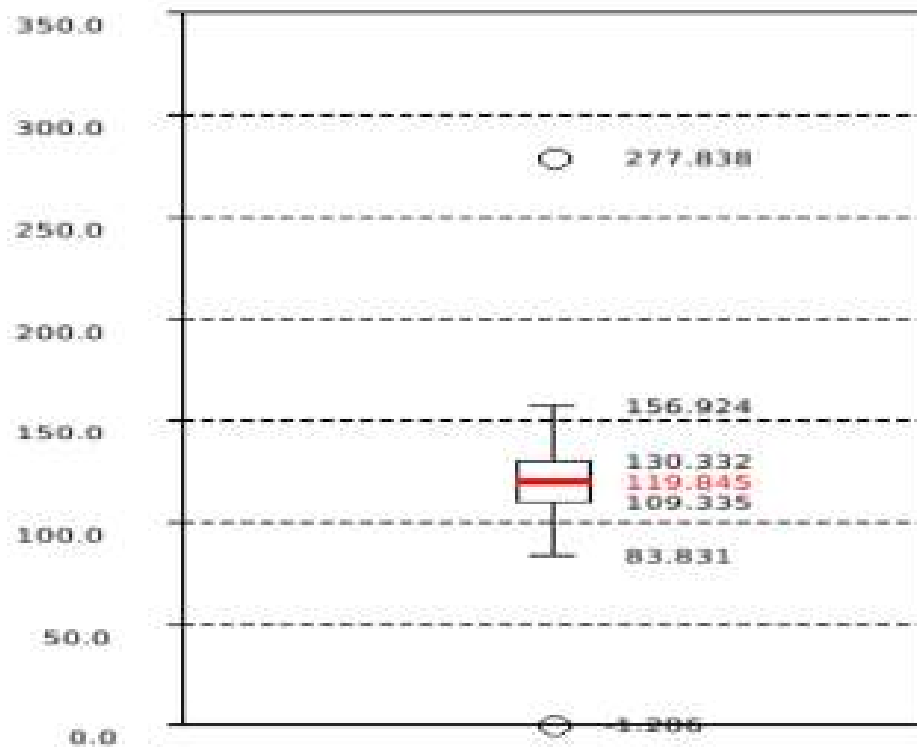


Figure 47 Depth In Stick & Slip (31% @ 119.84 RPM)

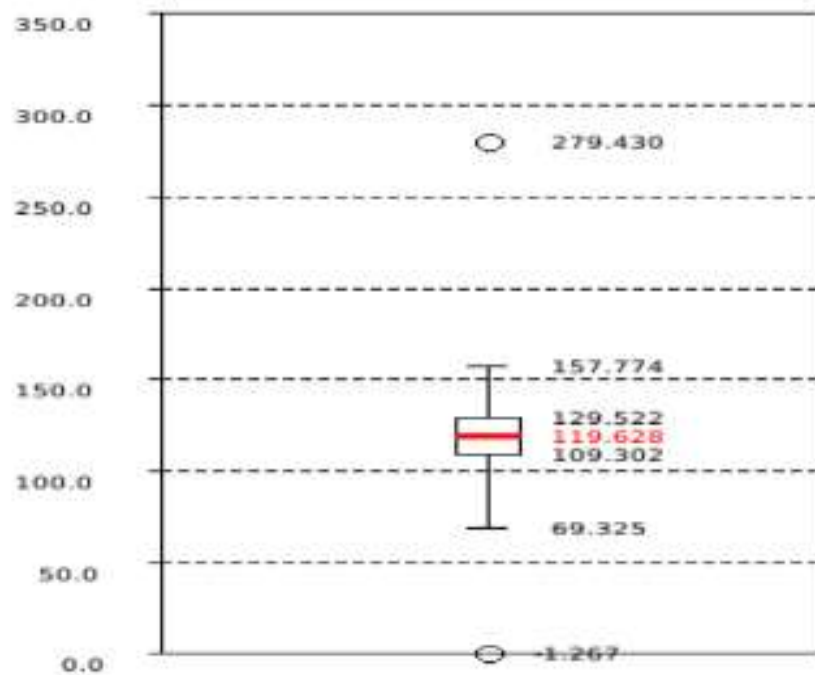


Figure 48 Depth Out Stick & Slip (37% @ 119.84 RPM)

The simulation showed the best combination of parameters for this BHA, 18 Klbs with 120 rpm, giving a maximum level of lateral vibration of 10-25 G's and a stick-slip level between 31-37%.

From the historical data analysis, this BHA has the following performance controllers:

- ✓ The recommended RPM to mitigate vibration is reducing the bit life (this is observed in some runs, where the RPM was increased for better performance; however, this is causing to pull out of the hole due to a premature bit worn out).
- ✓ The vibration level is not at an optimum level, reducing directional tool life.

The previous used BHA was modified by adding a string stabilizer close to 100 ft away from the bit, where a high pick of lateral vibration can be observed for the following reasons:

- ✓ To reduce the magnitude of the lateral vibration
- ✓ Minimize the risk of BHA whirl, reducing at the same time the stick and slip level
- ✓ Open the operating window in terms of RPM, looking for smooth drilling conditions with lower RPM, which will extend the bit life

The new BHA configuration proposed was described below

Table 7 Proposed BHA

Desc.	OD	Length	Cum. Length
Bit	5.875	0.69	0.69
RSS Stab	5.750	18.10	18.79
MWD	5.250	33.55	52.34
5 3/4" ILS	5.750	2.50	54.84

LWD Stab	5.750	25.50	80.34
Pony NMDC	4.750	15.00	95.34
5 5/8" Stab	5.625	4.50	99.84
4" HWDP	4.000	91.60	191.44
Jar	4.750	30.90	222.34
4" HWDP	4.000	61.64	283.98
4" DP	4.000	7974.11	8258.09
5 1/2" DP	5.500	Surface	

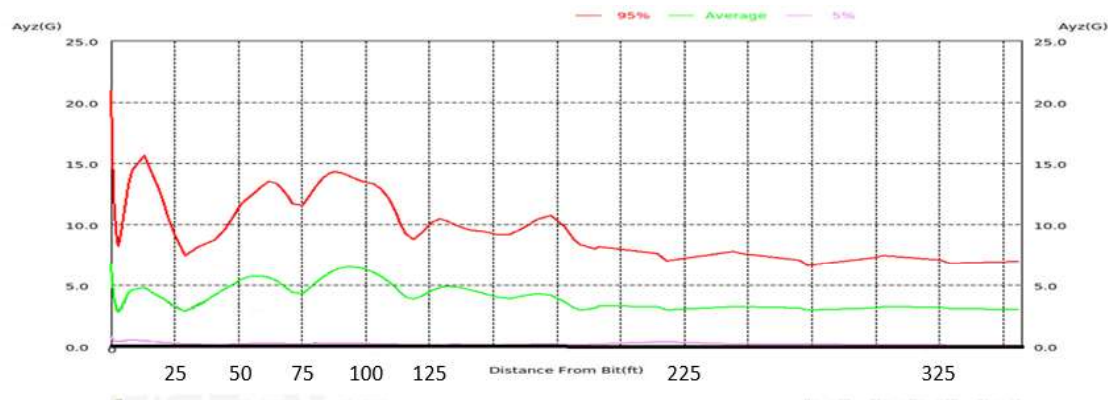


Figure 49 Lateral Vibration with Proposed BHA

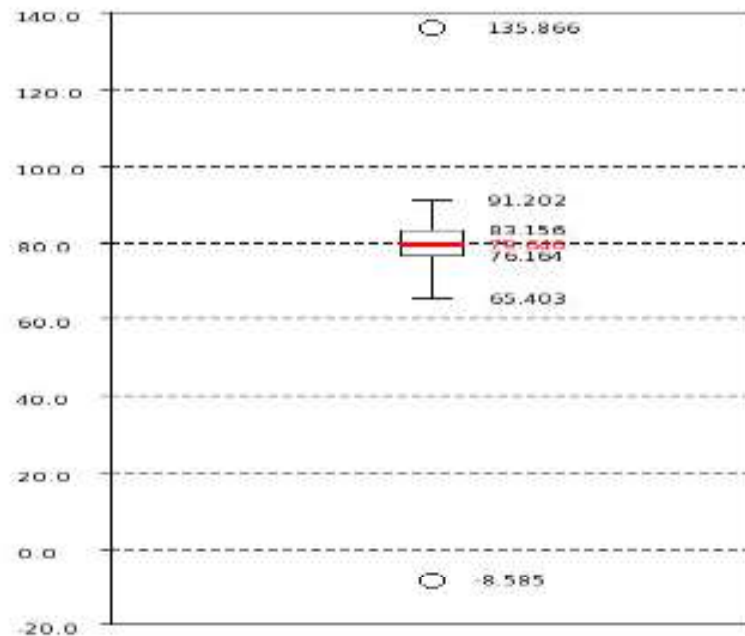


Figure 50 Depth In with Proposed BHA Stick & Slip (18.7% @ 79.64 RPM)

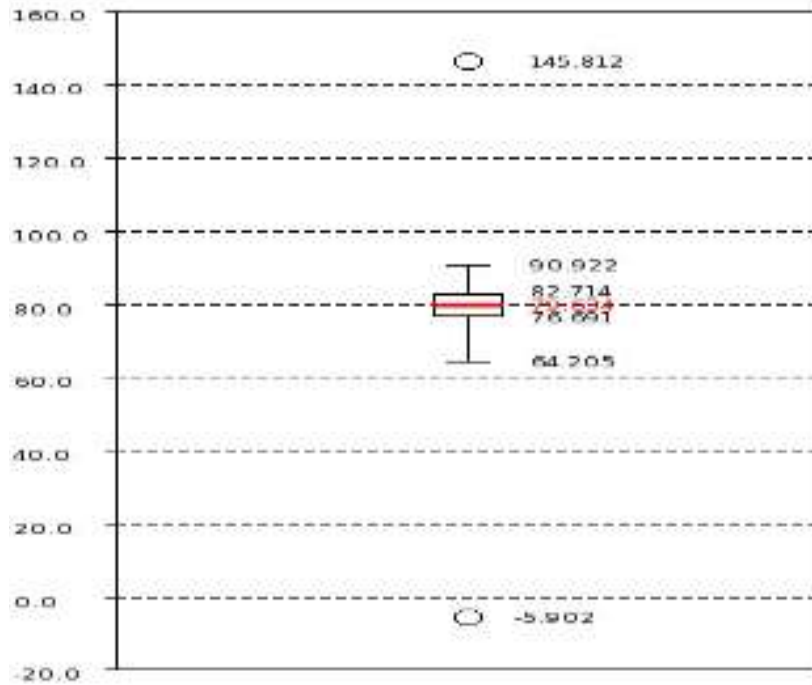


Figure 51 Depth out with Proposed BHA Stick & Slip (18.5% @ 79.62 RPM)

This new BHA configuration presented as optimum parameters the following combination of 18 klbs with 80 rpm, giving a considerably lower level of lateral vibration (around 8-16 G's) and lower stick and slip (around 18-19%).

		Standard BHA	Proposed BHA	Improvement %
Optimum Parameters	RPM	120	80	
	WOB	18	18	
Vibration	Lateral	25 G's	16 G's	36%
	S&S	37%	18%	51%

The proposed BHA shows lower lateral vibration and S&S with less RPM and the same WOB.

The next step is to perform a sensitivity analysis of parameters in a frequency model to determine the critical RPMs. It means at what RPM the BHA enters in resonance.

4.3.2 Frequency Simulation

After completing the transient simulation, a frequency simulation was done to confirm that the BHA will be not excited by any natural frequency of the string along the borehole, considering a variation of ± 1.5 deg in inclination (from 87 to 90 deg) and a variation in DLS from 0 to 2 deg/100ft.

The surface RPM variation for the analysis was performed between 40 to 150 RPM. The BHA excitation factor considered was 1x for the drill string, 6x for the bit selected, and 3x for the stabilizer used.

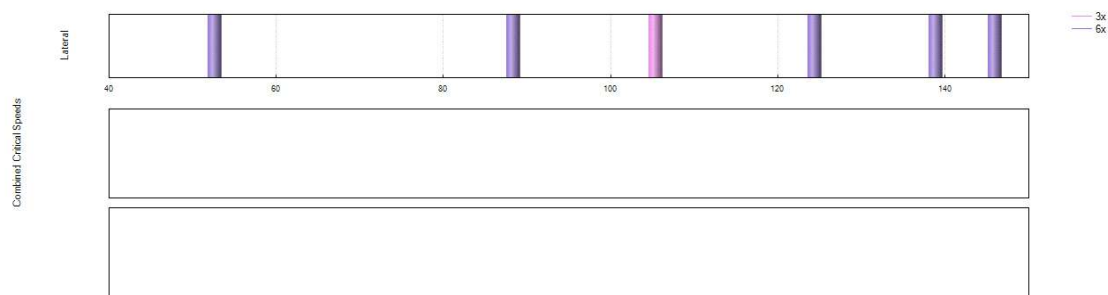


Figure 52 Critical RPM Values

Given the below results:

The free vibration analysis shows that the BHA is free of vibration between 60 – 80 rpm, which is inside the recommended parameters by the bit provider to preserve the bit inside abrasive formation and aligned with transient simulation recommending around 80 rpm.

However, the following RPM should be avoided:

- ✓ 53 rpm induces lateral vibration at 5.27 Hz
- ✓ 88 rpm induces lateral vibration at 8.84 Hz
- ✓ 124 rpm induces lateral vibration at 12.44 Hz
- ✓ 139 rpm induces lateral vibration at 13.88 Hz
- ✓ 146 rpm induces lateral vibration at 14.59 Hz
- ✓ This BHA configuration induces no axial or torsional vibration

4.4 Phase Four: Selecting Optimum Real-Time Drilling Parameters to Improve Drilling Efficiency across Abrasive Sandstone Formation

Based on the Transition modeling design, the best BHA configuration is represented below:

Table 8 Proposed BHA

Desc.	OD	Length	Cum. Length
Bit	5.875	0.69	0.69
RSS Stab	5.750	18.10	18.79
MWD	5.250	33.55	52.34
5 3/4" ILS	5.750	2.50	54.84
LWD Stab	5.750	25.50	80.34
Pony NMDC	4.750	15.00	95.34
5 5/8" Stab	5.625	4.50	99.84
4" HWDP	4.000	91.60	191.44
Jar	4.750	30.90	222.34
4" HWDP	4.000	61.64	283.98
4" DP	4.000	7974.11	8258.09

5 ½" DP	5.500	Surface	
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The optimum parameter guideline based on transient and frequency simulation is defined as below:

- ✓ WOB: 12-18 klbs
- ✓ RPM: 60-80 rpm
- ✓ On the interbedded layer (roof failure present), it is recommended to decrease the WOB (Monitor MSE)
 - Dark Green = Low shock and vibration (Interbedded and homogeneous layer)
 - Green = Low shock and vibration (Homogenous layer)
 - Yellow = Low-Medium shock and vibration
 - Orange = Medium shock and vibration
 - Red = High shock and vibration



Figure 53 WOB & RPM MAP

4.5 Phase Five: Evaluate the Effectiveness of This Research on the Improvement of Average ROP & Average Footage per Run on Two New Wells

The recommended BHA and parameter guidelines were implemented on two wells, obtaining the following results:

Well#13

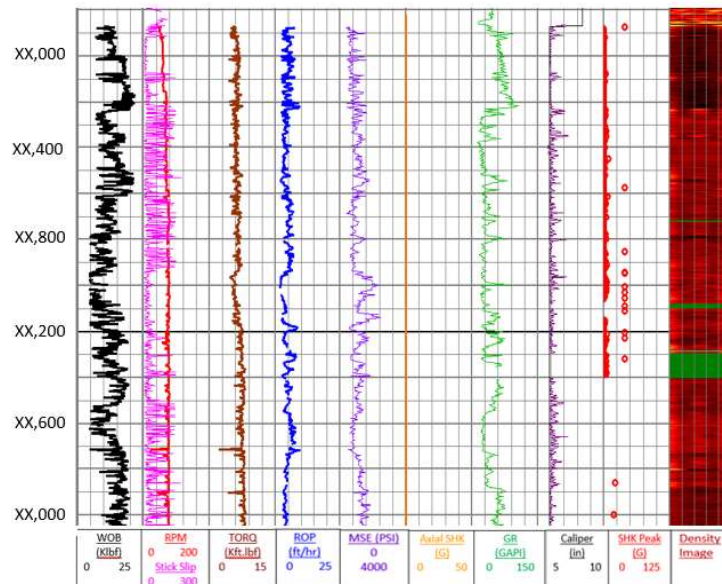


Figure 54 Well#13 Drilling & Downhole Data

Average footage per run extended over 780 ft, on interbedded formation as recognized by change on MSE and supported by density caliper and image log. The WOB was reduced to follow the model recommendation to save the bit, extending to almost double the bit life, saving at least two trips and two bits.

Related to the drilling dynamic, a very low level of lateral vibration can be observed around 12 Gs with some intervals of medium-high vibration around 40 Gs on the interbedded layer. It was identified that the WOB was reduced without entering the safe zone. There was an interval where the dynamic motion-induced was not released, and for that reason, the vibration was still present after reducing the WOB to the safe zone. This is required to pick up off the bottom to release the energy, and after that, the dynamic motion disappears. The stick and slip were around 18%.

The result showed that the model was quite accurate in predicting the drilling dynamic, required to reinforce the complaint on WOB adjustment on interbedded layers, which affected the performance in terms of ROP being slightly below the average.

Well#14

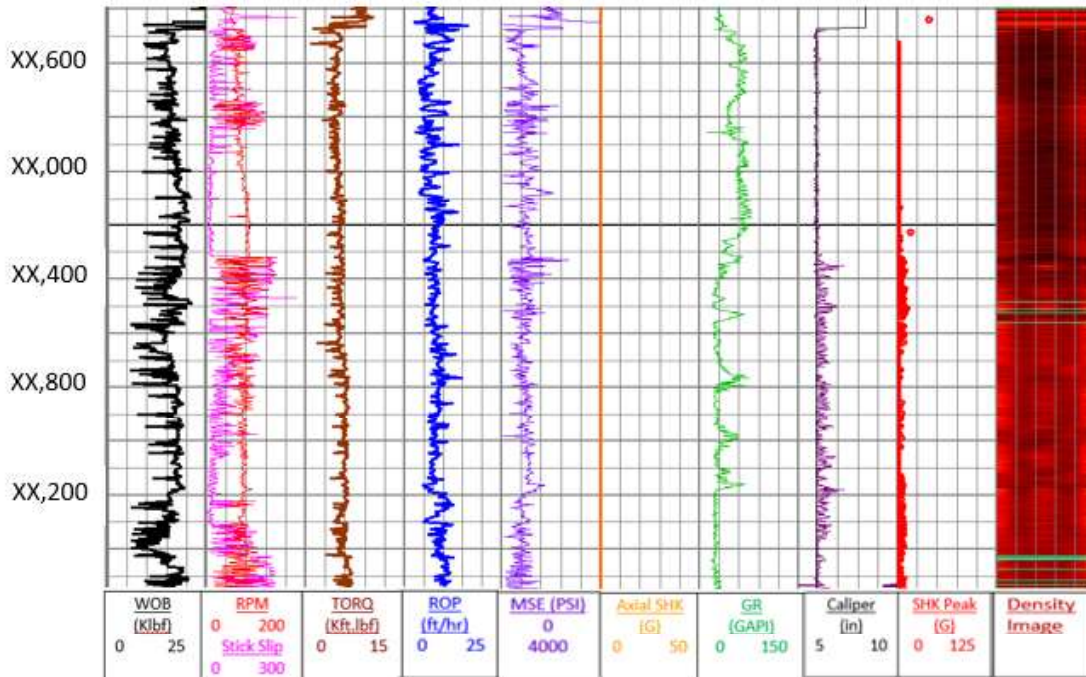


Figure 55 Well#14 Drilling & Dynamic Data

Average footage per run extended over 1090 ft, on interbedded formation as recognized by change on MSE and supported by density caliper and image log. The WOB was appropriately reduced, obtaining a remarkable performance saving at least 3 trips and 3 bits while maintaining the average ROP over 7 ft/hr above the average performance of around 20%.

Related to the drilling dynamic, a very low lateral vibration can be observed around 12 Gs and around 16% stick and slip. This shows a considerable decrease in the shock and vibration level and aligns with the transient simulation.

The full compliance of the parameter's guideline demonstrated a remarkable performance increasing the average footage per run by 180% and the ROP by around 21% compared to the historical data.

Result Summary

Table 9 Drilling Data for Validation Wells

Well Number	Depth in	Depth out	Drilled Footage ft	Total Hours While Drilling	ROP Ft/hr	Bit Dull Grading	Stabilizers Evaluations	Average Footage ft	Average Rate of Penetration ft/hr
Well 13	xx870	xx612	742	193.8	3.83	1-1-WT-BHA	1/16 UG	788 ft	4.00
	xx612	xx392	780	198.4	3.93	1-1-WT-BHA	1/16 UG		
	xx392	xx234	842	199.4	4.22	1-1-WT-TD	1/16 UG		
Well 14	xx471	xx636	1,165	180.0	6.47	1-1-WT-BHA	1/16 UG	1,095 ft	7.08
	xx636	xx660	1,024	129.3	7.92	1-1-WT-TD	1/16 UG		

Table 10 Average ROP Per Run & Average ROP for Validation Well#14

	Standard BHA	Modified BHA with Parameters Implementation	Improvement Percentage
Average Footage Per Run ft	391	1095	+ 180 %
Average ROP ft/hr	5.84	7.08	+ 21%

This improved the average footage per run by 180 %, and improved the average ROP by 21%.

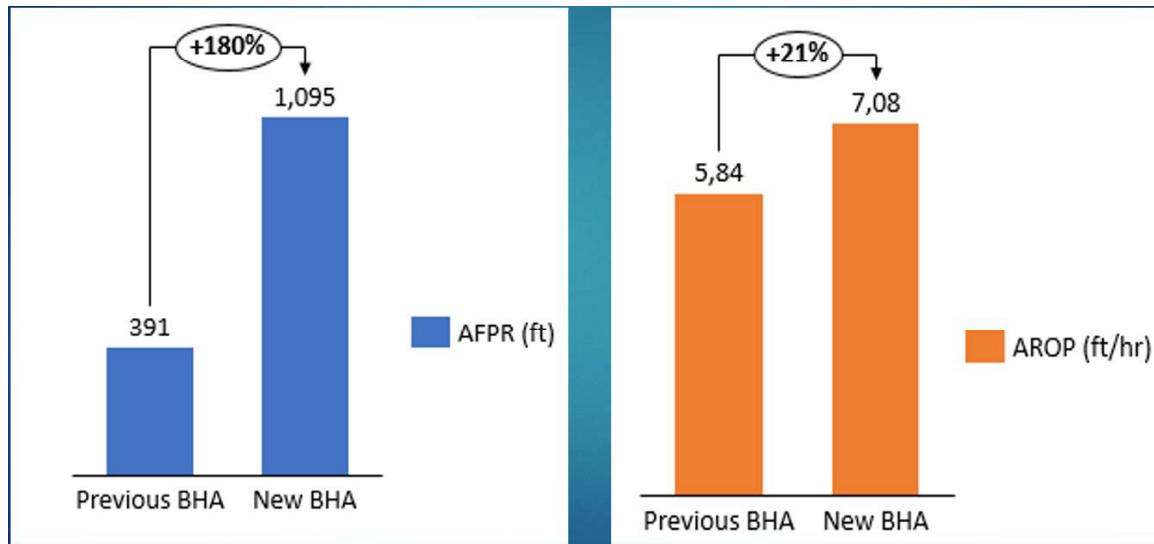


Figure 56 Comparison Between Average ROP with Standard BHA & Proposed BHA

The proposed BHA and parameters represented an effective solution to increase the performance of sandstone formation by:

- Improve the average footage per run by 180 % and improve the average ROP by 21 % if proper compliance with the drilling parameters guideline is achieved
- The transient simulation was accurate in predicting drilling motion allowing to optimize BHA design and define a drilling parameters road map
- This research results will allow to:
 - ✓ Save at least 3 bits trips (more than 120 hours saving on trips).
 - ✓ Have the potential to save 47 hours on bottom time by achieving a 20% improvement on ROP (Requires full compliance with parameters).
 - ✓ Save at least 3 bits cost.

CHAPTER 5

CONCLUSION

5.1 Conclusion

In conclusion,

- The methodology developed succeeded in Selecting Optimum Real Time Drilling parameters to Improve Drilling Efficiency Across Abrasive Sandstone Formations.
- The methodology is based on the analysis of Downhole Data from RSS and LWD Tools. Using the Downhole Data from RSS and LWD Tools, the Transient and Frequency Models were utilized to Select Optimum Drill String and BHA Design.
- This approach succeeded in Improving the Average ROP & Average Footage Per Run.

5.2 Future Work

For future extensions on the research, the following two areas would be of interest:

- Bit Design Modification: What will be the vibration level if the drilling bit number of plates is increased or decreased, if cutter orientation & cutter size are modified?
- Longer Lateral Length: What will happen to the vibration level if the lateral length is more than 2000 ft.

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