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Investigation of qualitative methods for diagnosis of poor bit performance using surface drilling parameters

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INVESTIGATION OF QUALITATIVE METHODS FOR DIAGNOSIS OF POOR BIT PERFORMANCE USING SURFACE DRILLING PARAMETERS

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ABSTRACT

Bit performance in deep shale when using water-based mud is typically poor. This study is part of a larger research project to improve that performance entitled “Automated Rig Controls for Improved Drilling Costs.” The objective of the project is diagnosis of changes in drill bit performance to provide a logical basis for automating draw works control, maximizing bit performance, and reducing drilling costs. The specific goal of this study is a means to diagnose bit performance, specifically to identify bit balling and lithology changes, using real-time drilling data.

The research began by identifying symptoms relating to specific causes of bit performance changes based on previously published research. Four published and six additional new potential parameters were identified for evaluation. Laboratory data was analyzed from both single cutter and full-scale tests to evaluate which diagnostic measures best indicated the causes of different or changing performance. Five of the diagnostic parameters were selected for further evaluation.

An example set of field data was acquired that included both surface records of operational parameters and an electric log of the formations in a 2600 foot interval. Rate of penetration was estimated using Lubinski’s method. Three published and two new diagnostic parameters were calculated for the entire interval. The sign, magnitude, and trend of these diagnostic parameters were compared to the changes evident in the data to establish the relationship between each diagnostic parameter, the lithology, and whether the bit was balled or drilling efficiently. As a result, a method for defining baseline values of each parameter, identifying lithology, and determining whether the severity of bit balling is constant, being reduced, or increasing is proposed and demonstrated. This method can potentially provide a basis for operational changes to improve bit performance, to help detect lithology changes, and to delineate bed boundaries more accurately.

1. INTRODUCTION

1.1. General Description and Objective

The cost of finding and developing new petroleum reserves to meet the rising demand for energy worldwide is increasing.[14] As reported in both the Oil and Gas Journal and World Oil, the estimated total of annual exploration and development costs for 1997 in the world were over $80 billion.[1,2] Drilling represents the major component of these costs; for example, the annual drilling cost in the U.S. alone was about $16 billion in 1997.[8] Therefore, effectiveness in drilling has significant influence on the economic success of the oil and gas industry.

Bit performance, which is usually measured in terms of the cost per foot over an interval of a hole, is a major factor in overall drilling costs. Bit performance is dependent on many things, such as how fast the bit drills, how far it drills, and how much the bit and other drilling resources cost. These depend on other factors, including the type of bit used, operating conditions, type of formation, depth of the well, and many other factors. One of the important factors affecting drilling performance is the speed with which the bit drills, which is defined as the rate of penetration (ROP). If the effect of this factor on other factors, such as the distance a bit can drill, is ignored, increasing the ROP proportionately improves bit performance. Thus, improving the rate of penetration highly influences the total cost of a well and, potentially, its economic success.

The majority of the footage drilled in oil wells is in shale and other shaly rocks. These rocks are usually not hard or abrasive; logically, they should be drilled at a high ROP.[14] However, because of the soft and sticky behavior of the cuttings produced and because of chemical and mechanical factors, the cuttings can stick together and to the bit and make the bit's cutters ineffective, causing the drilling to go much slower than expected.[1,2,14,37] This phenomenon is called "bit balling." The primary objective of this research is to diagnose changes in ROP to distinguish the onset of bit balling from other effects, such as a change in lithology. Conclusively knowing the cause of a change in bit performance should allow more appropriate actions by the driller or drilling control system to maximize bit performance under the new conditions.

1.2. Definition of the Problem

The term "balling" has been broadly applied in the field to situations, in which accumulation and compaction of clay-rich mineral cuttings in the front of the bit face, junk slots of a bit, or bottom hole assembly (BHA) surfaces impede the overall performance.[6,8] Shale cuttings may accumulate under the bit face and/or adhere to the bit body to cause global balling as shown in Figures 1.1 and 1.2. Cutting may also accumulate on cutter faces to cause cutter balling as shown in Figure 1.3.[1,2,8] Bottom balling is the accumulation of cuttings on the bottom of the hole, which can also interfere with bit performance. At least one in-depth study has concluded that global balling is the main cause of low ROP when drilling clay-rich shale with water-based mud.[1,2,8] Therefore, preventing or minimizing the effect of global balling can potentially improve bit performance and reduce drilling costs.

1.3. Conceptual Solutions

Ideally, bit balling could be prevented by having "sufficient hydraulics" or flow of drilling fluid at the work-front of the bit to remove and flush away the cuttings as soon as they are produced.[37] Furthermore, modification of the bit structure and cutters can improve the effectiveness of bit hydraulics.[37] However, even very high levels of bit hydraulics are not always successful in preventing balling. Another alternative method consists of modifying the mud to reduce the cohesion between cuttings or adhesion to the bit.[37] One strategy is to use water-based mud (WBM) treated chemically with higher salinity, lignosulfonates, polymers, mixed metallayered hydroxides, or organic additives.[37] The other strategy is to use an oil-based mud (OBM). It has been most successful because its non-polar nature inhibits cohesion between shale particles and adhesion to the bit; however, OBM cannot be used in many places because of severe environmental restrictions.[37] Consequently, one study estimates a potential saving in drilling costs of $500 million per year if bit performance in WBM could be improved to equal performance in OBM.[2] An additional method uses an electrical charge on bit surface to repulse the negative charges on shale surfaces, such as using a BHA in which a stabilizer above the bit acts as the anode while the bit is cathodic. [37,43,46,49] The method emphasized in this study is to detect balling in its earliest stages and to minimize its impact by changing the drilling operational parameters, such as weight on bit (WOB) and rotary speed (RPM). The potential of this method is demonstrated by the fact that a different driller can sometimes achieve a 50 percent improvement in overall penetration rate when all the physical conditions except operating parameters and personal technique are the same.[1,2]

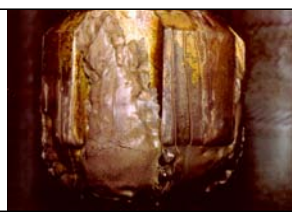		
Figure 1.1 - Global Balling[2]	Figure 1.2 - Global Balling[2]	Figure 1.3 - Cutter Balling[2]

1.4. Research Strategy / Plan / Method

This study is part of a larger research project entitled “Automated Rig Controls for Improved Drilling Costs.” Rapidly processing drilling data to detect and diagnose changes in drill bit performance could provide a logical basis for automating draw-works control and for appropriate responses to maximize overall performance. The overall objective of this project is to provide the logical basis for such diagnosis of real-time drilling data and for using the control system to make effective changes in operating parameters to achieve maximum bit performance. Developing a means to identify the cause of a change in bit performance, especially distinguishing bit balling from other causes of poor performance such as encountering a stronger rock, is a critical requirement for meeting this objective.

The principal goal of this study is to complete a comprehensive assessment of the practical feasibility of rapidly processing drilling data to successfully detect and diagnose the cause of a change in drill bit performance. The plan for accomplishing that goal is described in this report.

First, the symptoms relating to specific causes of bit performance changes are identified based on previously published research. The next step is to analyze laboratory data from both single-cutter and full-scale tests performed in previous research to evaluate which diagnostic measures best indicate the causes of different or changing performance. An example set of field data is processed to get indicators of or approximate equivalents of the important drilling parameters at bottom-hole conditions from surface information. Those parameters, such as corrected ROP, are used to calculate diagnostic parameters. The practical value of these parameters is assessed by comparison of the cause of change in bit performance from an example of actual drilling data evidencing known problems to the sign, magnitude, and/or trend of the diagnostic parameters. The knowledge gained, conclusions, and recommendations are documented to provide technology transfer to sponsors and the new graduate research assistant conducting the remaining phases of the project.

2. LITERATURE REVIEW

2.1. Overview

There has been extensive research on bit performance during the past fifty years, and many people are still researching the subject and producing many papers and patents. Because of the volume of available literature, only a selected sample is reviewed. The previous works are separated into four main categories: balling discussion, factors influencing bit performance, diagnosing performance problems, and relationship between surface and bottom-hole data.

2.2. Balling Discussion

2.2.1. Introduction

The accumulation and compaction of clay-rich cuttings on the bit or bottom-hole assembly can substantially impede overall bit performance, and is generally referred to as "balling." [6,8] Balling may cause the following undesirable effects:

- Severe reduction in penetration rate[1,2,3,14]
- Reduction in bit life due to ineffective drilling and temperature increase[1,2]
- Reduction of the life of the roller-cone bits because the rotation of individual cones may be stopped, and therefore the bit teeth wear more quickly[37]
- Increasing time required for trips due to swabbing and tight hole[14]
- Loss of circulation due to mud rings and hole pack-off[14]
- Lost time due to cleaning out surface flow lines[14]
- Stuck pipe[14]
- Difficulties in logging[14]
- High torque[1,2]

- Difficulties in running casing[14]

The bit balling has been explained in terms of mechanical and chemical factors.[35] Possible mechanical explanations relate balling, firstly, to differential sticking of the cuttings to the cutter due to the difficulty in getting fluid between the cutter and the cuttings, and secondly, to differential sticking due to dilatancy in the shear zone of the cuttings causing a drop in pore pressure within the cuttings. [35] There are two possible chemical explanations: 1) the tendency of the drilling fluid to wet the surface of the bit, and 2) sticking of the cuttings due to swelling as hydrophilic cuttings attempt to imbibe water, as the result of: 1) cohesion between cuttings, and 2) adhesion to bit surfaces.[1,2,35]

Based on previous research, Smith separates balling into global balling, cutter balling, and bottom balling.[1,2,8,51] Global balling is massive balling or any large-scale packing or jamming of cuttings between the bit body and the bottom of the hole. Cutter balling is the accumulation and adhesion of the sheared and deformed cuttings on the face of the PDC cutter. Bottom balling is produced by plastic behavior of shale cuttings under elevated mud pressures that inhibit PDC bit cutting action when a "kneaded" layer of cuttings accumulates on the bottom of the hole below the bit.

2.2.2. Verification of Balling as a Cause of Poor Bit Performance

When slow penetration rates are encountered, diagnosis of balling as the cause is confounded when, after tripping out with the bit, a clean bit face and BHA are observed with no apparent damage to or balling on the bit. [6] In this case, balling may be the cause of the slow penetration rate if the balled material falls off the bit while tripping out to change or examine the bit.[1,2,6] Smith studied poor bit performance in deep shale formations, and the two focuses of the study were: 1) to evaluate the hypothesis that the primary cause of the slow drilling shale problem is global bit balling and 2) to identify the impact of global balling and its symptoms versus the other possible causes of poor bit performance and their symptoms in an overall comparison of laboratory tests and actual field examples.[1,2,8,51]

2.2.3. Other Studies

A number of research studies study have considered the origin and effects of bit balling and other possible causes of low rate of penetration, ROP, when drilling clay-rich shales. The balling studies divide this phenomenon into mechanical and physio-chemical forces between cuttings-bit and cuttings-cuttings interactions.[6,7,11,12,14,35,43] They evaluate the effect of other possible parameters on bit balling by looking at shale properties (such as cation exchange capacity (CEC)),[31,35] mud properties,[6,14,19,31,32,37,43,46] down-hole pressure,[6,7,11,14,31] and bit and cutter design.[22,32] In total, they introduce several possible problems which balling may cause and several mechanical or chemical approaches to prevent it.

2.3. Factors Affecting Bit Performance

The factors influencing bit performance are rock characteristics, bottom-hole confining and wellbore pressure, bit design and condition, mud composition, hydraulics, and bit operating parameters.[2,3] In the following paragraphs, an overview of the effect of an individual factor is given.

- **Rock Characteristics**

The elastic limit and ultimate strength of the formation are the most important formation properties affecting ROP; however, the mineral composition of the rock can change the ROP. For example, rocks containing hard and abrasive minerals can cause rapid dulling of the bit teeth, and gummy clay minerals can cause the bit to ball up. The rock would be drilled very slowly in either case.[2,3]

- **Bottom-Hole Confining and Wellbore Pressure**

The strength of rocks is related to the effective confining stress on the rock. Furthermore, the difference between wellbore pressure and pore pressure is generally accepted as the effective confining stress. As confining stress increases, both the stress and strain to fail the rock increase. The increase in strain to failure increases the work required to fail the rock. Consequently, when the difference between the well-bore pressure and the pore pressure increases, ROP decreases.[2]

- **Bit Design and Condition**

The bit type selected and the design characteristics of the bit have a significant influence on ROP and effectiveness for the specific rock. Tooth length; number of cutters; cutter exposure or blade standoff; size, shape, surface, and angle of the cutter; and nozzle and jet design are some of the many bit characteristics which affect ROP and bit performance.[2,3,22,54] Bit condition, specifically the bit wear state, has influence on the effectiveness of drilling, and increased wear reduces ROP and bit performance.[2,3]

- **Mud Composition**

The properties of the drilling fluid highly affect ROP. Density, rheological flow properties, filtration characteristics, solids content and size distribution, and chemical composition are some of the properties which have a high influence on bit performance.[2,3,20] For example, using OBM can increase ROP up to 30 times in lab tests.[1]

- **Bit Operating Parameters**
    - **WOB**

        Weight on bit, WOB, is amount of the axial force applied to the bottom-hole formation to break the rock by the bit. It is calculated based on the difference between the measured weight of drill-string at the surface during off-bottom rotation and during the drilling operation. Typically, a plot of ROP vs. WOB, obtained experimentally with all other drilling variables held constant, will have the characteristic shape shown in Figure 2.1.[3] No significant ROP is obtained until the threshold WOB is applied. Then, the penetration rate increases rapidly with increasing WOB for moderate values of WOB, and at higher values of WOB, only slight improvements in ROP are observed. Finally, at extremely high values of WOB, ROP no longer increases. Despite increasing WOB, this behavior often is called bit floundering, and the point of maximum ROP is called flounder point.[3] The poor response of ROP at high values of WOB is usually attributed to less efficient bottom-hole cleaning.[3]

In shale, increasing WOB more than flounder point decreases ROP,[22,23] and "after flounder point, ROP is insensitive to WOB." [1,2,8,51] As shown Figure 2.2, in the situation of balling after WOB past flounder point, the bit starts to ball up and become ineffective, so the previous ROP is not achievable anymore.

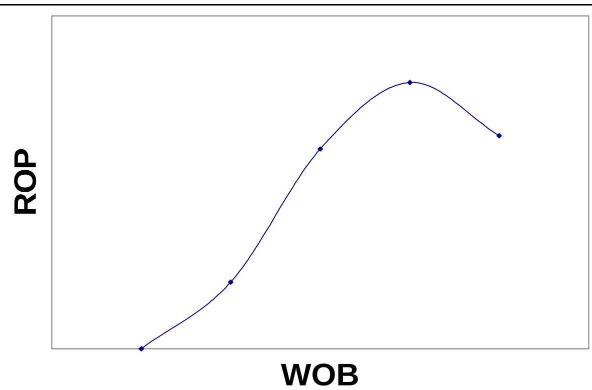

Figure 2.1 – ROP vs. WOB (Normal Behavior)

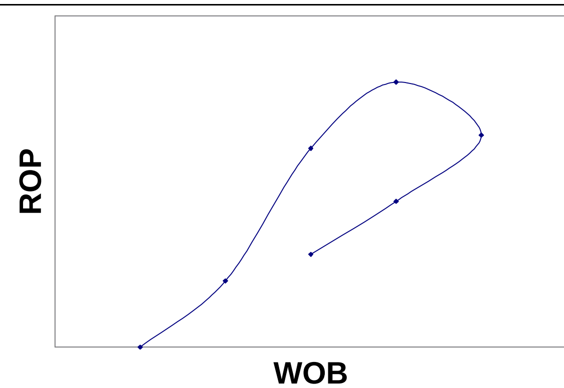

Figure 2.2 – ROP vs. WOB (Balling)

- **Rotary Speed (RPM)**

When all other drilling variables are held constant, ROP usually increases with RPM at low values. At higher values of RPM, the response of ROP to increasing RPM diminishes.[3] The poor response of ROP at high values of RPM usually is attributed to less efficient bottom-hole cleaning. [3]

In addition to previous information, choosing the appropriate WOB and RPM is highly influenced by types of rocks. For example, usually weak rocks drill with low WOB and high RPM,[55] and strong rocks drill best with high WOB and low RPM.[55]Also, low RPM increases the chance of stick slip, so the moderate RPM is preferred.[55]

- **Hydraulics**

Increasing bit hydraulics and flow rate is widely considered to have a significant influence on ROP. The level of hydraulics achieved at the bit affects the flounder point of the bit.[3] A flounder point is reached eventually when the cuttings are not removed as quickly as they are generated, so if the level of hydraulics is increased, a higher ROP will be achieved at the new bit flounder point.[3]

- **Bit Tooth Wear**

"Most bits tend to drill slower as the bit run progresses because of tooth wear. The tooth length of milled tooth rolling cutter bits is reduced continually by abrasion and chipping. The teeth of tungsten carbide insert-type rolling cutter bits typically fail by breaking rather than by abrasion. Reductions in penetration rate due to bit wear usually are not as severe for insert bits as for milled tooth bits unless a large number of teeth are broken during the bit run. Diamond bits also fail from cutter breakage or loss of diamonds from the matrix."[3]

2.3.1. John Rogers Smith, 1998-2000

These studies focus on poor bit performance in deep shale formations, and the objective of the study is to identify the characteristic symptoms of the problem of slow penetration rates in actual drilling of deep shales for subsequent comparison to the symptoms resulting from different possible causes in laboratory tests. The different possible causes that were investigated are included in this research. Furthermore, the effects of different drilling operating factors on balling are discussed. [1,2,8,9]

2.3.2. Other Studies

Many additional studies have been conducted with the goal of improving bit performance. An overview is provided here for broadening the reader's perspective of bit research. ROP is concluded to be a function of nine specific parameters, such as WOB, RPM, etc. Other research tried to find the relationship between those data using laboratory and field drilling operating parameters to separate drilling mechanics effects from the lithology effects.[10,18] One researcher tried to find the optimum situation at flounder point using selected relationship between nine parameters.[16] Some research studies introduce correlations between the bit performance and different rock formation properties,[25,47] such as Young's modulus, Poisson's ratio, unconfined or confined compressive strength, internal friction angle, etc., as well as formation fluid pressure, and in situ total stresses. Others have attempted to identify optimal drilling efficiency at the bit by using numerical analysis of data and experimental observations of performance problems.[27,45,47,67] Some researchers have also used artificial intelligence (fuzzy logic, neural networks, etc.) to find a relationship among all selected drilling parameters and the optimum situation.[48]

2.4. Relationship between Surface Data and Bottom-Hole Data

2.4.1. WOB, Torque, and RPM

For this project, these drilling operational parameters are measured in surface. WOB is calibrated during the connection time before start of drilling to zero and hook load at surface set as the origin, then during drilling, difference between actual hook load and the original one defines the actual WOB. Torque is typically measured using the electric current delivered to the rotary table or the top drive. RPM is measured by a rotary table RPM sensor. Because correcting these operational drilling parameters can require detailed dynamic analysis of drill-string and these subjects are beyond the objective of this project, no correction was chosen for these parameters (WOB, torque, and RPM).

2.4.2. Rate of Penetration

The conventional rate of penetration instrumentation does not provide a correct measurement indicating the progress of the bit.[57] It measures merely the progress of the downward motion of the upper end of the drill string by measuring block or drill line travel.[57] However, the drill string is continuously subjected to variation of length due to elastic deformations and dynamics of the drill string, so the motion of the block is not the same as the motion of the bit. In order to eliminate the errors resulting from a lack of allowance made for the elastic variations in the length of the drill pipe, the rate of drilling penetration is usually determined by the average value of the drilling rate over an appreciable depth or time.[57] Several approaches are proposed to calculate rate of penetration more accurately, and some of them will be introduced.

2.4.3. Arthur Lubinski,[57] 1949

Because the length of the drill string is affected by the change in forces due to elastic deformations, this approach assumed that the change in the drill-string length is equal to a linear function of the change in force due to the change in weight on bit, assuming the drill string behaves as a perfect spring. As shown in Equations 2.1 and 2.2, the speed of drilling at the bit, ROP, is equal to the sum of the change in length of drill string, which is proportional to the change in WOB, the elasticity coefficient of the drill string, and block speed at surface. This method neglected the effects of the dynamics of the drill string and of friction between the hole and drill string. More detail about this method is in Appendix II.

$$ROP = \frac{dD_s}{dTime} + K\frac{dWOB}{dTime} \quad (2.1)$$

$$K = \frac{L}{144EA} \quad (2.2)$$

2.4.4. Yves Kerbart,[60] 1989

Yves Kerbart's method[60] creates an empirical basis for Lubinski's method.[57] It calculates the elasticity coefficient of the drill string by using a statistical model of previous drilling operation data based on assumptions that the lithology does not change and the rate of penetration remains constant. As shown in Equations 2.3 and 2.4, the elasticity coefficient (K) is calculated from a linear regression of change in WOB and the difference between block speed and long-term ROP. Then a corrected ROP was calculated by using the calculated K in Lubinski's equation. More detail about this method is in Appendix III.

$$\left(ROP_L - \frac{dD_s}{dTime}\right) = K_{Kerbart}\frac{dWOB}{dTime} \quad (2.3)$$

$$ROP = \frac{dD_s}{dTime} + K_{Kerbart}\frac{dWOB}{dTime} \quad (2.4)$$

2.4.5. Other Methods

Other approaches continued Arthur Lubinski's method. One method used electrical instruments for measuring incremental changes in the length of the drilling string to calculate the elasticity coefficient of the drill string.[58] Other methods formulated mathematical models using the Kalman filter for estimating the elasticity coefficient of the drill string and minimizing inaccuracy in the rate of penetration interpretation.[62,63] A method has been developed using the Kalman filter to estimate the velocity and depth of the tool in the hole from accelerometer and cable depth measurements.[59]

2.5. Methods to Diagnose Performance Problems

2.5.1. Introduction

Using laboratory work-oriented and actual field observations, the following research studies correlate the relevance of proposed calculated diagnostic parameters on bit performance; therefore, after detecting the situation, the appropriate actions for specific events are recommended. In the following, some useful research studies will be introduced.

2.5.2. Charles H. King et al.,[66,69,70] 2000-2001

King et al. use a method of and system for optimizing bit rate of penetration while drilling by applying some special kind of linear regression (as shown in Equation 2.5) on he weight of the bit and the rate of penetration to continuously determine an optimum WOB (as calculated by Equation 2.6), based upon measured conditions.[66,69,70] The optimum WOB is maintained at the optimum level during relatively constant formation characteristics. As measured conditions change during drilling, the method updates the determinations of optimum WOB. More detail about this method is in Appendix I.

$$ROP_t = a + b_1 ROP_{t-1} + b_2 ROP_{t-2} + b_3 WOB_t \qquad (2.5)$$

$$WOB = \frac{ROP(1 - b_1 - b_2) - a}{b_3} \qquad (2.6)$$

2.5.3. I.G. Falconer et al.,[29,61] 1988

This research uses down-hole torque and WOB to calculate dimensionless torque (Equation 2.7) and apparent formation strength (FORS, Equation 2.8) in a method to separate the bit effects from the lithology effects during drilling.[29,61] "Dimensionless torque, T_D, is proportional to the bit efficiency and the ratio for the in-situ shear strength to the in-situ penetration strength."[29] "Apparent formation strength, FORS, is proportional to the in-situ penetration strength of the rock and inversely proportional to the bit efficiency."[29]

$$T_D = \frac{Torque}{WOB * (Bit\ Diameter)} \quad (2.7)$$

$$FORS = \frac{5 \times WOB * RPM}{12 \times ROP * (Bit\ Diameter)} \quad (2.8)$$

Or if R_D, dimensionless ROP, is used:

$$R_D = \frac{ROP}{60 \times RPM * (Bit\ Diameter)} \quad (2.9)$$

$$FORS = \frac{WOB}{144 \times R_D * (Bit\ Diameter)^2} \quad (2.10)$$

As shown in Figure 2.3, the research separates different situations based on these two proposed diagnostic parameters. Many field case studies have been done to examine the effects of lithology changes on the drilling response. They claim that the techniques can provide: 1) rock strength and lithological correlation (classified into three categories: porous, argillaceous (shaly), and tight, corresponding to high, medium and low torque respectively), 2) wear state of the bit teeth in shales (using trends in bit torque and rate of penetration in shale type formations to separate the wear of milled tooth and PDC bits from changes in shale strength, and reaching the conclusion that it was not possible to interpret bit wear in non-shaly type formations), 3) excessive torque and cone locking, and 4) insensitivity of surface drilling measurements to major formation changes (e.g. sand/shale boundaries), particularly in deviated wells.

2.5.4. R.C. Pessier et al.,[41] 1992

This research study uses a comparison between full-scale simulator tests and field data to develop an energy-balanced model for drilling under hydrostatic pressure.[41] Using specific energy (Equation 2.11), mechanical efficiency (Equation 2.12), and the bit-specific coefficient of sliding friction (Equation 2.13) as key indexes of drilling performance, the method makes bit selection and diagnoses different drilling operation situations.

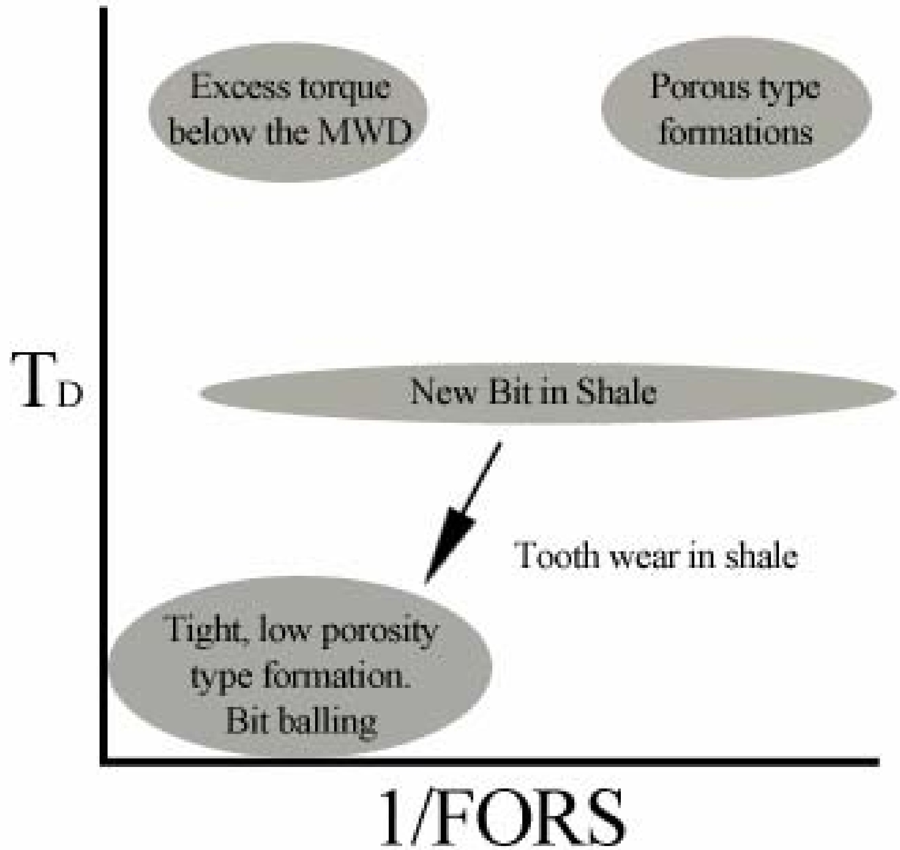

Figure 2.3[29] - Falconer's Diagnosis

$$E_S = \frac{WOB}{(Borehole\ Area)} + \frac{120p * RPM * Torque}{(Borehole\ Area) * ROP} \ldots\ldots (2.11)$$

$$EFF_M = \frac{E_{S\min}}{E_S} * 100 \ldots\ldots (2.12)$$

$$m = 36 \frac{Torque}{(Bit\ Diameter) * WOB} \ldots\ldots (2.13)$$

The authors define specific energy as the work done per unit volume of rock drilled. It assumes that the minimum specific energy required to drill is roughly equal to the compressive strength, σ, of the rock being drilled.

$$E_{S\min} \approx s \ldots\ldots (2.14)$$

Therefore, the energy efficiency of drilling, EFF_M, can be estimated by comparing the actual specific energy required to drill an interval with the minimum expected to be needed to drill that interval, EFF_{SMmin}, or in Equation 2.12. The research analyzes the values of these three parameters in different rock types against ROP under different situations, such as under atmospheric and hydrostatic pressure, different bits, different WOB and RPM, and different hydraulics. The following interpretations of drilling data are concluded: 1) detection and correction of major drilling problems, 2) analysis and optimization of drilling practices, 3) bit selection, 4) failure analysis, 5) evaluation of new drilling technologies and tools, 6) real-time monitoring and controlling of the drilling process, 7) analysis of MWD data, and 8) further development of expert systems.

2.5.5. John Rogers Smith,[1,2,8,9] 1998-2000

These research studies investigated poor bit performance in deep shale formations,[1,2,8,9] and the focus of the study was to identify the characteristic symptoms of the problem for subsequent comparison to the symptoms resulting from different possible causes in laboratory tests. It used two measures for quantifying bit performance: mechanical-specific energy (Equations 2.15 and 2.16) and force ratio (Equations 2.17 and 2.18). Mechanical-specific energy is mechanical work being done at the bit per unit volume of rock removed. The force ratio is the ratio of the force acting to push the bit tooth or cutter laterally through the rock to break and remove it divided by the force acting downward to engage the tooth or cutter in the rock. It is similar to the dimensionless torque and coefficient of friction in the previous references. As observed in shale, if bit performance decreases due to a balled bit, the force ratio is going to decrease, and specific energy is going to increase.

For full-scale test and field data:

$$E_S = \frac{WOB}{(Borehole\ Area)} + \frac{120p * RPM * Torque}{(Borehole\ Area) * ROP} \qquad (2.15)$$

For single-cutter tests:

$$E_S = \frac{(Axial\ Force)}{p\,(Diameter\ of\ Path)(Width\ of\ PDC)} + \frac{(Tangential\ Force)}{(Depth\ of\ Cut)(Width\ of\ PDC)} \qquad (2.16)$$

For full-scale test and field data:

$$R_f = 48\frac{Torque}{(Bit\ Diameter) * WOB} \qquad (2.17)$$

For single-cutter tests:

$$R_f = \frac{(Tangential\ Force)}{(Axial\ Force)} \qquad (2.18)$$

2.5.6. Other Studies of Performance Diagnosis

Other research studies correlate laboratory or field drilling operating parameters to separate drilling mechanics effects from the lithology effects, or to detect drilling problems. Some (this is similar to the method uses by Falconer[29,61]) use dimensional and dimensionless diagnostic parameters (similar to what was introduced in the previous section, such as specific energy, force ratio, or volume of cutting) to optimize the situation that maximizes performance and to distinguish abnormal behavior which effects drilling efficiency, such as balling and vibration of bit.[52,53] Another study analyzes the effects of different situations on specific energy.[56]

2.6. Other Related Research

There are many other related research studies investigating poor bit performance. Using single-cutter tests analyses and mathematical models, some describe techniques evaluating the rock failure and cutting process during drilling[15,21] while others use this information in general bit design for better performance.[24,26] One compares field and laboratory-simulated tests to improve the interpretation of analyzed field data. One study develops an expert dynamic drilling method to optimize the drilling program, to select the best drill bit, and to maximize bit performance.[42] Despite the fact that vibrations generated while drilling cause problems, such as bit damage and drill-string wear (some give recommendation about how to detect and to prevent the vibration[40,55]), one researcher considers vibrations generated while drilling as information, promising interpretations related to lithology, bit wear, drill-string/borehole interpretations, and even as a possible seismic source.[38] Using laboratory-oriented work, this researcher has developed a de-convolution process to separate drill-string resonances from surface vibrations to yield estimates of the bit that generated the signal.[38] Some studies introduce different intelligent and informatics systems for field drilling procedures to assist the driller in replicating problem solving, diagnosis, and planning.[33,34,36,39,45,64,65,68,71]

2.7. Nomenclature

ROP = Rate of Penetration, ft/hr

D_S = Block Position, ft

Time = Time, hr

WOB = Weight on Bit, lbs

Torque = Torque, ft-lbs

Bit Diameter = Bit Diameter, ft

K = Elasticity Coefficient of Drill-String, ft/lbs

L = Length of Drill-String, ft

E = Modulus of Elasticity, psi

RPM = Rotary Speed, rev/min

A = Bit Area, ft^2

α = King's Parameters, ft/hr

β_1, β_2 = King's Parameters, dimensionless

β_3= King's Parameters, ft/hr/lbs

T_D = Dimensionless Torque

FORS = Apparent Formation Strenght, psi

R_D = Dimensionless ROP

Borehole Area = Borehole Area, in^2

σ = Compressive Strength, psi

EFF_M = Energy Efficiency of Drilling, psi

EFF_{SMmin} = Minimum Energy Efficiency of Drilling, psi

μ = Bit-Specific Coefficient of Sliding Friction, dimensionless

Axial Force = Axial Force, lbs

Tangential Force = Tangential Force, lbs

Diameter of the Path = Diameter of the Path, in

Width of PDC = Width of PDC, in

Depth of Cut = Depth of Cut, in/rev

R_f = Force Ratio, dimensionless

3. ANALYSIS OF LABORATORY TESTS

3.1. Introduction

One use of the laboratory drilling simulations is to evaluate various factors affecting overall bit performance. These tests are not as complicated as drilling in the field, and the conditions and results are measured more accurately; furthermore, it is easier to control the conditions and distinguish the result of individual effects. Unfortunately, in real field situations, many of the known factors in laboratory tests are not known completely or accurately enough (such as rock type, confining stress, etc.), but analyzing laboratory data can give us a good guideline for performance analysis. In this chapter, after the description of the tests, an auxiliary variable (cutting area as the indicator of ROP) is introduced. Next, one calculation method is shown, and some observations are discussed. After that, some diagnostic factors are proposed to differentiate between various situations, and in those situations, possible reasons for each behavior are discussed. These diagnostic parameters are evaluated based on basic physical phenomenon and observations. Previously published parameters are correlated versus the known control conditions during the test. Then the appropriate parameters that show a distinctive response for a given physical phenomenon are selected, and based on the observed responses, new diagnostic parameters are developed.

3.2. Full-Scale Test Description

A full-scale test or simulation involves using an actual bit to drill a rock sample in a pressure vessel under simulated well-bore conditions while recording the mechanical parameters, forces, and position of the bit.[4,5] Full-scale drilling simulations have been conducted to develop guidelines for bit applications and improvements in bit design.[4,5,22] Also, these simulations are also used to evaluate various factors affecting overall bit performance, such as performance of current bit design, understanding the relationship to formation properties, and the effects of bit dullness, drilling fluid, rotary speed, borehole pressure, hydraulics, and number of cutters.[4,5,19,22] Full-scale tests have also been used to study the expensive field problem of low penetration rates when drilling shale at high borehole pressures with water-based drilling fluids and PDC bits. Specific research goals were to determine the mechanism causing these low penetration rates, to investigate the efficiency of various measures, to improve penetration rates with environmentally acceptable drilling fluids, and to evaluate potential penetration improvement of different PDC drill bits and drilling fluids.[4,5,22] (The effects of WOB, when all other measures are constant, are investigated in our project).

	
Figure 3.1 Single-Cutter Test – Cutter's Holder[2]	Figure 3.2 Single-Cutter Test - Test Apparatus[2]

3.3. Single-Cutter Test Description

A single-cutter test consists of using one cutter to drill a rock sample in a pressure vessel under simulated well-bore conditions while recording the mechanical parameters, forces, and position of the bit. Photographs of the cutter's holder and test apparatus are shown in Figures 3.1 and 3.2.[2] The cutting process of a PDC in sedimentary rock under simulated down-hole conditions can be helpful in studying the information obtained from full-scale bit testing. These kinds of tests concern effects of all cutters on a bit, which are all subjected to different cutting and cleaning conditions. Hence, the net results of individual effects are hard to distinguish.[28]

Single-cutter testing can provide high-quality information regarding the rock-cutting process, such as dynamic cutting forces, condition of the cutting track, and cuttings character without distortion by drilling fluid jets or by interfering cutters. [2,8,28] This information can provide the key input for numerical models that are being developed to analyze the performance bits.[28] Furthermore, single-cutter testing is attractive because the equipment cost and operating costs are relatively low compared to the costs of full-scale bit testing.[28]

3.4. Data and Calculations

3.4.1 Description of the Data

For this section, 44 single-cutter tests, from the Smith's research study,[2] and one full-scale test data, provided by Hughes Christensen Research, are analyzed; different forces and position were recorded for all tests. For a single-cutter test, five different confining-pressures (300, 1000, 3000, 6000, and 9000 psi) were tested, but most tests, 33, were run at 9000 psi. Their different conditions include three kinds of rock (Catoosa shale, Pierre shale, and TC Siltstone), three of mountings (cantilever, cantilever chip breaker, and plate), two kinds of drilling-fluid (water and mineral oil), three kinds of cutters (polished, standard, and with 15° bevel), four different depth of cuts (0.006, 0.011, 0.033, and 0.075 in/rev), and three different back-rakes (5, 10, and 20 degree). If plate mounting is chosen, mounting cutter below a flat plate trapped the cuttings between the plate and the rock surface, forcing a massive balling condition to occur. For the cantilever mounting, produced cuttings are not trapped and therefore do not interfere with drillings. Seven tests were run in hundred percent fluid-saturated conditions. HCC provided one new data set for the full-scale test with Catoosa shale and a PDC bit (HC DP0553, 8.5 in) at 6000 psi in water-based mud (9.5 ppg). A summary of the conditions for each of the laboratory tests is in Appendix IV. The permission to present the full-scale Hughes Christensen data is in Appendix IX.

3.4.2. Cutting Area as the Indication of ROP

In single-cutter tests, all tests used the same rotary speed and the same size cutter. The only parameter showing the rate of penetration is depth of cut, DOC. It is the increase in depth per each revolution of the bit, and it is shown in Equation 3.1 in which ROP is in ft/hr, RPM is in rev/min, and DOC is in in/rev. For all single-cutter tests, DOC remained constant during each individual test.

$$DOC = \frac{ROP}{5 \times RPM} \quad \text{...}(3.1)$$

In earlier stages of the test, when the cutter is not in full contact with the rock, the depth of cut is not a good indicator of ROP; therefore, the only valid time that the depth of cut can be used as the indicator of ROP is when the cutter is in full contact with the rock. But the test duration is a very short time, and the time of full contact is a small proportion of the total time. Therefore, if the depth of cut is used as an indicator of ROP, only a small proportion of the test data at constant ROP can be used from a given test. Consequently, the area of the cutter face in contact with the rock (cutting area) during the test is calculated because the cutting area shows the volume of removed rock by the cutter. Thus, the cutting area is a better indicator of ROP because all recorded test data are used, and our new ROP indicator starts from zero and reaches to the steady-state value. As a result, more information about the change in drilling parameters versus each other can be gained. The method used for calculating the cutting area is given in Appendix V.

3.4.3 The Method for Calculating ¶Y/¶X

For calculating the ∂Y/∂X ratio, as shown in Figure 3.3, a part of all data sets for X and Y is selected (for the region for which the ∂Y/∂X is needed to be calculated), and the slope of the line for these two sets of X and Y is calculated using linear regression (polynomial curve fitting of degree one using least square method – MATLAB™ function polyfit). Thus, ∂Y/∂X is equal to this slope. A complete description is in Appendix VIII.

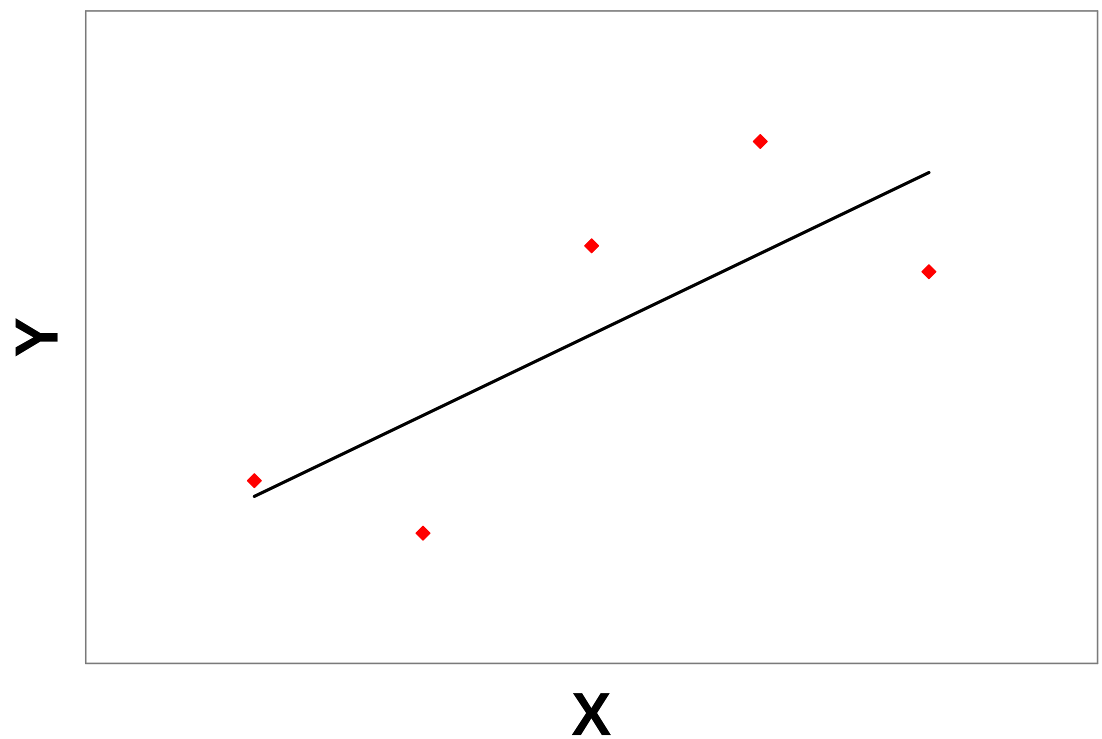

Figure 3.3 – X and Y

3.4.4. Overview of the Laboratory Data

3.4.4.1. The Full-Scale Test

In this section, the test data is separated into different regions where each region represents one phenomenon. For this reason, different points, which show the start or end of each region, are selected. As shown in Figure 3.4, during the early data starting from the origin and ending in point S, the bit is not in full contact with the rock, so the ROP calculation is not valid. Only the data after these points is used in the next sections. From point S to point A, increasing WOB increases ROP, and this region is concluded to be a “clean drilling” region. From point A to point B, increasing WOB increases ROP, but not as much as the rate of clean drilling region. This region is concluded to be a “cleaning limited” region. From point B to points C, D, and E, increasing (region B-C), constant (region C-D), or decreasing (region D-E) WOB decreases ROP, and this region is considered to be the "balling" region. The bit was in fact found to be balled at the end of the test. Also, point B is called the "flounder point" based on the definition in Bourgoyne.[3]

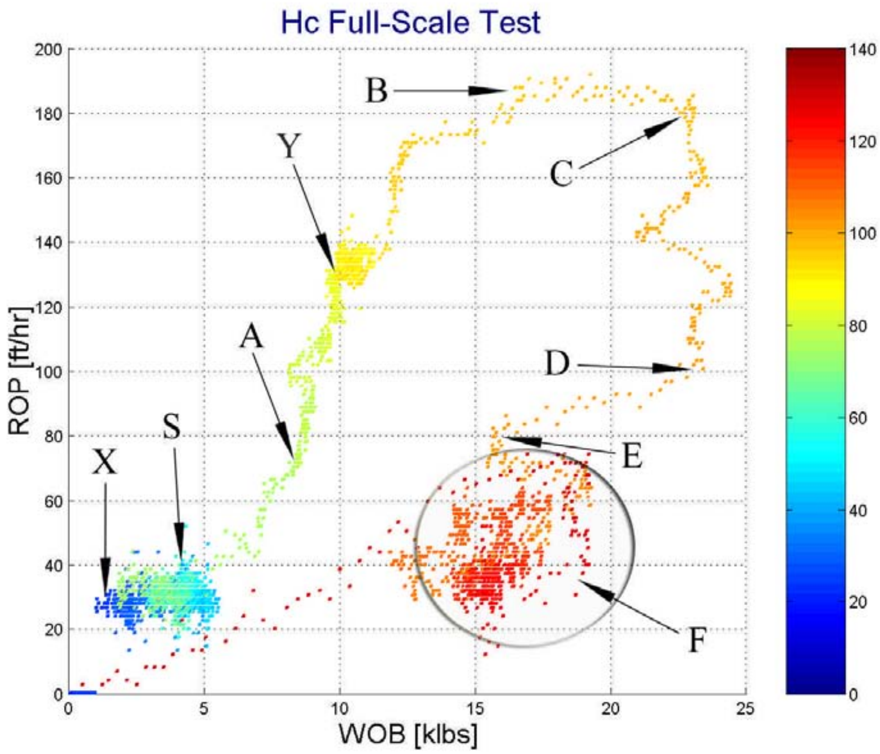

Figure 3.4 – Full-Scale Test - ROP vs. WOB vs. Time (Color)

As shown in Figure 3.5, point S reveals the earliest valid data. From point S to point A, increasing WOB increases torque, and this region is called the "clean drilling" region. From point A to point B, increasing WOB increases torque, and this region is called the "cleaning limited" region. From point B to points C, D, and E, increasing (region B-C), constant (region C-D), or decreasing (region D-E) WOB decreases ROP, and this region is called the "balling" region. Also, point B is called the "flounder point." The same points and regions are shown versus time in Figure 3.6 for WOB and time, in Figure 3.7 for ROP and time, and in Figure 3.8 for torque and time.

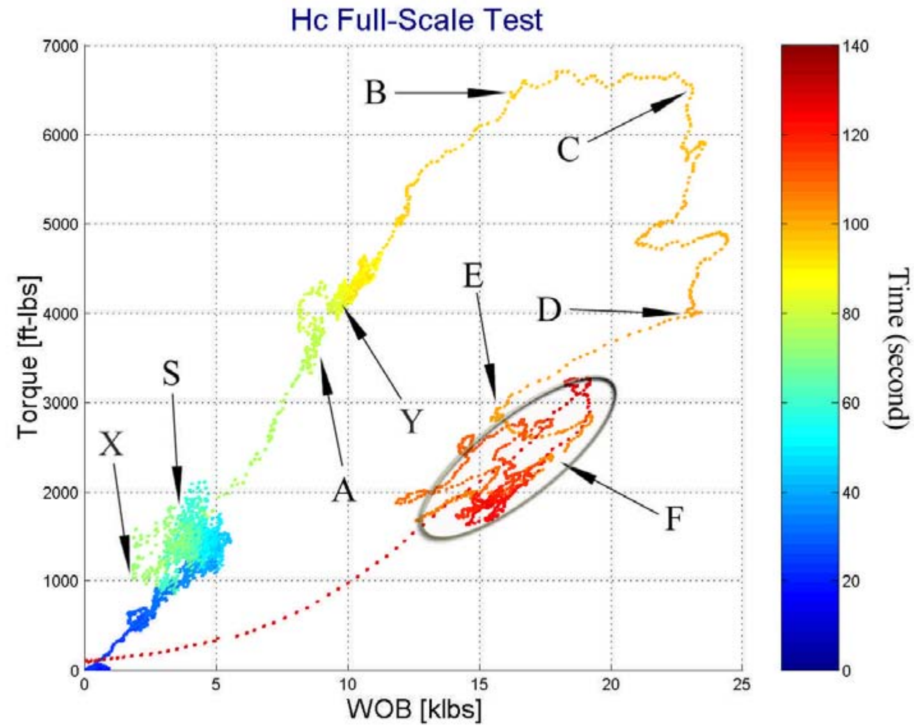

Figure 3.5 - Full-Scale Test - Torque vs. WOB vs. Time (Color)

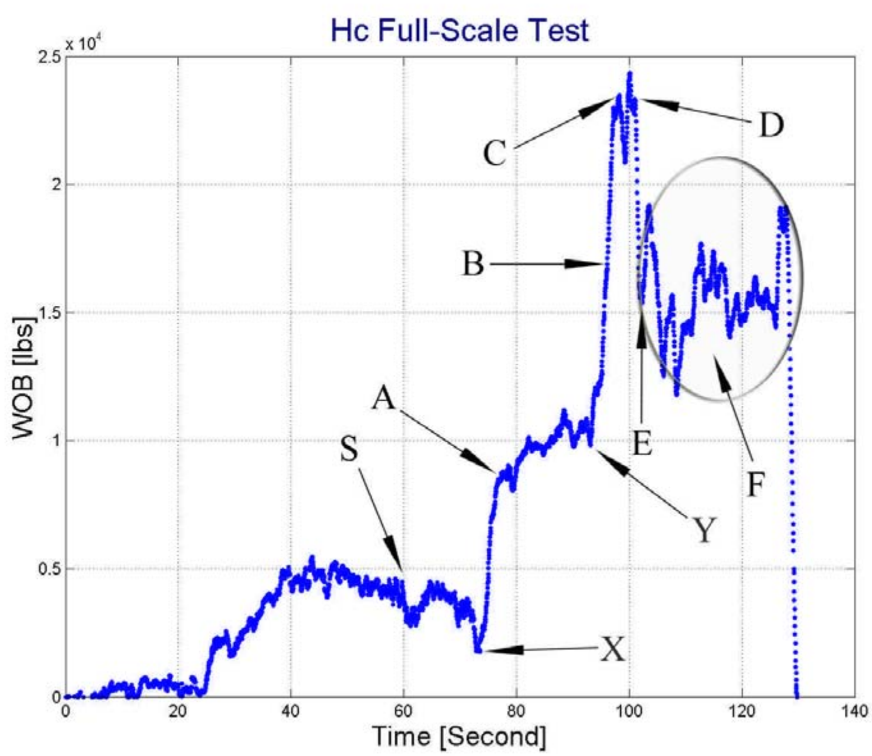

Figure 3.6 - Full-Scale Test - Time vs. WOB

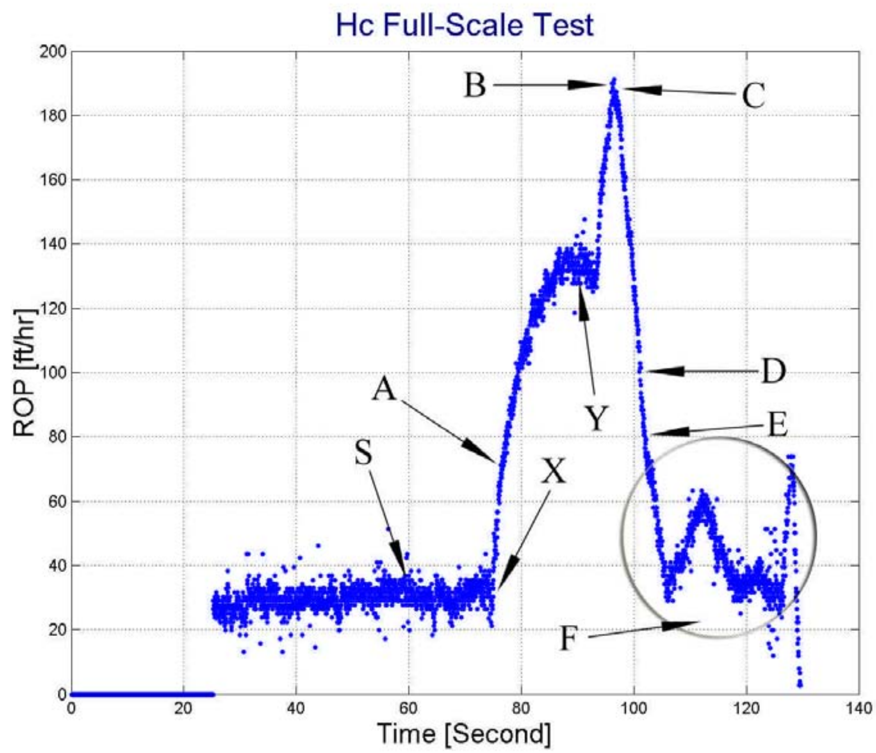

Figure 3.7 - Full-Scale Test - Time vs. ROP

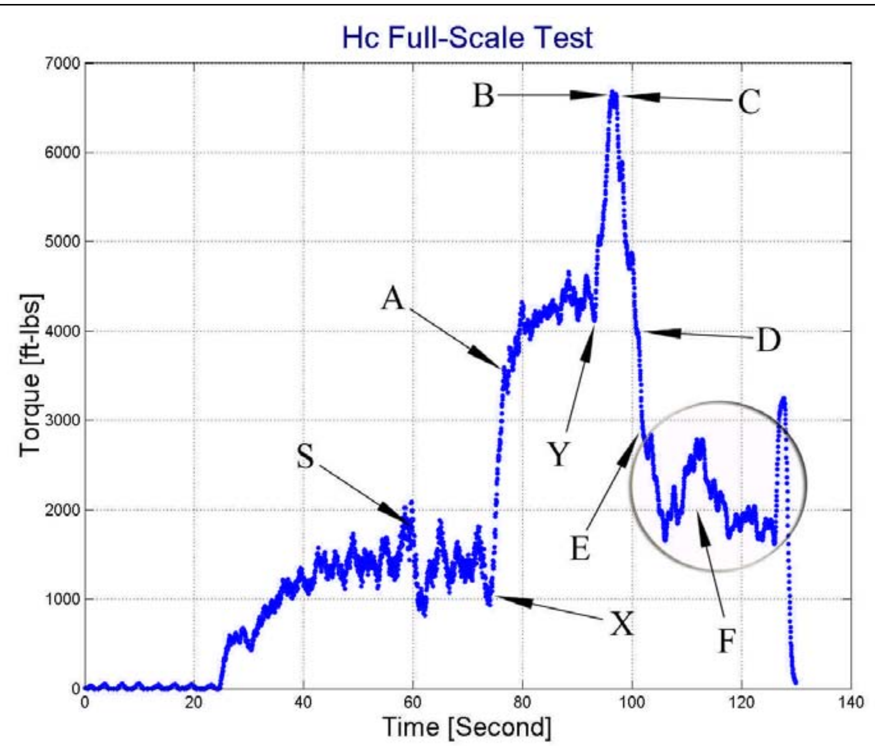

Figure 3.8 - Full-Scale Test - Time vs. Torque

A conventional diagnostic parameter, force ratio, is shown in Figure 3.9. In the clean drilling region (before A), the force ratio is increased gradually. In the cleaning limited region (A-B), the force ratio decreases gradually at first, but the rate of decrease is greater as the operating conditions approach the flounder point. In the balling region (B to points C, D, and E), the force ratio is decreases more rapidly.

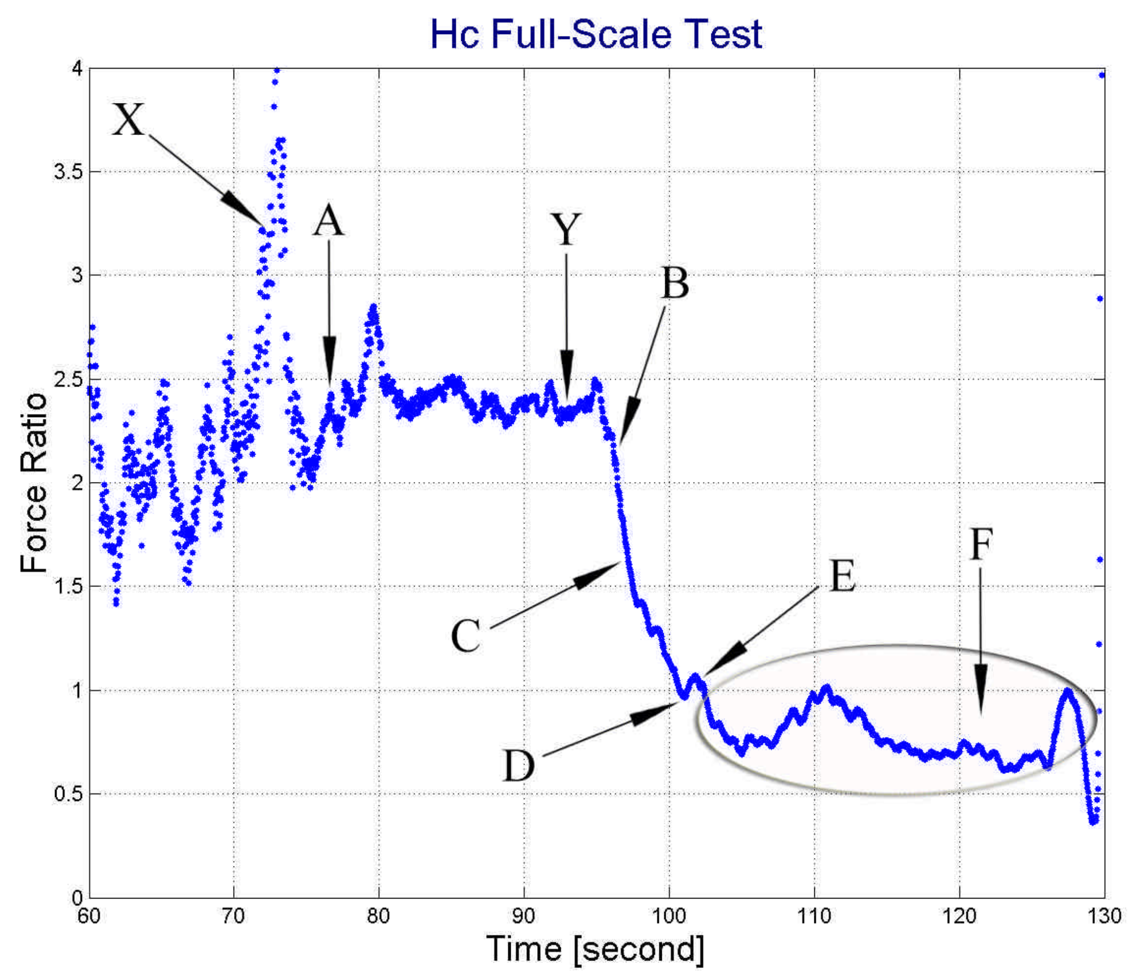

Figure 3.9 - Full-Scale Test - Time vs. Force Ratio

Another conventional diagnostic parameter, specific energy, is shown in Figure 3.10. In the clean drilling region (before A), the specific energy decreases gradually. In the cleaning limited region (A-B), the specific energy decreases gradually, also. In the balling region (B to points C, D, and E), the specific energy increases gradually.

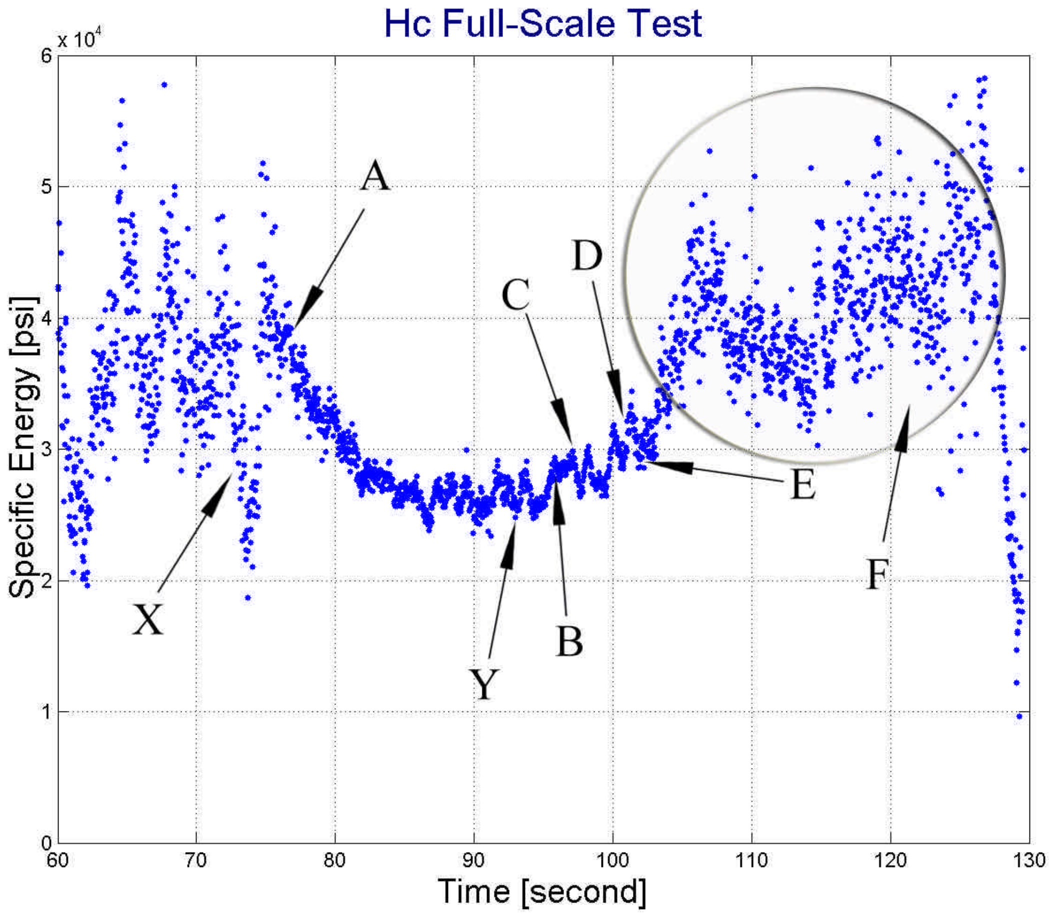

Figure 3.10- Full-Scale Test - Time vs. Specific Energy

3.4.4.2. Single-Cutter Tests

Because of the limited time and constant ROP in single-cutter tests, the previously introduced regions cannot be shown precisely. Therefore, the only possible observable point is discussed. The values of axial force (representative of WOB) versus cutting area (representative of ROP) for clean drilling (cantilever) and balling (plate) are shown in Figure 3.11. Logically, point B is the beginning of the balling, and as cutting area increases, the severity of the balling increases.

The values of axial force versus cutting area for clean drilling (Cantilever) in Catoosa shale and siltstone are compared in Figure 3.11. Logically, point B could be the beginning of the balling, and as cutting area increases, the severity of the balling increases.

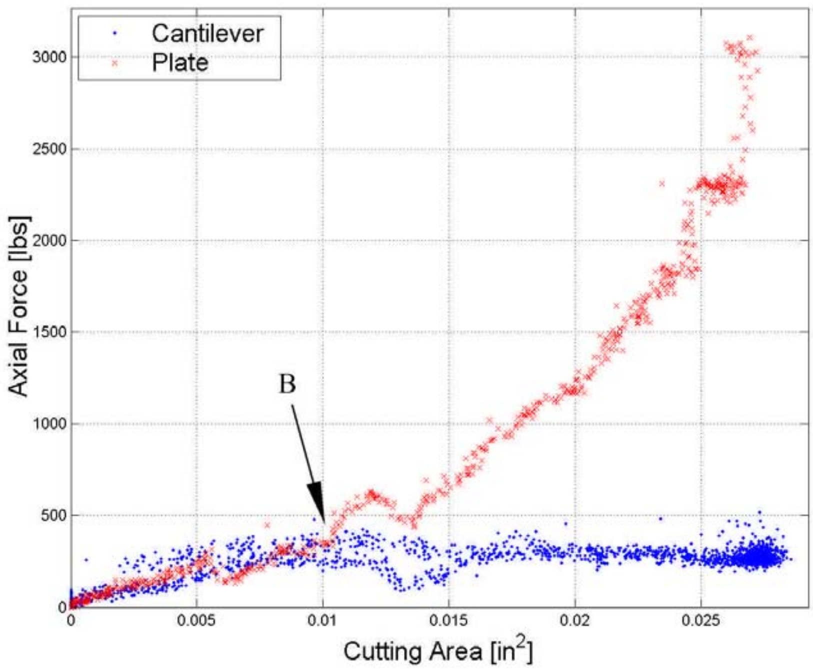

Figure 3.11 – Single-Cutter Test – Cutting Area vs. Axial Force for Plate and Cantilever (Tests 7058B and 7074B-Catoosa-Polished-Water-10BR-9000psi-0.075DOC)

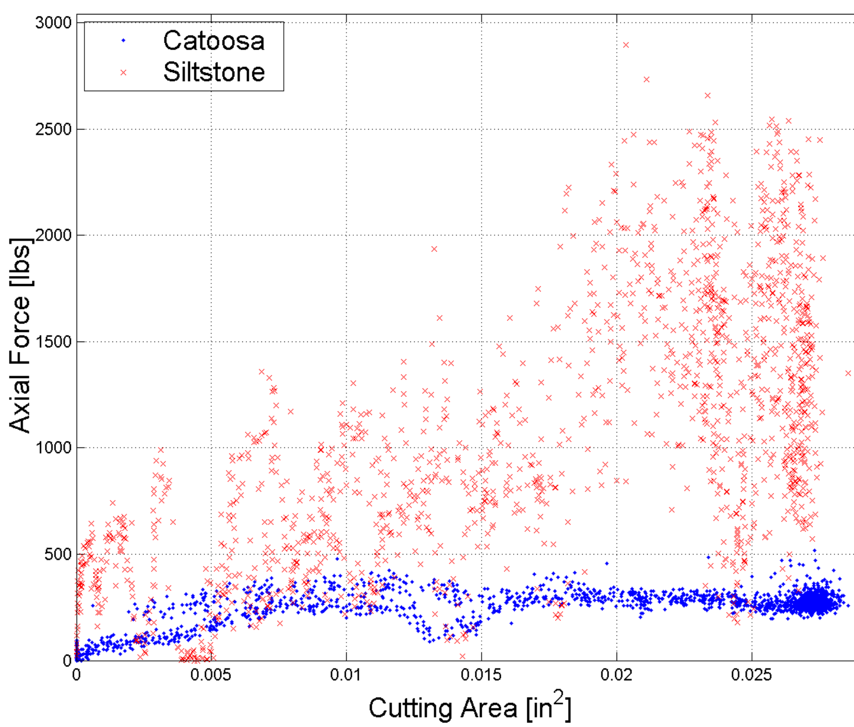

Figure 3.12 – Single-Cutter Test – Cutting Area vs. Axial Force for Catoosa and Siltstone (Tests 7058B and 7058U-Cantilever-Polished-Water-10BR-9000psi-0.075DOC)

3.4.5. Some Observations of Different Conditions

3.4.5.1. Introduction

Comparing the trend and values of selected factors in different conditions in laboratory tests gives some ideas about the relationship between the parameters and events. These observations are needed to support the bit performance diagnosis concepts to be considered in this research.

3.4.5.2. Possible Crack or Heterogeneity in Rock Samples

Because of the possible crack or heterogeneity in rock samples, sometimes a few records do not act as expected. For example, in the relationship between torque and cutting area, few points scatter from the expected trend (shown in Figure 3.13).

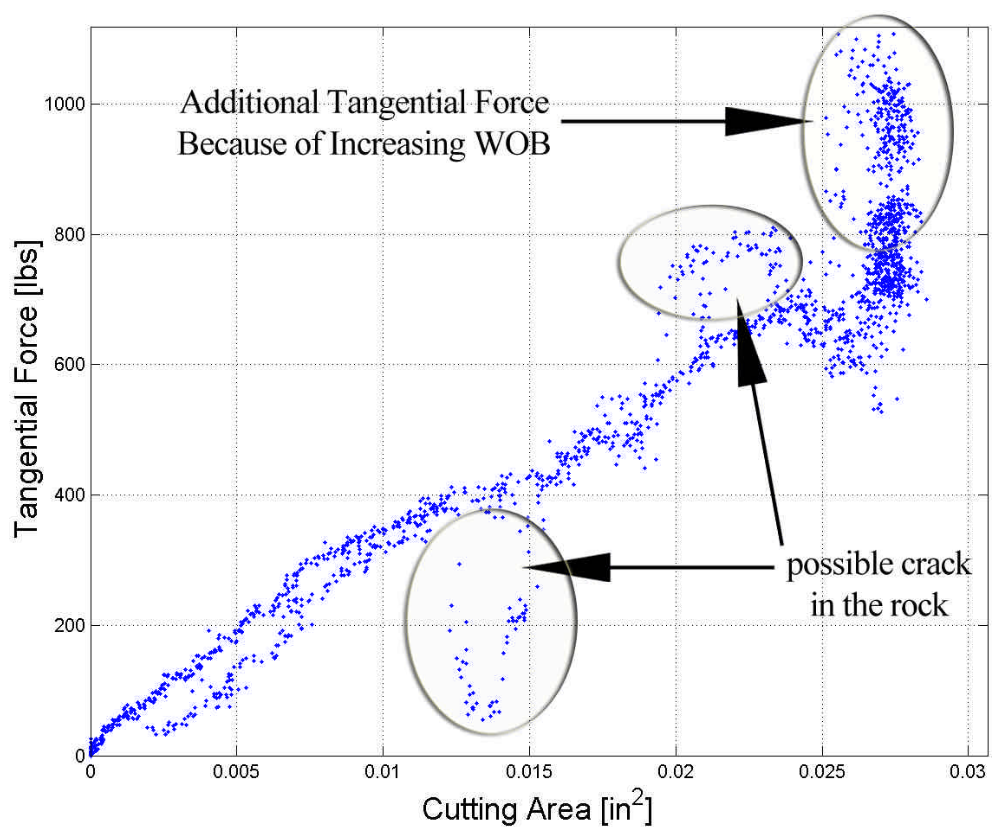

Figure 3.13 – Single-Cutter Test – Cutting Area vs. Tangential Force for Catoosa (Test 7058B-Catoosa-Cantilever-Polished-Water-10BR-9000psi-0.075DOC)

3.4.5.3. Making Constant ROP Is Not Realistic

In all single-cutter tests, the cutter moves at a constant speed. But in the early stages of drilling because the cutter is not in full contact with the rock, the amount of cutting starts at zero (at the first contact of the cutter with the rock sample) to a constant value (at a final speed in steady-state condition), and it remains in that steady-state condition for some time. Thus, in all these tests, the speed is set at input, and axial, tangential, and radial forces are the outputs. However, in real situations in the fields, the input is WOB, and outputs are ROP and Torque.

This variation makes some differences in the behavior of drilling, especially in balling or flounder point situations. For example, in the situation of the balling after WOB increases more than the flounder point, in real situations the ROP is reduced; however, in the single-cutter test situation, because ROP is constant, WOB increases. As shown in Figures 3.14 and 3.15, it can be seen that this difference could be misleading.

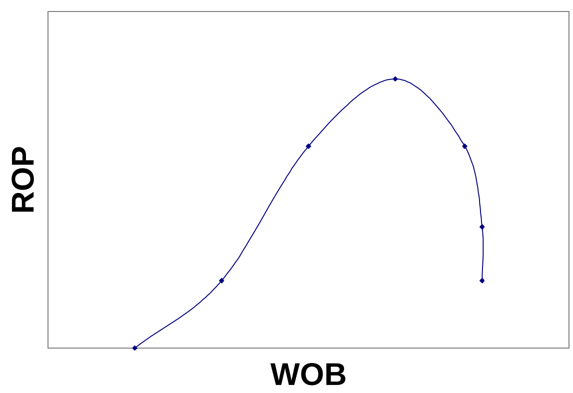

Figure 3.14 – WOB vs. ROP (in Field)

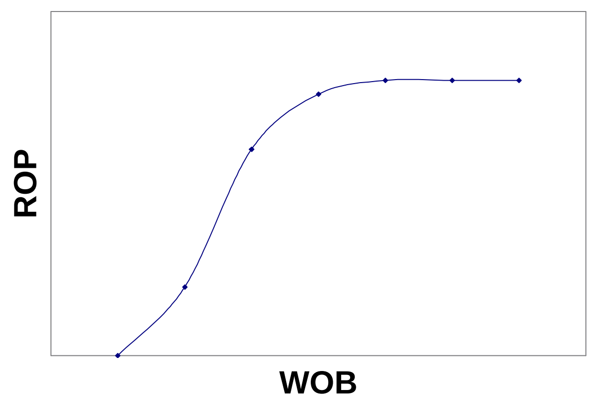

Figure 3.15- WOB vs. ROP (in Single-Cutter Tests)

3.4.5.4. High Noise in Strong Rock

In all single-cutter tests on siltstone, high noise is observed, and when DOC is increased, the noise is increased. Therefore, because of high noise in all measured data, the cutting area calculation probably is not accurate in these tests (shown in Figure 3.16)

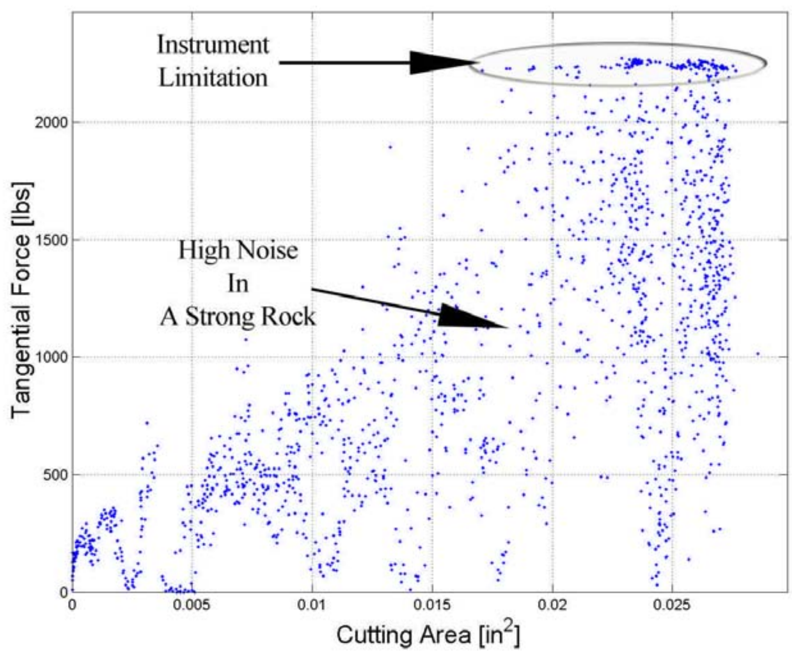

Figure 3.16 – Single-Cutter Test – ROP vs. Torque for Siltstone
(Test 7058U-Siltstone-Cantilever-Polished-Water-10BR-9000psi-0.075DOC)

3.4.5.5. An Opinion about the Maximum Measured Tangential Force

It seems that because of instrument limitations, the maximum measured tangential force is not measured correctly at values larger than some definite number. As shown in Figure 3.16, after the tangential force is increased more than the limitations, the value of tangential force is measured as the limit value, so this limitation could be misleading.

3.4.5.6. Similarity in Tests with Different DOC

Cutting area is used during the stage before steady-state, as indicative of performance at a lower ROP to make a comparison between tests with different DOC (all other drilling operating and cutter design parameters are the same). As a result, in all clean-drilling tests (not balling) for both siltstone (shown in Figures 3.17 and 3.18) and Catoosa (shown in Figures 3.19 and 3.20), axial and tangential forces follow the similar values versus cutting area. So Therefore, if something makes forces to change path, then probably some of the conditions (like balling) are changed, and these changes could be helpful to find the causes of them.

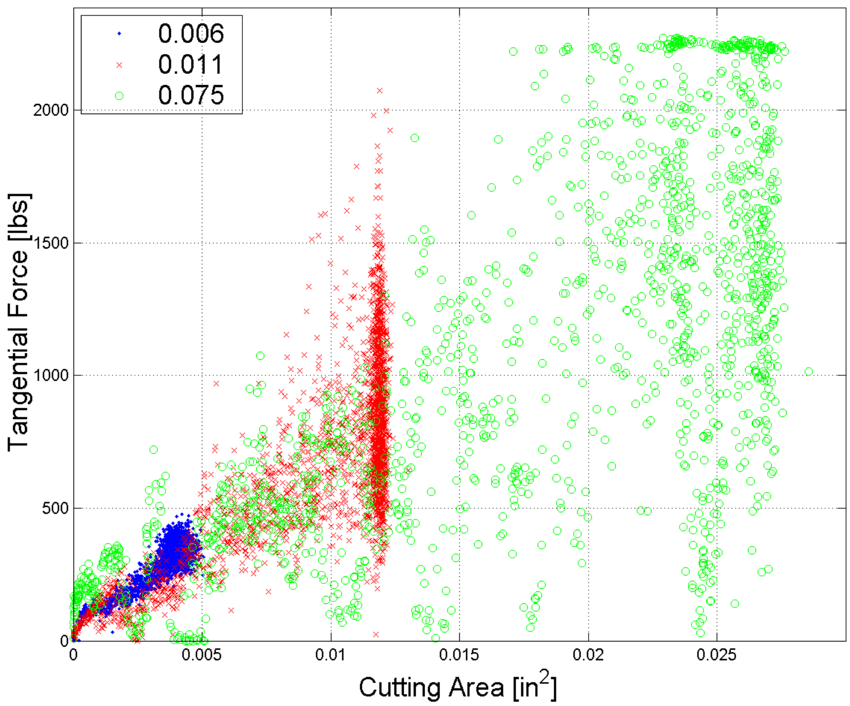

Figure 3.17 – Single-Cutter Test – ROP vs. Torque for Siltstone – Different DOC
(Tests 7058I,7058Q,7058U-Siltstone-Cantilever-Polished-Water-10BR-9000psi)

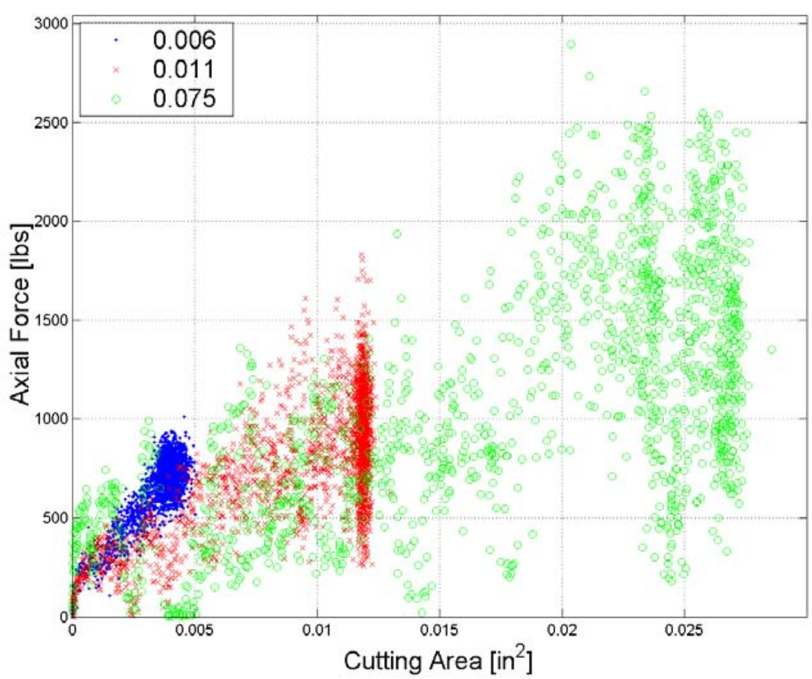

Figure 3.18 - Single-Cutter Test – ROP vs. WOB for Siltstone – Different DOC
(Tests 7058I,7058Q,7058U-Siltstone-Cantilever-Polished-Water-10BR-9000psi)

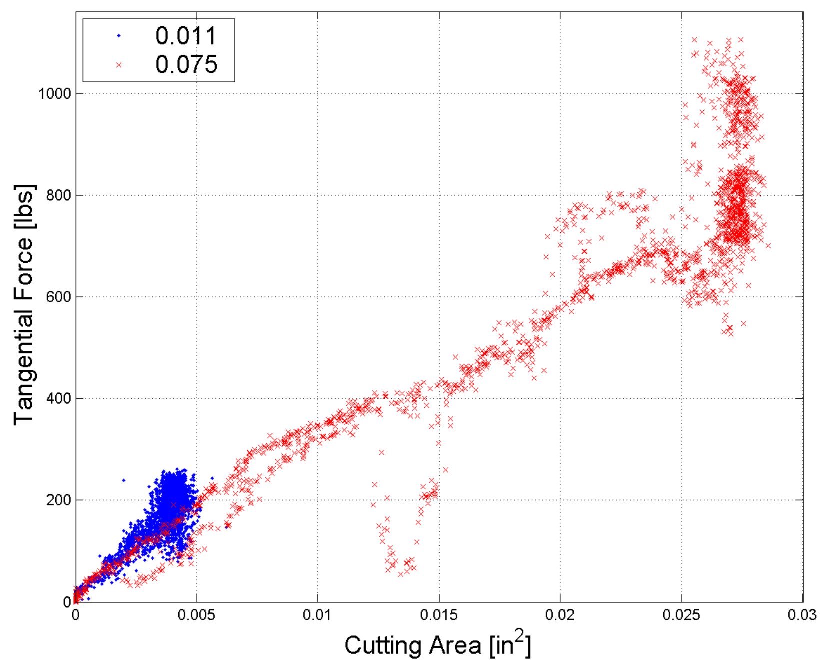

Figure 3.19 – Single-Cutter Test – ROP vs. Torque for Catoosa – Different DOC
(Tests 7058A,7058B-Catoosa-Cantilever-Polished-Water-10BR-9000psi)

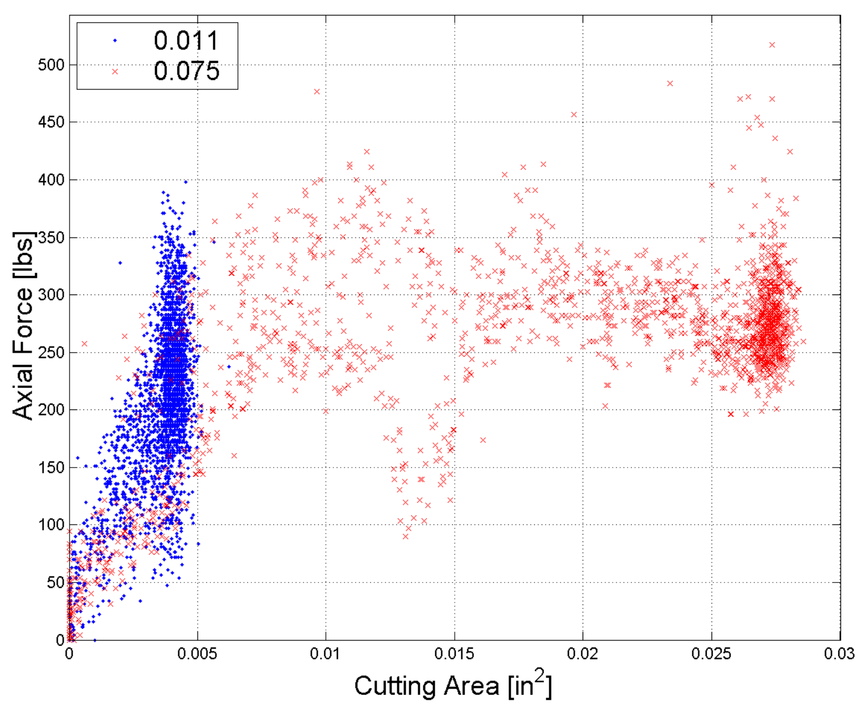

Figure 3.20 – Single-Cutter Test – ROP vs. WOB for Catoosa – Different DOC
(Tests 7058A,7058B-Catoosa-Cantilever-Polished-Water-10BR-9000psi)

3.4.6. A Hypothesis about the Relationship between Torque and ROP

3.4.6.1. Separate Torque to Different Terms

As shown in Equation 3.2, the torque (tangential force in single-cutter tests) could be separated into different terms as following:

$$Torque_{Total} = Torque_{BreakingRock} + Torque_{Friction} + Torque_{Acceleration} + Torque_{MovingCuttings} \text{ ....(3.2)}$$

The first term ($Torque_{BreakingRock}$) is a function of ROP, rock properties, and confining pressure; furthermore, for a specific rock, increasing ROP will increase this term. Also, this part is not effected significantly by WOB, fluid type, or balling.

The second term ($Torque_{Friction}$) is the friction force, and it includes two parts: 1) a constant friction force at zero WOB and 2) a variable friction force which increases with increasing WOB. Both terms of this friction appear to depend on rock properties, fluid type, confining pressure, etc., but changing ROP probably does not affect this friction much. However, balling reduces the rate of increasing the friction force with WOB because balled material fills spaces between cutters of the bit, and the friction coefficient of bit is reduced.

The third term ($Torque_{Acceleration}$) is the force due to acceleration in the bit, cutters, and cuttings. Because the force due to acceleration is equal product of mass and acceleration and because both the mass of and acceleration in the cutting are relatively small, this term is probably negligible.

The fourth term ($Torque_{MovingCuttings}$) is the force due to moving produced-cuttings, and this force is equal to zero at the start of drilling, increasing gradually (in single-cutter tests) because of an accumulation of cuttings which are not removed. This torque is negligible most of the time, but the accumulation of cuttings interferes with drilling. Moreover, it requires an increase in WOB to accomplish the requested ROP (which is preset for the single-cutter test), so the frictional torque increases (shown in Figures 3.13 (additional torque) and 3.21 (additional WOB)).

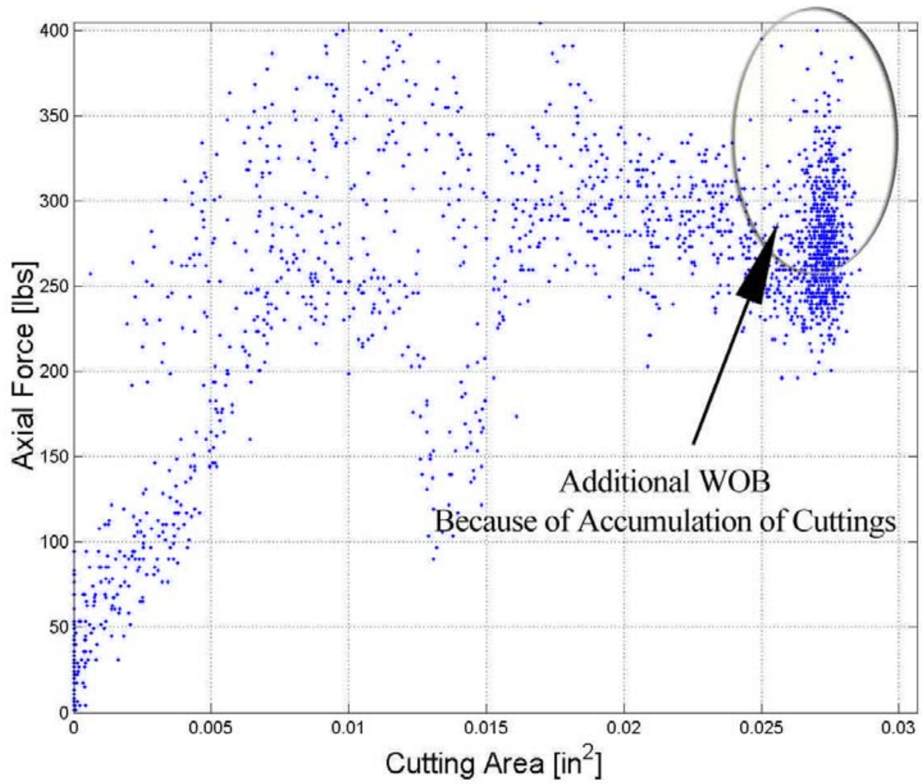

Figure 3.21 – Single-Cutter Test – ROP vs. WOB for Catoosa
(Test 7058B-Catoosa-Cantilever-Polished-Water-10BR-9000psi-0.075DOC)

As seen in Tables 3.1 and 3.2, if DOC is increased from 0.011 in/rev to 0.075 in/rev (6.8 times larger) and axial force remains constant, the total tangential force is increased from 275 lbs to 1100 lbs (4 times larger). In addition to that, if the cutting area remains constant (similar to ROP constant) and the axial force is increased from 275 lbs to 2200 lbs in an attempt to overcome balling (8 times larger), the tangential force is increased from 700 lbs to 1100 lbs (1.6 times larger). As shown, the effect on the tangential force of changing DOC at constant WOB is 4/6.8=0.6, and the effect of changing WOB at constant ROP is 1.6/8=0.2. Comparing these two values, the effect of changing ROP is three times greater than the effect of changing WOB; thus, the effect of $Torque_{BreakingRock}$ is much greater than the effect of $Torque_{Friction}$.

Table 3.1 – Effect of ROP on Torque (Catoosa-Plate-Polished-Water-10BR-9000psi)		
Axial Force = 2200 lbs	Balling 0.011 DOC (Test 7074A) lbs	Balling 0.075 DOC (Test 7074B) lbs
Tangential Force	275	1100

Table 3.2 – Effect of WOB on Torque (Catoosa- Polished-Water-10BR-9000psi-0.075DOC)		
Cutting Area = 0.025 in^2	Clean Drilling (Cantilever) (Test 7058B) lbs	Balling (Plate) (Test 7074B) lbs
Tangential Force	700	1100
Axial Force	275	2200

3.4.6.2. The Hypothesis about the Effect of Other Drilling Parameters on the Relationship between Torque and ROP

As mentioned in the previous sections, total torque may be viewed as being separated into four parts. However, in field situations, the forces are not changed rapidly, and as stated before, the torque to move cuttings is negligible; thus, only the first two parts of torque remain. If the sample is drilled at low WOB, the first part ($Torque_{BreakingRock}$) is much bigger than the second part ($Torque_{Friction}$) (Section 3.4.6.1). As shown in Figures 3.22 (increase in axial force) and 3.23 (increase in tangential force) (0.075 DOC), and 3.24 (increase in axial force) and 3.25 (increase in tangential force) (0.011 DOC), changing WOB to high values increases the frictional torque a little. Furthermore as shown in Table 3.3 and Equation 3.3, the cutting area is constant in all the points of that test; because the $Torque_{BreakingRock}$ is constant. Therefore, changing total torque changes just the $Torque_{Friction}$. As shown, increasing the first 1000 lbs increases $Torque_{Friction}$ 50 lbs, but increasing the second 1000 lbs increases $Torque_{Friction}$ just 30 lbs. Consequently, the figures show WOB increasing to very high values; also, by reducing the friction coefficient, the rate of increasing frictional torque decreases while WOB increases. As a result, there is not much difference between severe balling torque (such as test 7058O in which friction coefficient is smaller) and small balling (at the end of test 7058B in which friction coefficient is larger).

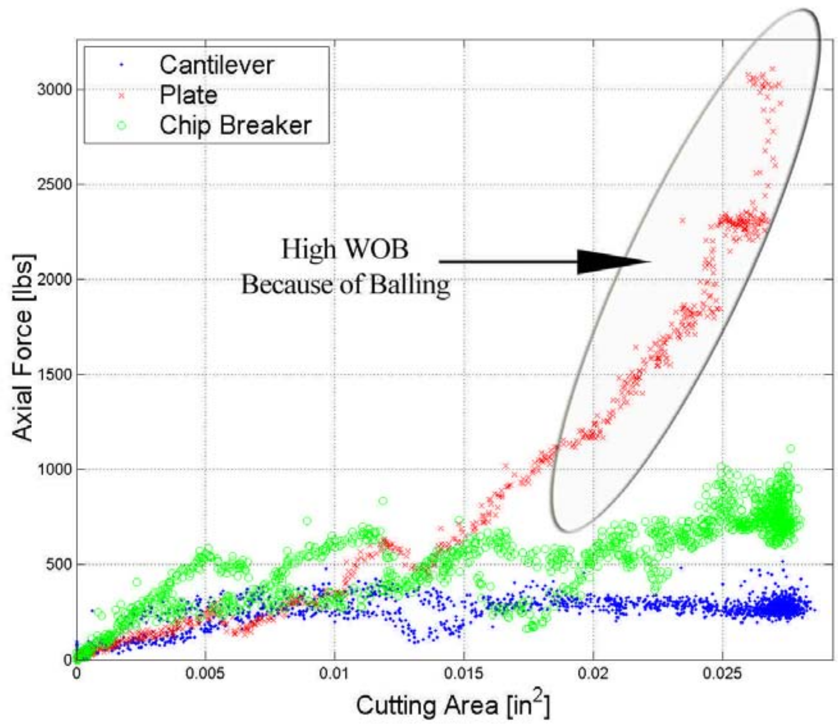

Figure 3.22 – Single-Cutter Test – ROP vs. WOB for Catoosa–Different Mounting
(Tests 7058B,7058O, and 7074B-Catoosa-Polished-Water-10BR-9000psi-0.075DOC)

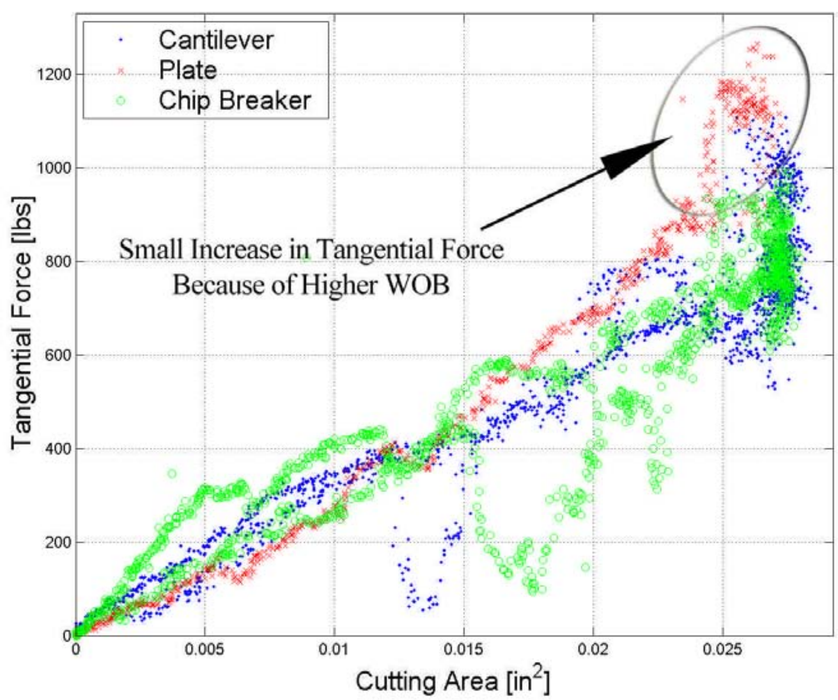

Figure 3.23 – Single-Cutter Test – ROP vs. Torque for Catoosa–Different Mounting
(Tests 7058B,7058O, and 7074B-Catoosa-Polished-Water-10BR-9000psi-0.075DOC)

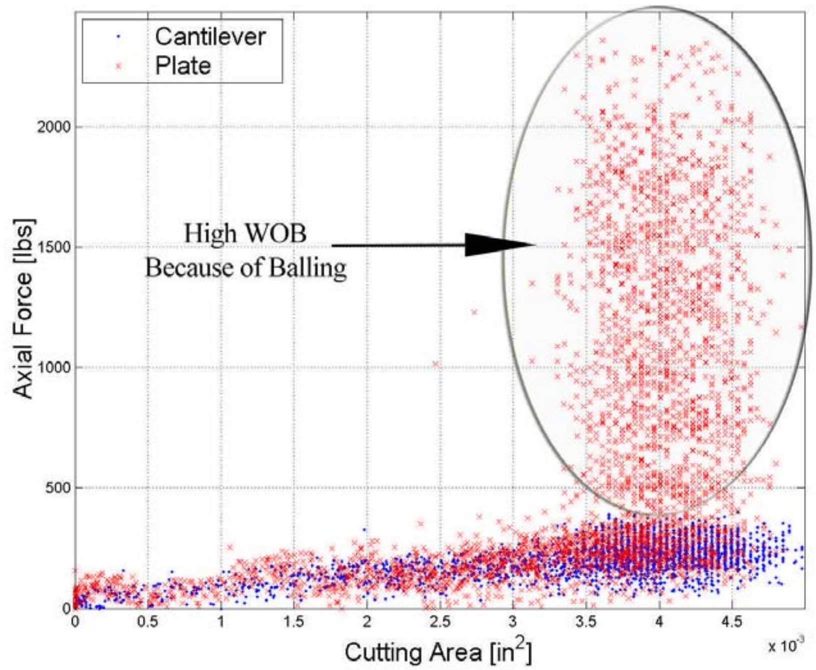

Figure 3.24 – Single-Cutter Test – ROP vs. WOB for Catoosa–Different Mounting (Tests 7058A, and 7074A-Catoosa-Polished-Water-10BR-9000psi-0.011DOC)

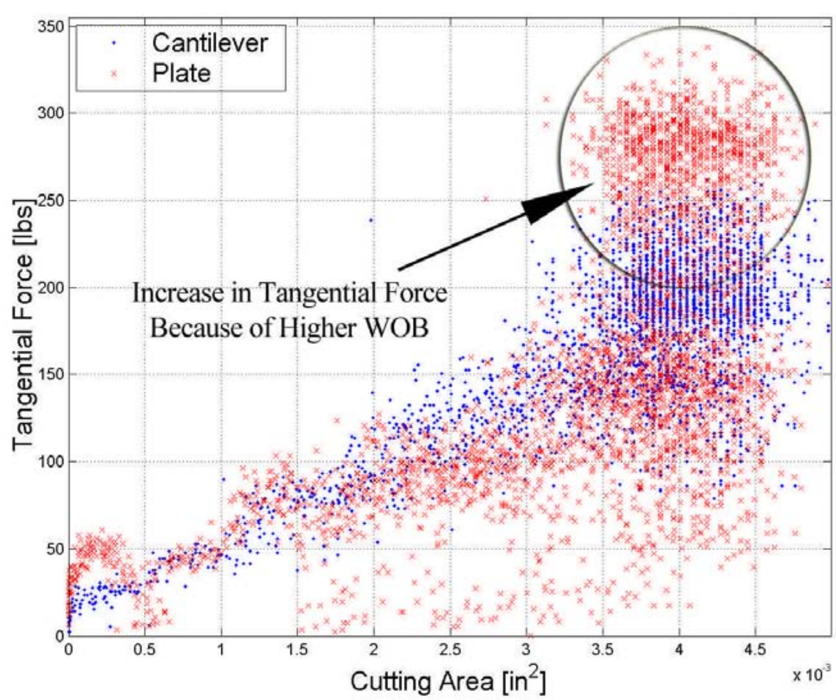

Figure 3.25 – Single-Cutter Test – ROP vs. Torque for Catoosa–Different Mounting (Tests 7058A, and 7074A-Catoosa-Polished-Water-10BR-9000psi-0.011DOC)

Table 3.3 – Friction Coefficient Effect (Catoosa- Polished-Water-10BR-9000psi-0.011DOC)		
Cutting Area = 0.004 in^2	Axial Force lbs	Tangential Force lbs
Clean Drilling (Cantilever) (Test 7058A) and Balling (Plate) (Test 7074A) Point1	250	200
Balling (Plate) (Test 7074A) Point2	1250	250
Balling (Plate) (Test 7074A) Point3	2250	280

$$Torque_{Total} = Torque_{BreakingRock} + Torque_{Friction} \quad \text{..(3.3)}$$

Furthermore, as seen in Figure 3.26 for the full-scale test (the points in the figure are the same points as Section 3.4.4.1 and Figure 3.4), increasing WOB increases ROP up to the flounder point (point B); then balling occurs, and ROP decreases. However, in this case WOB is higher for clean drilling, and because WOB is not so high, the frictional part of torque is still negligible compared to the torque required to break the rock. As a result, the torque comes back on the same path as when the WOB is lower, and the changing WOB in this test does not affect the relationship between ROP and torque.

Comparing two different kinds of rocks (Catoosa and siltstone), the tangential force in the siltstone is much higher because the siltstone is stronger than the shale. Conversely, the effects of different fluids (Water and Mineral Oil), or different fluid saturation (100% and 0% water saturation) on torque in the same kind of rock (shale) are negligible. Thus, the kinds of rock and bit design mostly control the relationship between ROP and Torque, and WOB has little influence on this relationship (shown in Figure 3.27). In conclusion, the torque at the bit is controlled primarily by rock type, bit design, and the rate of penetration, and it changes in other parameters, such as WOB, bit balling, fluid type, and saturation, having little or no effect on changing this relationship.

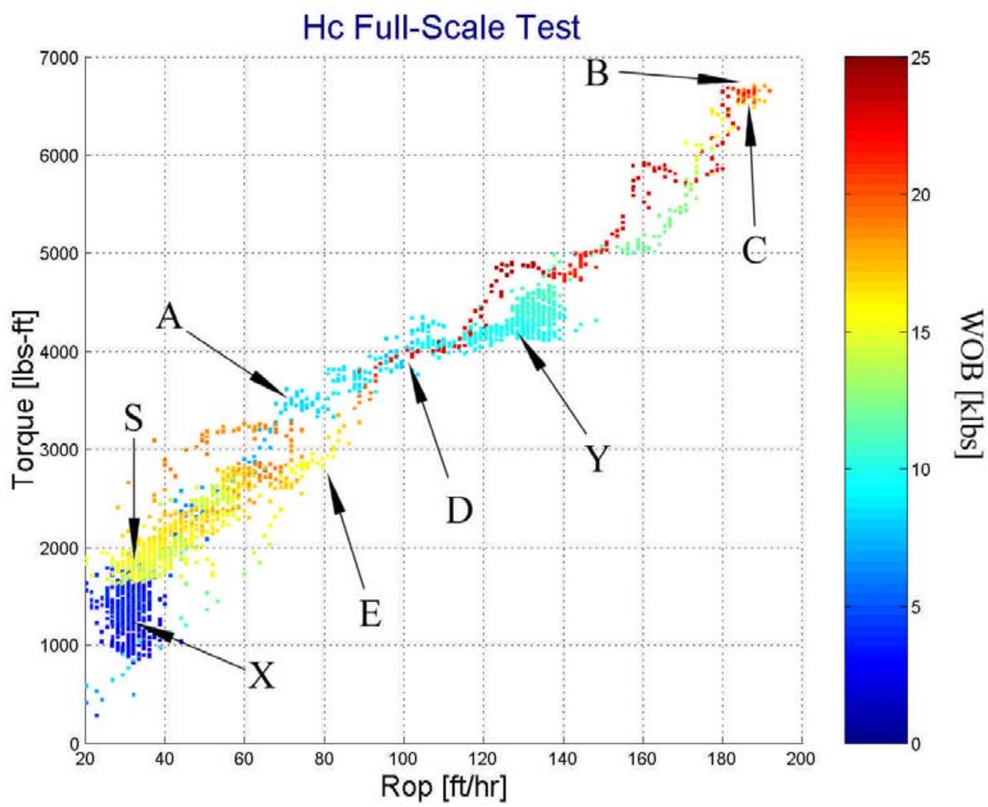

Figure 3.26 – Full-Scale Test – ROP vs. Torque
(Full-Scale Test – Torque, ROP, and WOB (Color))

3.4.6.3. Opinion about Very High WOB in a Single-Cutter

In all single-cutter tests in the situation of balling, the axial force on a cutter reaches to 2500 lbs (shown in Figure 3.11 for the plate). The situation is not strongly related to field situations because a very high force in a single-cutter is equal to a very large WOB in real situations (for example, for 20 cutters in a bit, WOB could be around 50-60K lbs). Therefore, as mentioned in Section 3.4.6.1, $Torque_{BreakingRock}$ primarily controls total torque, and $Torque_{Friction}$ could be neglected. However, if the WOB reaches high values, $Torque_{Friction}$ also has an effect on the value of total torque, and reaching results from different phenomenon, which are probably negligible in the field, could be misleading.

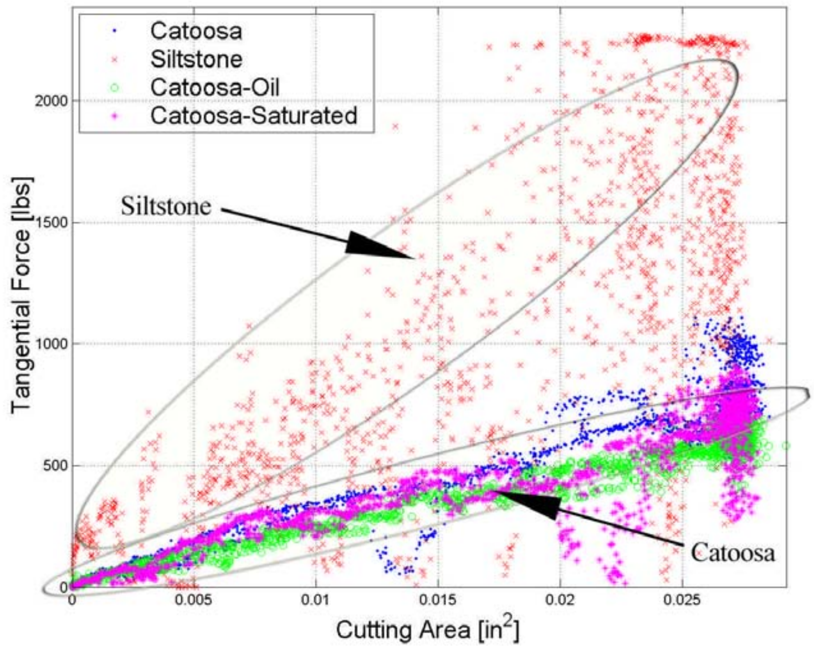

Figure 3.27 – Single-Cutter Tests - ROP vs. Torque - Comparison of Different Rocks (Tests 7058B,7058U,7058L, and 7058R, Polished-10BR-9000psi-0.075DOC)

3.4.7. Evaluation of Potential Diagnostic Parameters

3.4.7.1. Introduction

Based on observations in the previous section and the research studies of others (as mentioned in Chapter two), two kinds of diagnostic parameters are discussed in the following sections: 1) those parameters which are possible indicators (main diagnostic parameters) and 2) those parameters which are not used in the final method but could be beneficial for future research. Furthermore, in contrast to previous research studies, the values of the main diagnostic parameters are not used for detection of events, and diagnosis with these parameters is done by comparison to a selected baseline value for the data set. That baseline is selected from the data set, and the procedure is introduced in the following sections. For this diagnostic method, all other input variables (such as RPM, Flow rate, bit and cutter design, etc., except WOB, ROP, and Torque) should ideally remain constant during comparison. If one of those variables is changed, the entire baseline selection procedure should be repeated again.

3.4.7.2. ROP/WOB (Cutting Area/Axial Force in Single-Cutter Tests)

The value of this diagnostic parameter is similar to 1/FORS, as mentioned in Chapter two of Falconer's method (Equation 2.7).[29,61] That equation includes RPM, bit diameter, and a conversion factor (just for single-cutter tests) of changing cutting area to ROP, which are constant values in all of these tests, and they should remain constant for the proposed method. Because the method is not using values as the indicator, as in previous research, ROP/WOB shows exactly the same concepts as 1/FORS. As shown in Figure 3.28 for a hypothetical rock, the smallest WOB (in which drilling starts and ROP = 0), is called WOB_{Min}, and for a WOB less than this number, the cutter cannot drill the rock. After that point, increasing WOB increases ROP until the flounder point (in which WOB is equal to WOB_{Flund}, ROP is maximum ROP_{Max}), and increasing WOB more than the flounder point decreases ROP. The ROP/WOB ratio is calculated for the specific kind of rock. As seen in Figure 3.28, this ratio shows the angle of the line from the actual point to the origin. For increasing WOB from the minimum, the ratio starts from zero and increase to a maximum value, $(ROP/WOB)_{Max}$, similar to point A at Figure 3.4. However, this value is not maximum at the flounder point (similar to point B at Figure 3.4), and the ratio decreases with increasing WOB more than the flounder point. Consequently, if it is assumed that the flounder point is known for a weak rock, then the ROP/WOB ratio can be calculated at the flounder point. The ROP/WOB ratio from all other points will be compared with the ratio at the flounder point. If something is changed, such as RPM, the shape and behavior of the main weak rock is not going to change, but the ratio at the flounder point will be changed; the ratio at the new condition is calculated, and the comparison continues with a new value. Thus, in this research for all diagnostic parameters, the values are not important, and they are just used for comparison to the ratio at the flounder point.

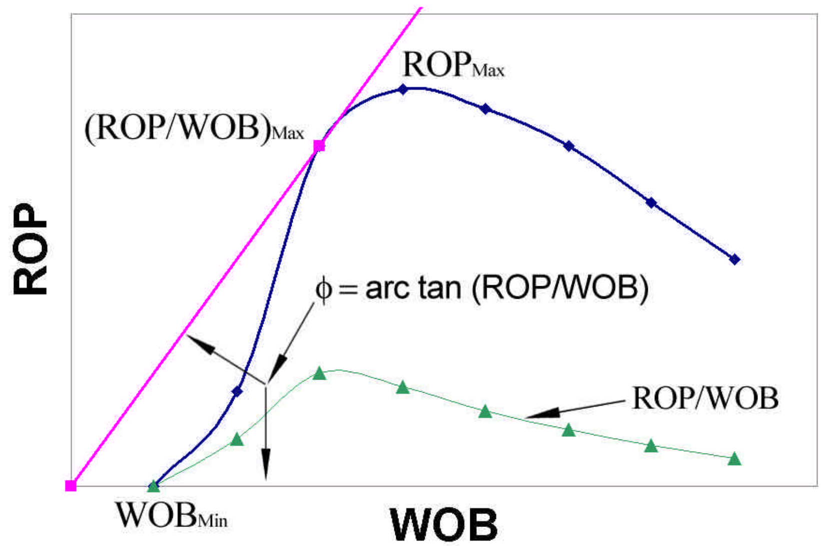

Figure 3.28 – WOB vs. ROP – Hypothetical

Figure 3.29 shows the ROP/WOB ratio in three different regions (clean drill (S-A), cleaning limited (A-B), and balling regions (B-CDE), shown in Section 3.4.4 and Figure 3.4). Note that the early time data does not show in this figure because the bit is not in full contact with the rock, and both ROP and WOB are unrealistic for this region. In the clean drilling region (except those points where ROP is inaccurate because the bit is not in full contact with the rock), the ratio is increased as moving from point S toward point A, and the values of the ratio are moderate to large. In the cleaning limited region, the ratio is increased to a maximum value, $(ROP/WOB)_{Max}$ and is reduced to the value at the flounder point (point B), so the values of the ratio are large to moderate. In the balling region, the ratio decreased (if WOB is increased) or remained constant (if WOB decreased), but the value of the ratio is always small.

If all other drilling operation parameters are the same and a stronger rock is drilled (hypothetical comparison shown in Figure 3.30), then the change in the ROP/WOB ratio can be helpful in distinguishing between different kinds of rocks or events. However, the ROP/WOB ratio could be the same in a balling situation in a weak rock (low because of low ROP and high WOB) and in a strong rock with low WOB (low because High WOB minimum and lower slope).

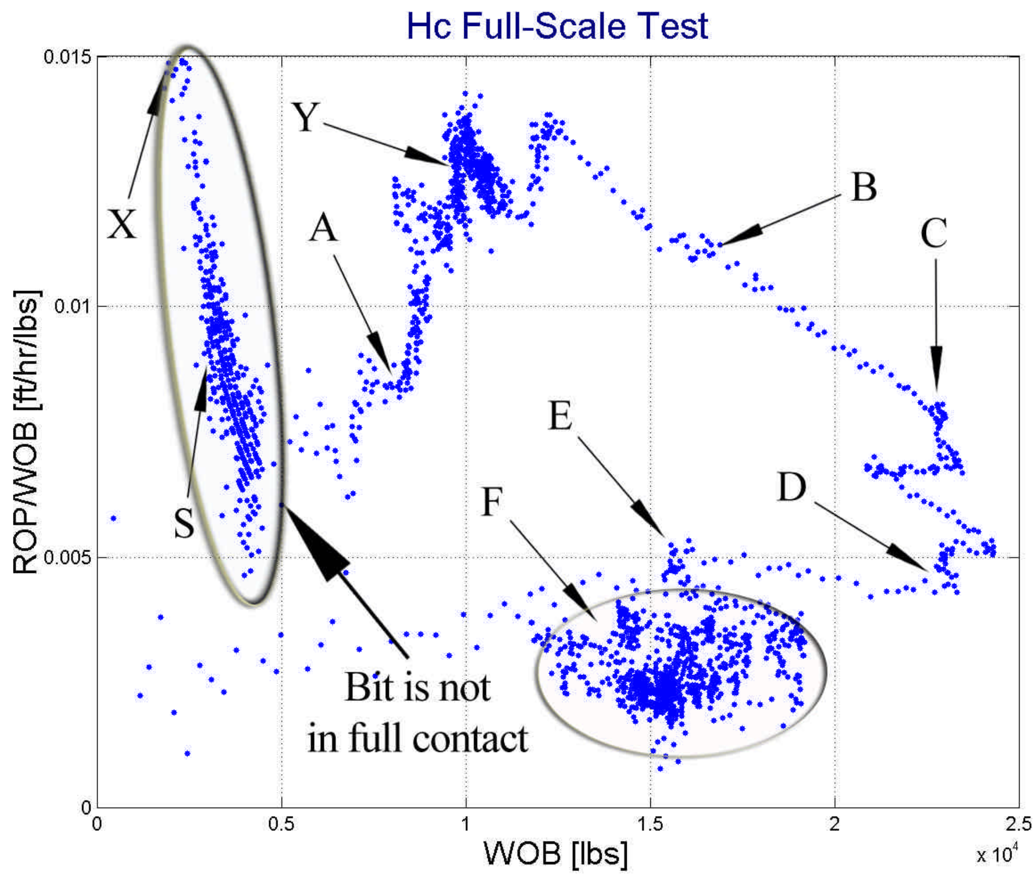

Figure 3.29 – Full-Scale Test – WOB vs. ROP/WOB

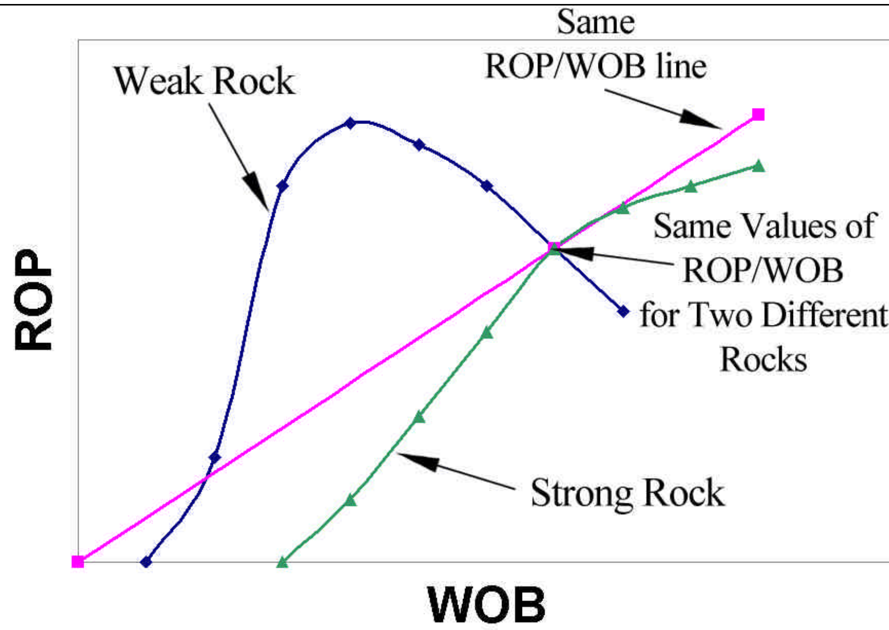

Figure 3.30 – WOB vs. ROP – Hypothetical – Two Rocks

For a hypothetical weak rock, the ROP/WOB ratio starts from zero (at low WOB) and progresses to a high value, then dropping off in the situation of balling to a very low value (low ROP and high WOB). But for the strong rock, the ratio increases versus WOB. The same concept is shown in Figure 3.31 for actual single-cutter tests, but as seen in the graph, the ratio in the balling situation is very close to the ratio in a strong rock. At constant WOB, the ratio is slightly higher in strong rocks during balling because ROP reduces in the balling situation versus time, while the ratio in strong rocks remains the same.

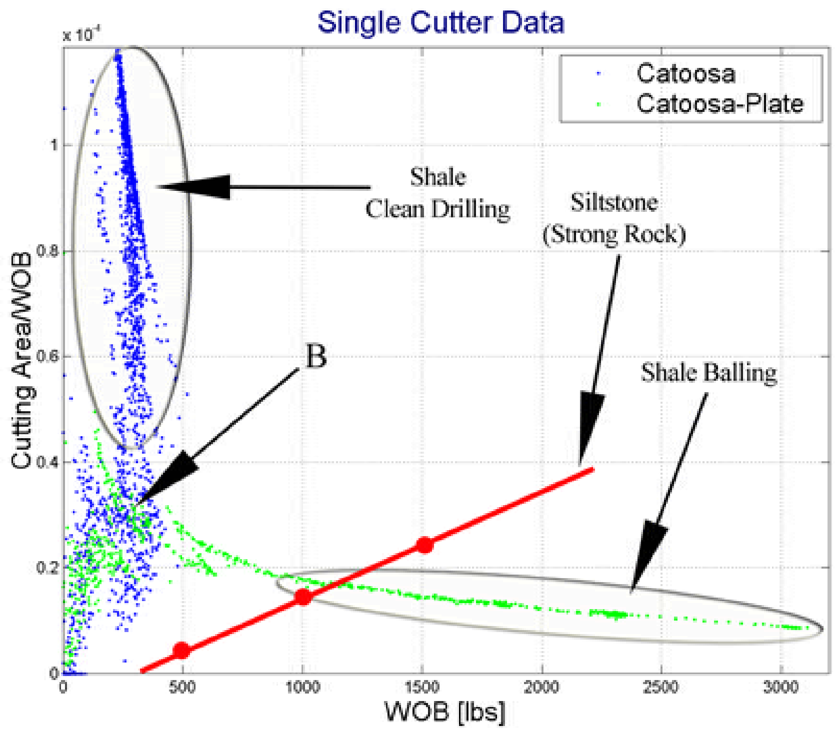

Figure 3.31 – Single-Cutter Test – WOB vs. ROP/WOB
(Tests 7058B and 7074B-Catoosa-Polished-water-10BR-9000psi-0.075DOC)
(Big points on the Figure: Tests 7058U(0.075DOC), 7058Q(0.033DOC), and 7058I(0.011DOC)-Siltstone-Polished-water-10BR-9000psi)

In conclusion, in comparison to the flounder point ratio, the ratio is higher for clean drilling in weak rocks and lower for balling and strong rocks. Furthermore, in balling, the ratio may decrease with time because the ROP reduces more due to the increase in severity of balling, but in strong rock the ratio remains the same.

3.4.7.3. Torque/ROP (Tangential Force/Cutting Area in Single-Cutter Tests)

The value of this diagnostic parameter is similar to specific energy concepts from other research studies (Equations 2.14 and 2.15).[1,2,8,9,41] These equations include two parts and assume that the DOC is constant for a given single-cutter test. A new formula for specific energy for a single-cutter test is introduced in Equation 3.4, in which cutting area is used instead of DOC. Using more of the compared data to analyze only the steady-state region with constant DOC, the new equation result is shown in Figures 3.32.

$$E_S = \frac{(Axial\ Force)}{p\,(Diameter\ of\ Path)(Width\ of\ PDC)} + \frac{(Tangential\ Force)}{(Cutting\ Area)} \quad (3.4)$$

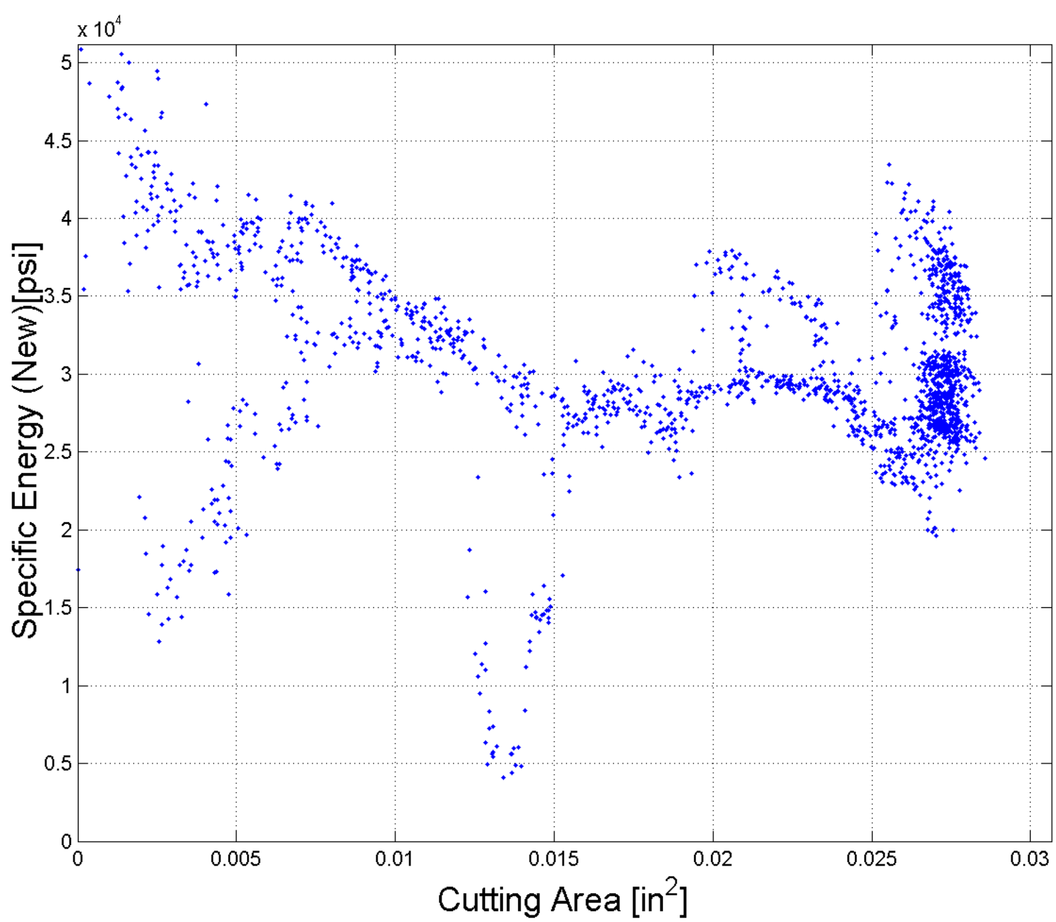

Figure 3.32 – Single-Cutter Test – ROP vs. Specific Energy
(Test 7058B-Catoosa-Cantilever-Polished-Water-10BR-9000psi-0.075DOC)

As shown in Figure 3.33, the first part of Equation 3.4 has much less effect on the value of specific energy than the second part. In the given figure, it can be seen that the effect of first part is less than 0.5%. Furthermore, in all laboratory tests the maximum value of the first part is less than 1% of the total value of specific energy. Consequently, the effect of a change in WOB on the specific energy is less than 1%. Having WOB in the diagnostic parameter based on specific energy is a complication that adds no real value to the parameter. Therefore, only the torque/ROP ratio is used as the diagnostic parameter in this study. The conceptual idea for specific energy and the torque/ROP ratio is the same. The only differences are that a conversion factor is used only for the full-scale test and that a maximum 1% difference occurs because of the WOB part of the specific energy equation. Because the value is not used in the method, but the values in the same situation (while the conversion factors are constant) are compared, the conversion factors do not change the detection procedure of using this diagnostic parameter.

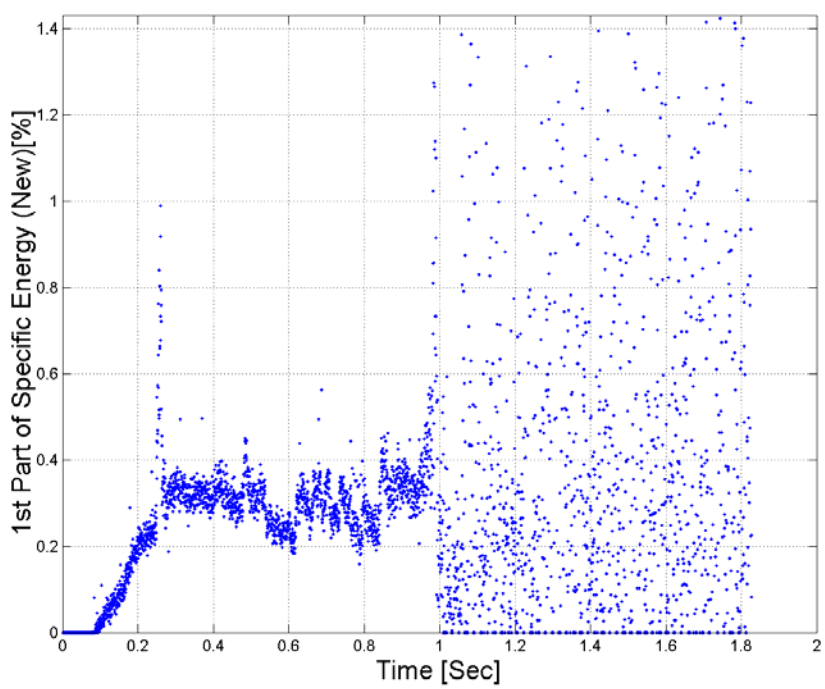

Figure 3.33 – Single-Cutter Test – Comparison of Two Terms of Specific Energy (Test 7058B-Catoosa-Cantilever-Polished-Water-10BR-9000psi-0.075DOC)

As shown in Figure 3.34 for a hypothetical rock, at the start of drilling (ROP=0), torque is equal to $torque_{Min}$ due to friction. Then increasing ROP increases torque, and as mentioned in Section 3.4.6, WOB does not have high effect on torque. As seen in the figure, the Torque/ROP ratio (which shows the angle of the line from the actual point back to the origin) is infinity at ROP=0 and is reduced as the ROP increases. The rate of reduction is much higher at lower ROP's.

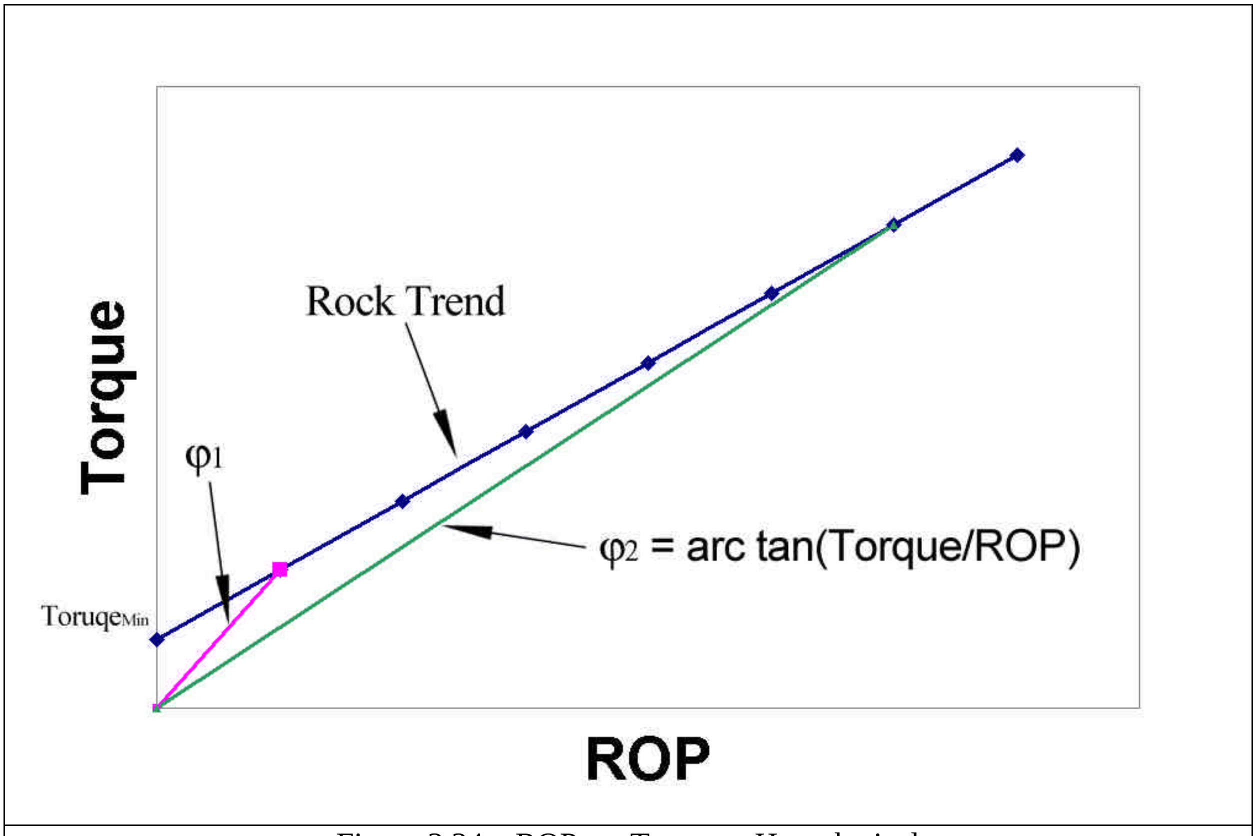

Figure 3.34 – ROP vs. Torque – Hypothetical

As shown in Figure 3.35, the trend of torque and ROP in a weak rock starts from a lower $torque_{Min}$ than in a strong rock because the friction is typically lower in weak rock, and the slope of the line in a weak rock is lower than in a strong rock because higher energy is needed to drill a stronger rock. Therefore, if torque/ROP ratios of two different rocks are compared, the ratio of a strong rock is always higher for the same ROP than the ratio of a weak rock. Figures 3.36 (0.011

DOC) and 3.27 (0.075 DOC) show the actual trend of torque versus ROP for single-cutter tests at two different DOCs. Figure 3.26 shows the same relations for the full-scale test. But there is a difference between these two kinds of laboratory tests, single-cutter and full-scale tests, in the situation of balling in shale. The ratio for the full-scale test increases less than observed in single-cutter tests, because WOB in single-cutter tests in the situation of balling is increased to a large value, more than eight times, so the effect of second part of the torque, $Torque_{Friction}$, has influence on this matter when the first part of torque , $Torque_{BreakingRock}$, is constant. However, in the full-scale test, the WOB increases less than two times and the first part of torque ($Torque_{BreakingRock}$) is changing, so the effect of second part of the torque ($Torque_{Friction}$) is negligible. As shown in Figure 3.26, effect of WOB on total torque is negligible, and the ratio is just influenced by reduction of ROP and increases less than in single-cutter tests.

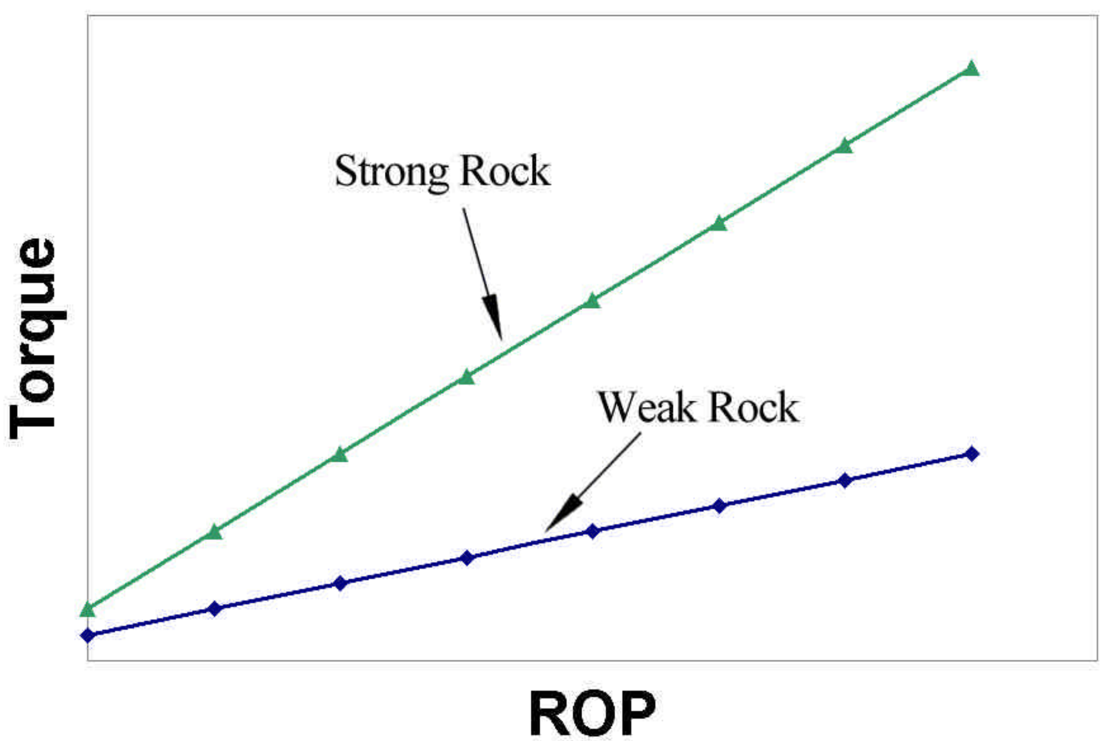

Figure 3.35 – ROP vs. Torque – Hypothetical – Two Rocks

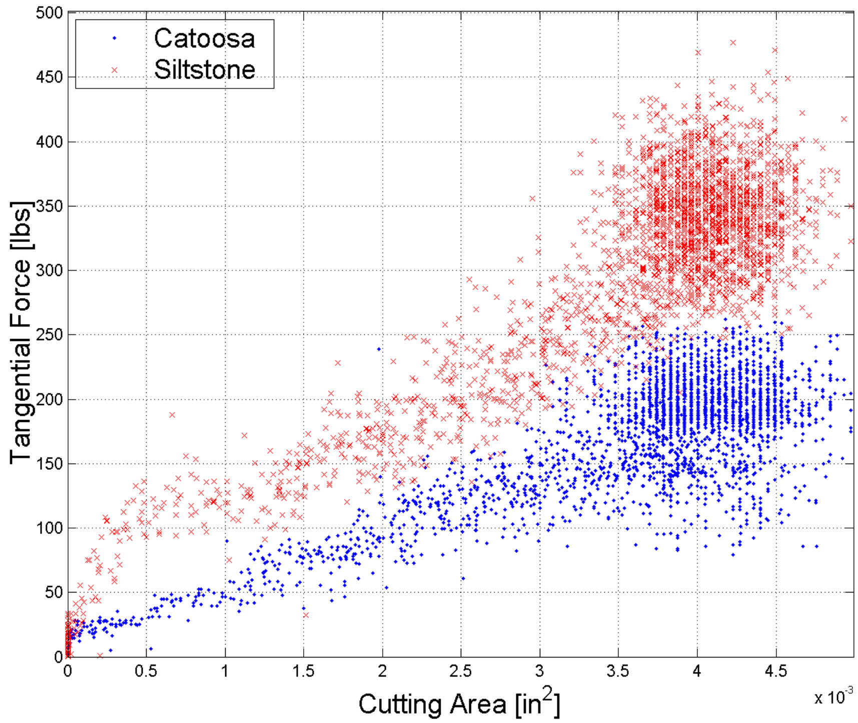

Figure 3.36 – Single-Cutter Test – ROP vs. Torque – Catoosa vs. Siltstone
(Tests 7058A and 7058I -Cantilever-Polished-Water-10BR-9000psi-0.011DOC)

3.4.7.4. Torque/WOB (Tangential Force/Axial Force in Single-Cutter Tests)

The value of this diagnostic parameter is similar to that used in other research, such as force ratio (Equations 2.16 and 2.17),[1,2,8,9] coefficient of sliding friction (Equations 2.12),[41] or dimensionless torque (Equation 2.7).[29,61] The difference between torque/WOB ratio and force ratio is that the second parameter is dimensionless. The conceptual basis of both parameters is exactly the same because bit diameter is constant during a bit run and any change in both parameters would be proportionately the same. In laboratory single-cutter tests, (tangential force)/(axial force) ratio is used which is exactly like Equation 2.18, but for the full-scale test, the values of torque/ROP and Equation 2.17 are different only by the bit diameter and geometry constant. As shown in Figure 3.37 for a hypothetical rock, the smallest WOB at which drilling begins is called WOB_{Min}, and for WOB less than this number, the cutter cannot drill the rock.

The minimum torque due to friction at ROP=0 is called $torque_{Min}$ and is a result of the friction on the rock. If the torque/WOB ratio is calculated for the specific kind of rock (as seen in Figure 3.37, the ratio shows the angle of the line from the actual point back to the origin), the ratio increases to a maximum value, $(torque/WOB)_{Max}$, before reaching the flounder point. After the flounder point, the ratio continues to decrease with increasing WOB. Similar to previously proposed diagnostic parameters, the ratio at the flounder point is calculated, and the ratios of torque/WOB from all other points are compared with this ratio.

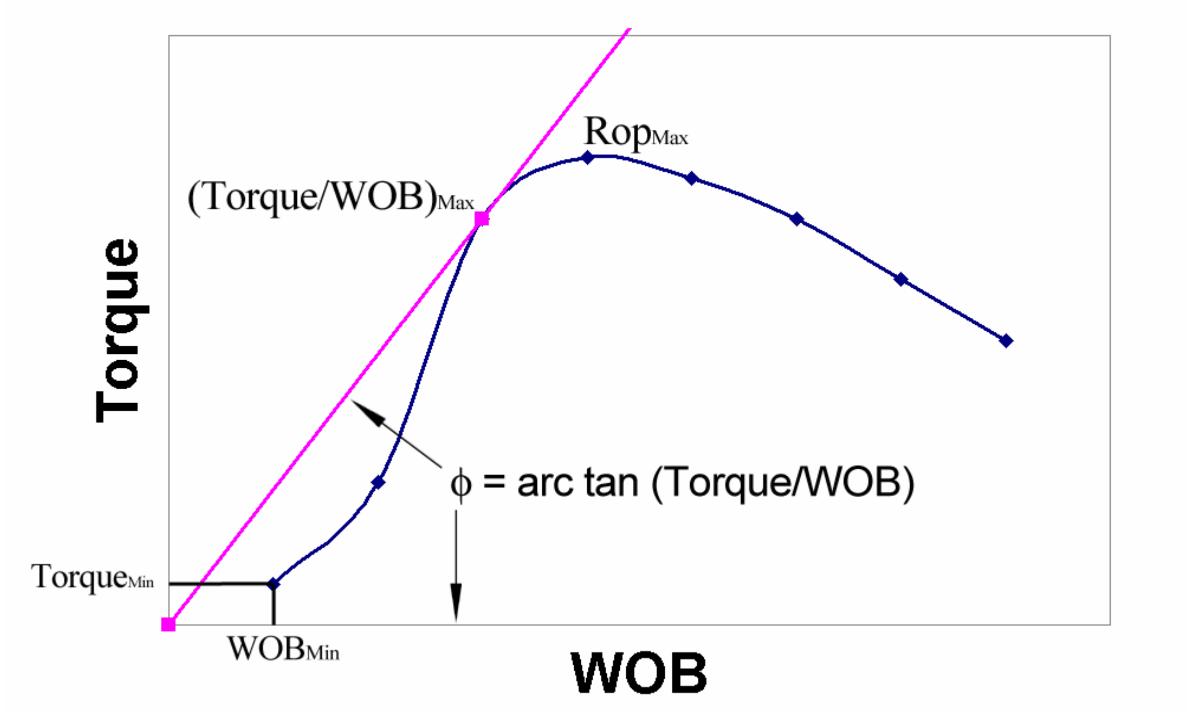

Figure 3.37 – WOB vs. Torque – Hypothetical

Figure 3.38 shows the torque/WOB ratio in three different regions (clean drill (S-A), cleaning limited (A-B), and balling regions (B-CDE), shown in Section 3.4.4 and Figure 3.4). Note that the early time data does not show in this figure because the bit is not in full contact with the rock and both ROP and WOB are unrealistic for this region. In the clean drilling region (except for those points where WOB is unrealistic because the bit is not in full contact with the rock), the ratio is increased as moving from point S toward point A, and the values of the ratio are moderate to large. In the cleaning limited region, the ratio is increased to a maximum value, $(torque/WOB)_{Max}$, and is reduced to the value at the flounder point (point B), so the values of the ratio are large to moderate. In the balling region, the ratio is decreased (if WOB is increased) or remains constant (if WOB is decreased), but the value of the ratio is always small.

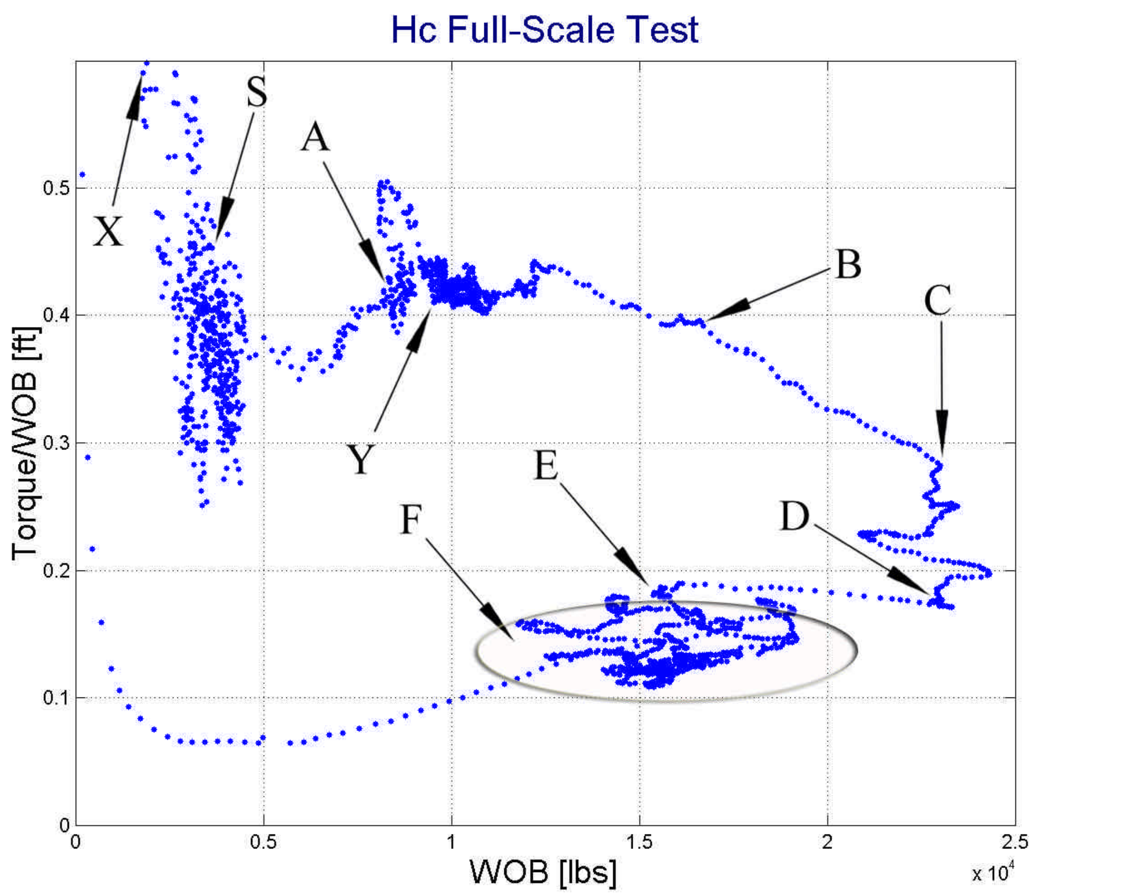

Figure 3.38 – Full-Scale Test – WOB vs. Torque/WOB

If all other drilling operation parameters are the same and a stronger rock is drilled, the hypothetical case shown in Figure 3.39. The method uses the ratios at different points in a strong rock to compare it with the ratio of this parameter at the flounder point in shale. As seen in the figure, the torque/WOB ratio could be the same in the balling situation in shale and drilling in a strong rock. However, as balling severity increases, the ROP reduces more severely, and the ratio becomes lower in balling situation in shale than for drilling in a strong rock.

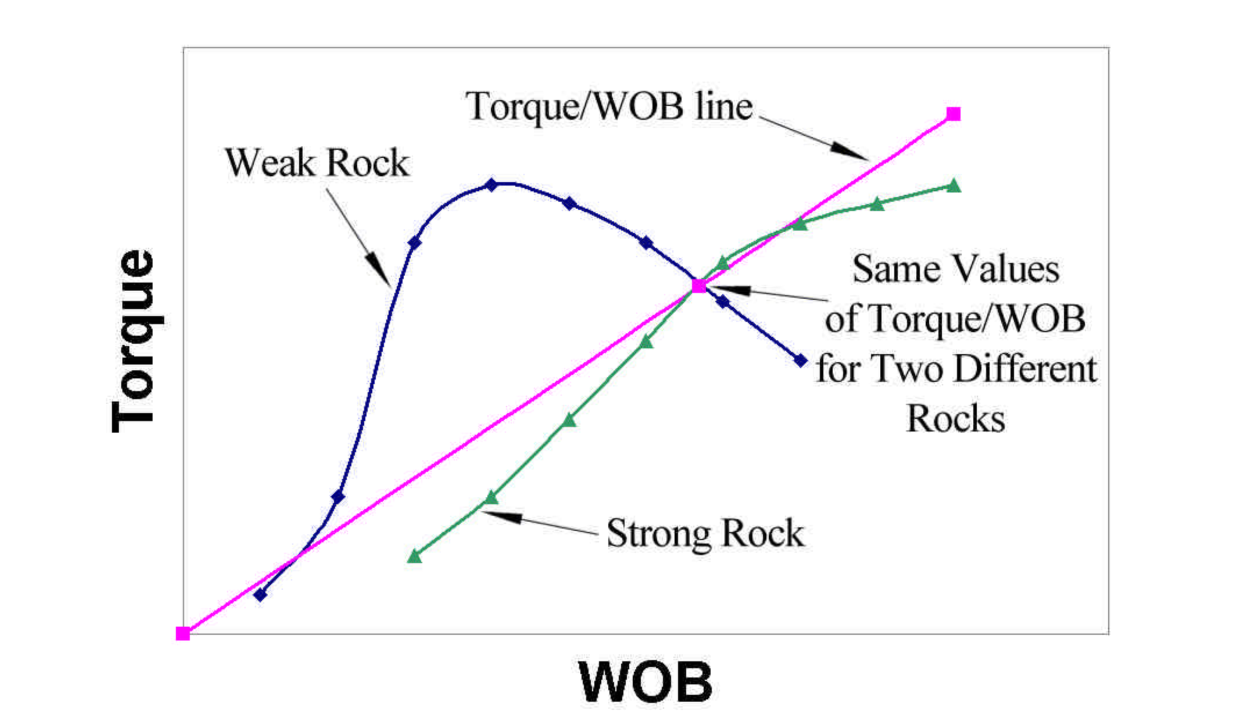

Figure 3.39 – WOB vs. Torque – Hypothetical – Two Rocks

For increasing WOB in a weak rock, the values of torque/WOB increase from a low ratio at low WOB to the highest ratio, and then drop. In the event of balling, the ratio can be very low. As seen in Figure 3.40 for actual single-cutter tests, the ratio is higher in stronger rock than for balling. As a result, the torque/WOB ratio in the strong rock is higher in this case than the flounder point ratio, but it is lower than clean bit drilling in a weak rock.

The ratio of torque/WOB is shown Figures 3.38, but as could be seen in Figure 3.41, force ratio acts similar to the torque/WOB ratio. The figures show that the torque/WOB ratio is a relatively high value at low WOB, and then increasing WOB increases the ROP until the bit balls up and the ratio is reduced. Decreasing the WOB does not change the ratio because the bit remains balled. In conclusion, the ratio is higher for clean drilling in weak rocks and lower for balling, and it is higher for strong rocks, but not as high as clean drilling in weak rocks. Typically, the ratio will decrease with time if balling occurs because the ROP decreases as the severity of balling increases.

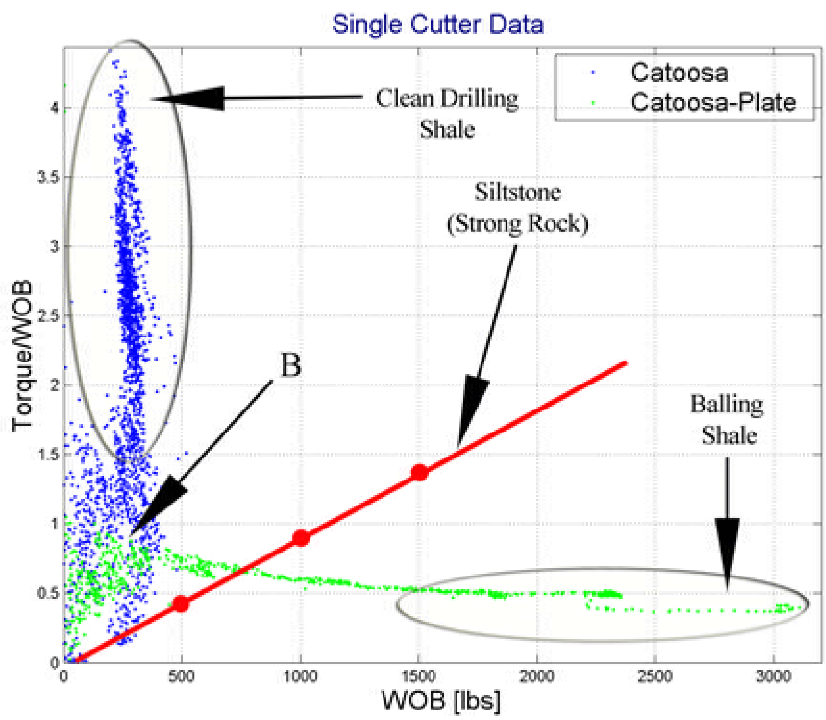

Figure 3.40 – Single-Cutter Test – WOB vs. Torque/WOB
(Tests 7058B and 7074B-Catoosa-Polished-water-10BR-9000psi-0.075DOC)
(Big points on the Figure: Tests 7058U(0.075DOC), 7058Q(0.033DOC), and 7058I(0.011DOC) -Siltstone-Polished-water-10BR-9000psi)

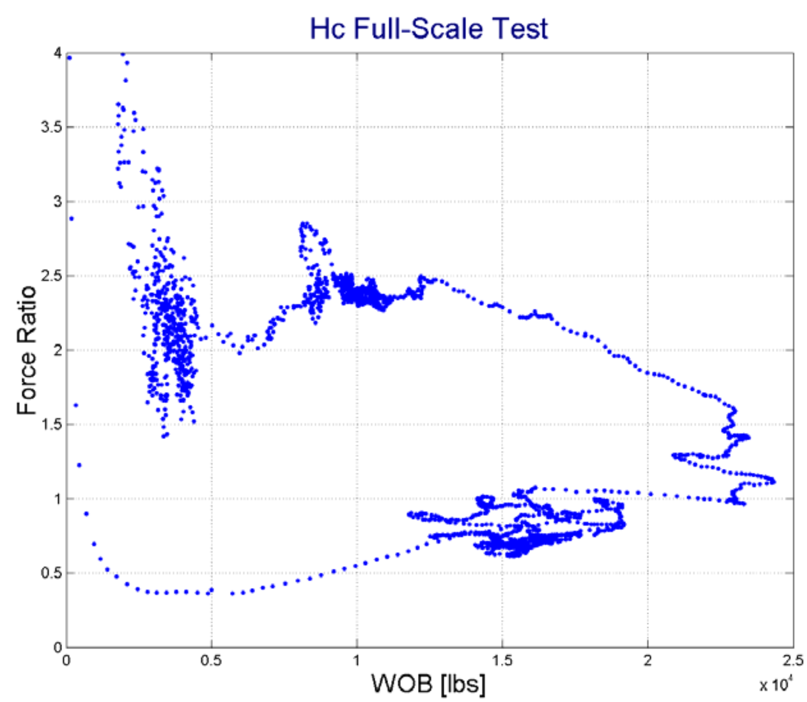

Figure 3.41 – Full-Scale Test – WOB vs. Force Ratio

3.4.7.5. ¶(ROP/WOB)/¶(WOB)

This new parameter is developed by calculating the slope of ROP/WOB versus WOB using linear regression, over 4 seconds for the full-scale test and 100 points of data for single-cutter tests to consider how changes in the diagnostic parameter ROP/WOB versus WOB might be used for additional diagnosis of conditions at the bit. Cutting area and axial force are used instead of ROP and WOB in single-cutter tests. Including the effect of an increasing or decreasing trend in the ROP/WOB ratio, in addition to the value of the ratio itself, potentially gives a more conclusive diagnostic parameter to distinguish between drilling in a strong rock or bit balling in a weak rock. The values of the new parameter will be different in these two situations even if the ROP/WOB ratios are the same. As seen in Figure 3.29, the ROP/WOB ratio is increased by increasing WOB until it reaches $(ROP/WOB)_{Max}$ point (point A), so the ∂(ROP/WOB)/∂(WOB) ratio is positive. Increasing WOB more than WOB at $(ROP/WOB)_{Max}$ will decrease the ROP/WOB ratio, so the ∂(ROP/WOB)/∂(WOB) ratio will be negative after that point. The ROP/WOB ratio to the WOB is separated into four sections. The first region before the flounder point exhibits a high ROP/WOB ratio and represents drilling with a clean bit. It is defined as the "clean drilling" region in Figure 3.29 (S-A), where the ROP/WOB is increasing gradually. The region just before the flounder point is called the "cleaning limited" region in Figure 3.29 (A-B region). Note that the ROP/WOB is decreasing despite WOB increasing. The region after the flounder point is called the "balling" region in Figure 3.29 (B-CDE region), where ROP is reduced from 200 to 100 ft/hr and the ROP/WOB is decreasing rapidly. The last region is interpreted to be a balled region where a new, lower value of ROP/WOB is relatively constant versus the WOB in Figure 3.29 (region F). The ratios of different sections are shown in Figure 3.42. Thus, the ∂(ROP/WOB)/∂(WOB) ratio is a conclusive diagnostic parameter. If the ratio is a larger negative number compared to the ratio in the flounder point, the WOB should be increased to achieve a better ROP. If the ratio is a smaller negative number compared to the ratio in the flounder point, the WOB should decrease to prevent the severity of the balling.

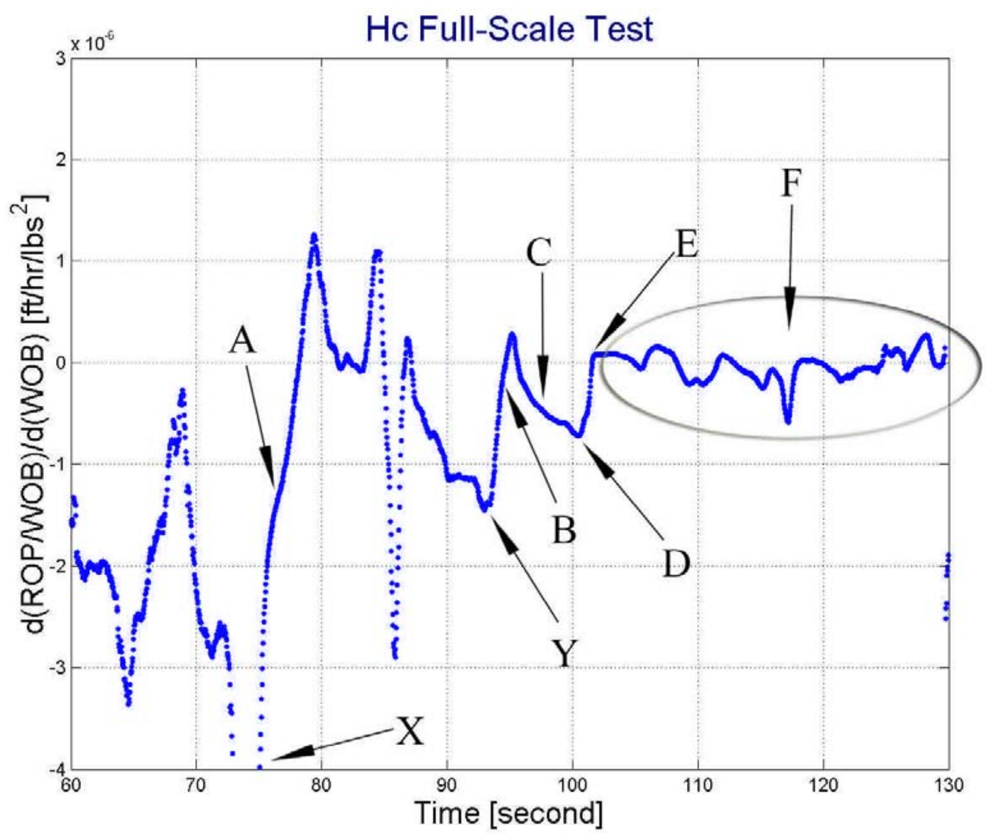

Figure 3.42 – Full-Scale Test – Time vs. d(ROP/WOB)/d(WOB)

In a strong rock, because the WOB used to drill shale typically is much smaller than the strong rock's flounder point, WOB_{Min} is much higher in this kind of rock, and ROP is very low for strong rock with low WOB; therefore, the flounder point region is bigger in this kind of rock. When comparing the ∂(ROP/WOB)/∂(WOB) value in a strong rock and the flounder point in shale, the absolute values are similar, but postive for a strong rock and negative for shale. Because the ratio is higher in a strong rock than the event of bit balling, these two different situations could potentially be separated by this new diagnostic parameter (the slopes of these different situations can be seen in Figure 3.31).

3.4.7.6. ¶(Torque/WOB)/¶(WOB)

This new parameter is developed by calculating the slope of Torque/WOB versus WOB relationship using linear regression, over 4 seconds for the full-scale test and 100 points of data for single-cutter tests to consider how the diagnostic parameter torque/WOB changes versus the WOB. Ttangential force and axial force are used instead of torque and WOB in single-cutter tests.-) This parameter is evaluated for additional diagnosis of conditions at the bit. Including the effect of an increasing or decreasing trend in the torque/WOB ratio, in addition to the value of the ratio itself, potentially gives a more conclusive diagnostic parameter to distinguish between drilling in a strong rock or bit balling in a weak rock. The values of the new parameter will be different in these two situations even if the torque/WOB ratios are the same. As seen in Figure 3.38, the torque/WOB ratio is increased by increasing the WOB until $(\text{torque/WOB})_{Max}$ point (point A), so the ∂(Torque/WOB)/∂(WOB) value is positive. Increasing the WOB more than the WOB at $(\text{torque/WOB})_{Max}$ will decrease the torque/WOB ratio, so the ∂(Torque/WOB)/∂(WOB) value will be negative after that point. The torque/WOB ratio to the WOB is separated into four sections. The first region before the flounder point exhibits a high torque/WOB ratio and represents drilling with a clean bit. It is defined as the “clean drilling” region in Figure 3.38 (S-A), where torque/WOB is increasing gradually. The region just before the flounder point is called the “cleaning limited” region in Figure 3.38 (A-B region). Note that the torque/WOB is decreasing despite the WOB increasing. The region after the flounder point is called the “balling” region in Figure 3.38 (B-CDE region), where ROP is reduced from 200 to 100 ft/hr and the torque/WOB is decreasing rapidly. The last region is interpreted to be a balled region where a new, lower value of torque/WOB is relatively constant versus the WOB in Figure 3.38 (region F). The values of different sections are shown in Figure 3.43. Thus, the

∂(Torque/WOB)/∂(WOB) value is a conclusive diagnostic parameter. (The following was TOO SIMPLE, see if you agree with the following suggested change.) Clean drilling approaching, but well before, the flounder point seems to be represented by a large negative value, such as $-5x10^{-5}$ in Figure 3.43. If the value is in this region is a much larger negative number compared to the value at the flounder point, the WOB could potentially be increased to achieve a better ROP. If the value is a smaller negative number compared to the flounder point, the WOB should decrease to prevent the worsening the severity of the balling.

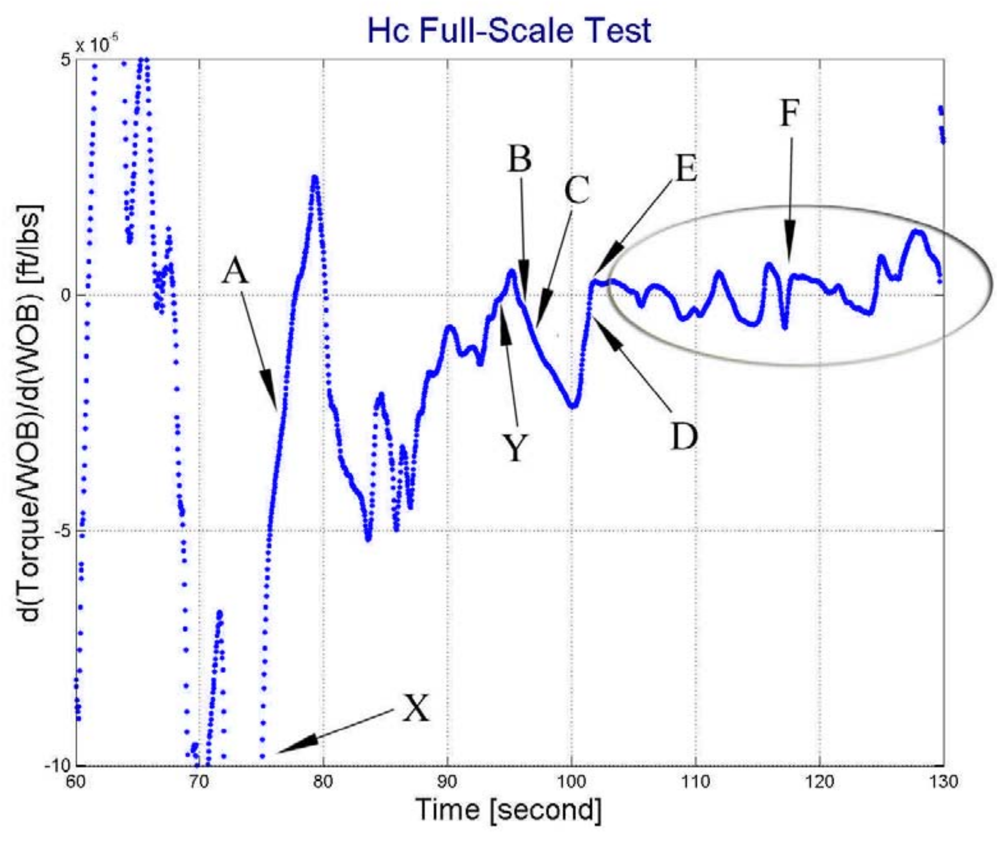

Figure 3.43 - Full-Scale Test – Time vs. d(Torque/WOB)/d(WOB)

In a strong rock, because the WOB used to drill shale is typically much smaller than the strong rock's flounder point, WOB_{Min} is much higher in this kind of rock, and the ROP is very low for strong rock with a low WOB; therefore, the flounder point region is bigger in this kind of rock. When comparing the ∂(Torque/WOB)/∂(WOB) value in a strong rock and the flounder point in shale, the absolute values are similar, but postive for a strong rock and negative for shale. Because the ratio is higher in a strong rock than the event of bit balling, these two different situations could be potentially separated by this new diagnostic parameter (the slopes of these different situations can be seen in Figure 3.40).

3.4.7.7. The Torque Parameters

It was hypothesized in Section 3.4.6.1 that the total torque is equal to two parts: one due to friction and the other due to breaking the rock. Using this hypothesis, it can be assumed that the torque due to breaking the rock is linearly proportional to the stress applied by the bit tooth or cutter face to break the rock in front of it, so it should be linearly related to depth of cut, or ROP, and rock strength. Also, the frictional force opposing rotation of the bit is related to the force acting perpendicularly to its surface, i.e., the WOB, so a conceptual equation can be written for total torque, as shown as Equation 3.5.

$$Torque = a * WOB + b * ROP \quad (3.5)$$

α and β are defined as the friction and cutting coefficients, respectively.

$$\rightarrow a * \frac{WOB}{Torque} + b * \frac{ROP}{Torque} = 1 \quad (3.6)$$

$$\rightarrow \frac{ROP}{Torque} = A * \frac{WOB}{Torque} + B \therefore A = -\frac{a}{b}, B = \frac{1}{b} \quad (3.7)$$

If we use linear regression for the three terms of the equation and find the best linear fit for the data in one range of time (4 seconds for full-scale test, and 100 points of data for single-cutter tests), then torque parameters A and B can be estimated. Furthermore, the torque parameters A and B are related to the friction and cutting coefficients. Then if events, such as balling or a change in rock strength, occur afterwards the changes in these parameters can be evaluated as potential indicators for determining the cause of such a change. Figures 3.44

(single-cutter tests in three different conditions: clean drilling in shale, balling in shale, and clean drilling in strong rock (siltstone)) and 3.45 (the full-scale test in different regions) show the parameter B, the inverse of the cutting coefficient. Figures 3.46 (single-cutter tests) and 3.47 (the full-scale test, the A value is strongly negative as balling begins) show the parameter A, which is mixture of the cutting and friction coefficients; however, as it can be seen, it shows noises, and using the parameter is not conclusive.

From these graphs, it can be seen that in situations of severe balling, the B-value is increased to a value two to five times greater than the value when effectively drilling shale or siltstone under the same conditions. The B-value stays high even if the WOB is reduced. Therefore, the B-parameter is potentially a conclusive diagnostic parameter for distinguishing decreasing ROP due to bit balling from the effect of stronger rock.

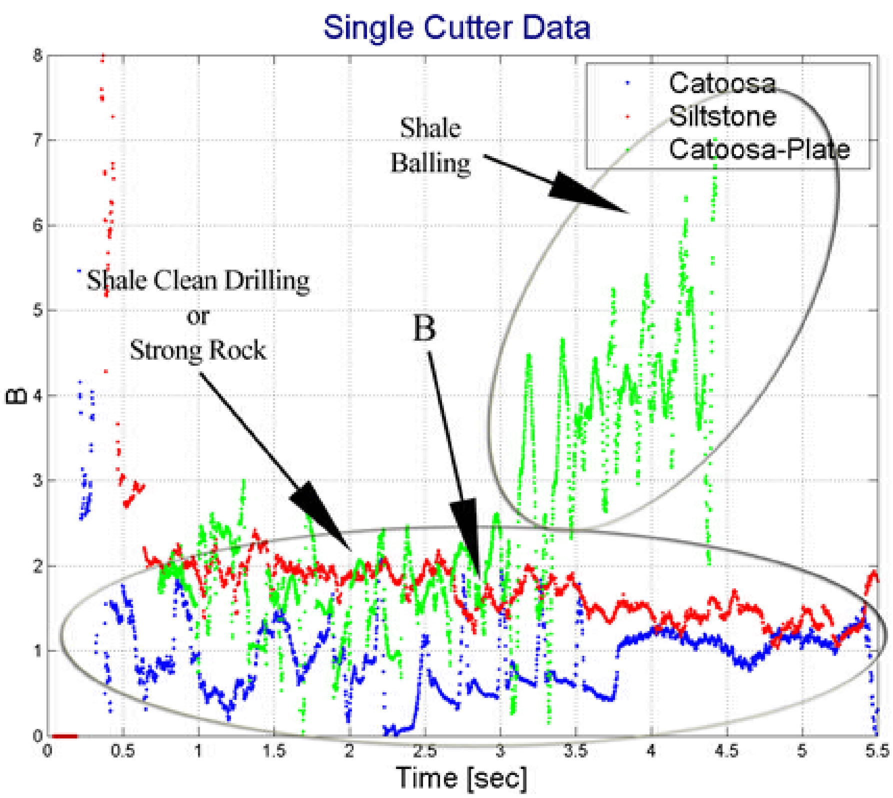

Figure 3.44 – Single-Cutter Test – Time vs. B
(Tests 7058A, 7058I and 7074A-Catoosa-Polished-Water-10BR-9000psi-0.011DOC)

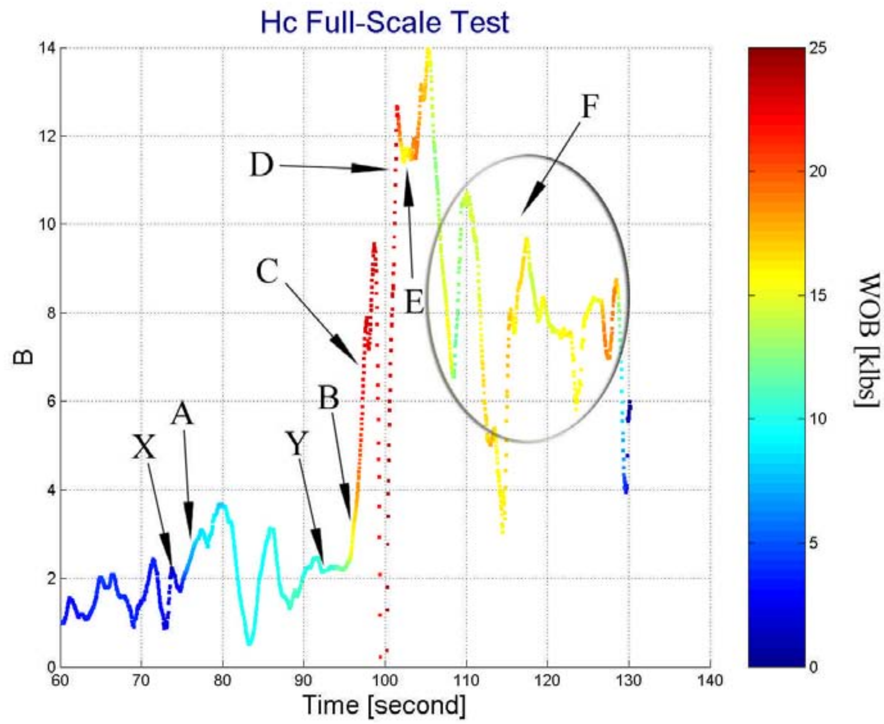

Figure 3.45 - Full-Scale Test – Time vs. B

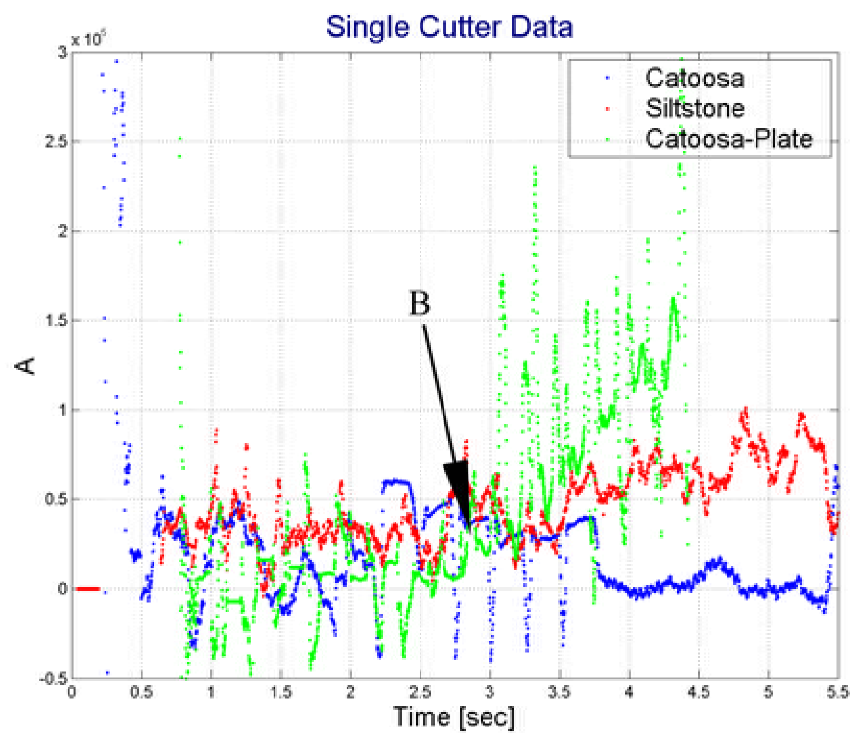

Figure 3.46 – Single-Cutter Test – Time vs. A
(Tests 7058A, 7058I and 7074A-Catoosa-Polished-Water-10BR-9000psi-0.011DOC)

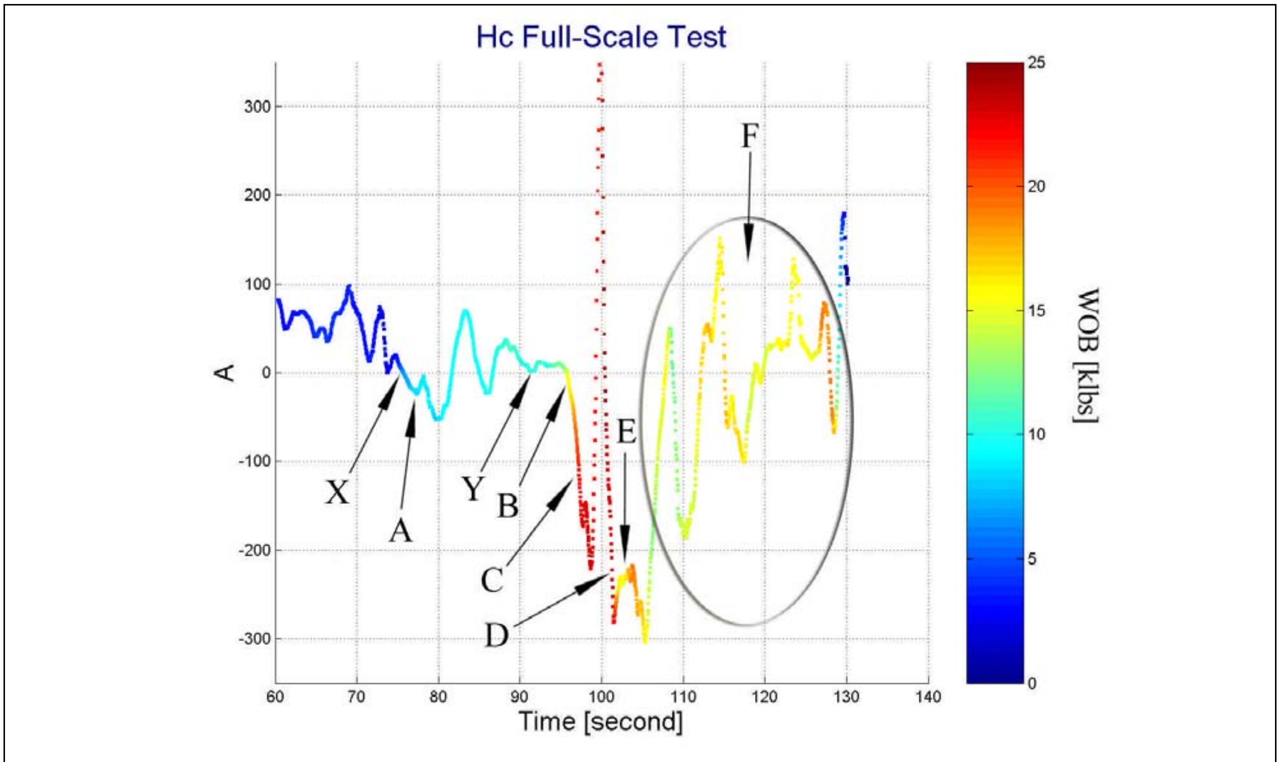

Figure 3.47 – Full-Scale Test – Time vs. A

3.4.7.8. Preliminary Evaluation of Other Possible Diagnostic Parameters

Other possible parameters, such as King's parameters (reported to be successful in practice), ∂(Torque)/∂(WOB), ∂(Torque)/∂(ROP), ∂(ROP)/∂(WOB) (the most important of king's parameters), etc. are introduced in the following sections. Some of these diagnostic parameters, such as King's parameters, d-exponent, etc., are not discussed in detail, because using them was not expected to be beneficial to the project. For example, a preliminary investigation of King's parameters did not show good results, probably because the method uses an intentional change of WOB, and evaluating this method is not conclusive using previously recorded data. Another reason is that similar diagnostic parameters show the physical phenomenon in better conclusive way; for example, d-exponent shows a similar behavior compared to 1/FORS which gives more conclusive results. Three of these possible parameters, ∂(Torque)/∂(WOB), ∂(Torque)/∂(ROP), and ∂(ROP)/∂(WOB), are discussed in the following sections.

3.4.7.8.1. ¶(ROP)/¶(WOB)

Figure 3.11 shows the cutting area, equivalent to the ROP, versus axial force for two single-cutter tests. The cantilever curve shows the ROP versus the WOB tread for a clean cutter. The plate curve shows a trend with a much bigger slope, ∂(ROP)/∂(WOB) (calculated similar to other derivative parameters over 4 seconds for full-scale test, and 100 points of data for single-cutter tests), at the axial force greater than 500 lbs (point B in the Figure 3.11) because balling is beginning to occur. These trends are also evident in Figure 3.48. As seen, another parameter, (∂(ROP)/∂(WOB))/∂(WOB), could be useful because the slope of ∂(ROP)/∂(WOB) to the WOB is changed from positive to negative around 500 lbs, which is the beginning of the balling.

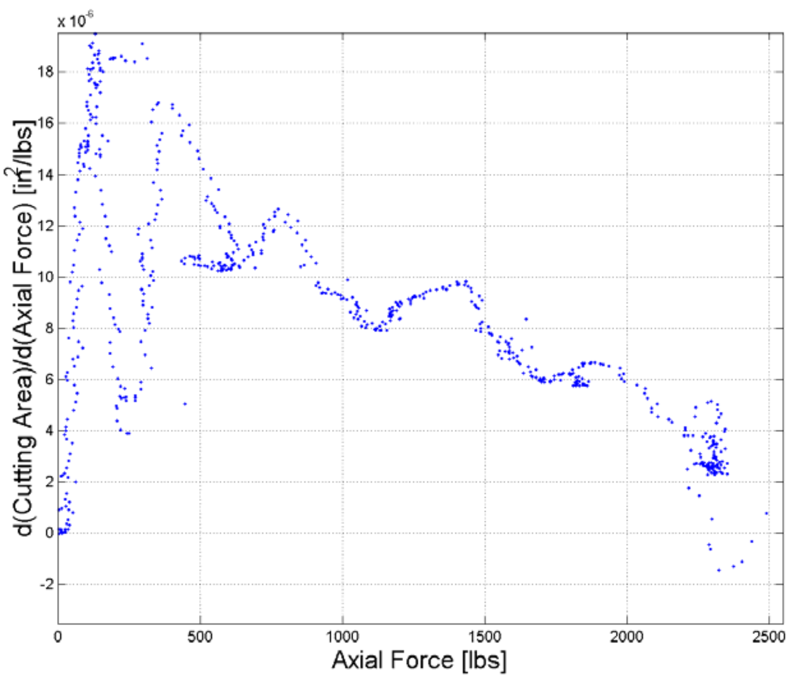

Figure 3.48 – Single-Cutter Test – WOB vs. d(ROP)/d(WOB)
(Test 7074B-Catoosa-Polished-Plate-Water-10BR-9000psi-0.075DOC)
(Regression over 100 points of data)

Figure 3.4 shows the ROP versus the WOB for the full-scale test, and different regions show different trends. For example, for the balling region shows a trend with a much bigger slope, ∂(ROP)/∂(WOB), (C-D region) compared to the trend at the clean drilling (S-A) or limited cleaning regions (A-B). These trends are also evident in Figure 3.49. As shown in both previous figures, the parameter looks too eratic to be an ideal, conclusive diagnostic. A hypothetical explanation is given in Section 3.4.7.8.4.

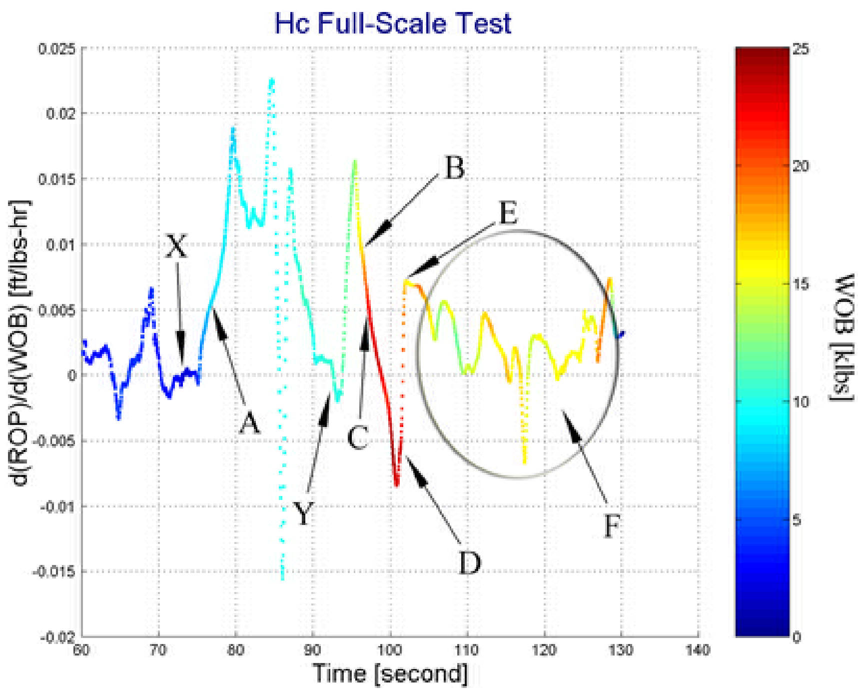

Figure 3.49 – Full-Scale Test - WOB vs. d(ROP)/d(WOB) (Regression over 4 second)

3.4.7.8.2. ¶(Torque)/¶(ROP)

Figure 3.23 shows tangential force versus axial force for three single-cutter tests. All curves show trends with similar slope, ∂(Torque)/∂(ROP) (calculated similar to other derivative parameters over 4 seconds for full-scale test, and 100 points of data for single-cutter tests); small change is observed after the beginning of balling at the cutting area of 0.01 in^2 on the plate curve because balling is beginning to occur and additional axial force is increasing frictional tangential forces. These trends are also evident in Figure 3.50. As seen, another parameter, (∂(Torque)/∂(ROP))/∂(WOB), shows a positive, gradual increase in the ∂(Torque)/∂(ROP) ratio versus the WOB. Therefore, it could also be useful for detection of rock types and frictional coefficient estimation.

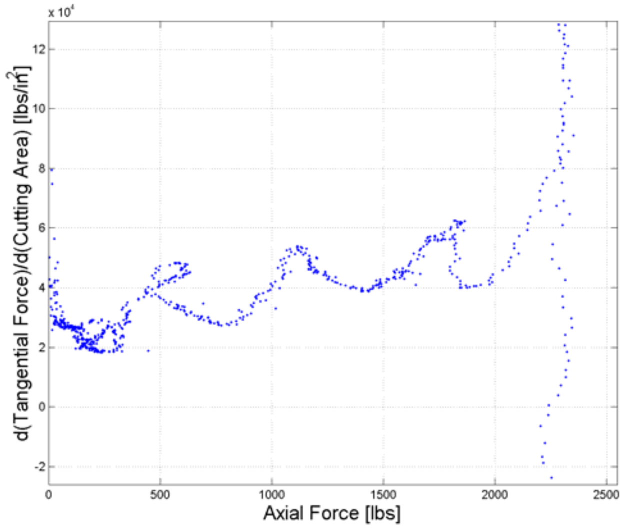

Figure 3.50 – Single-Cutter Test - WOB vs. d(Torque)/d(ROP)
(Test 7074B-Catoosa-Polished-Plate-Water-10BR-9000psi-0.075DOC)
(Regression over 100 points of data)

Figure 3.26 shows torque versus WOB for the full-scale test, and different regions show the same trends; these trends are also evident in Figure 3.51. As shown in both previous figures, this parameter looks too erratic to be an ideal, conclusive diagnostic. A hypothetical explanation is given in Section 3.4.7.8.4.

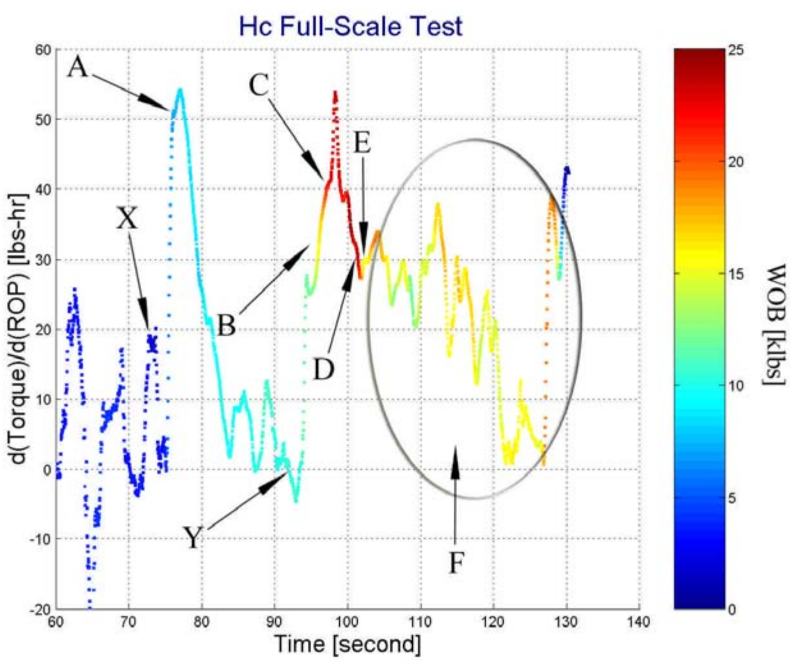

Figure 3.51- Full-Scale Test - WOB vs. d(Torque)/d(ROP) (Regression over 4 second)

3.4.7.8.3. ¶(Torque)/¶(WOB)

Figure 3.52 shows tangential force versus axial force for two single-cutter tests. The cantilever curve shows the ROP versus the WOB tread for a clean cutter. The plate curve shows a trend with a much lower slope, ∂(Torque)/∂(WOB) (calculated similar to other derivative parameters over 4 seconds for full-scale test, and 100 points of data for single-cutter tests), at the axial force greater than 500 lbs because balling is beginning to occur.

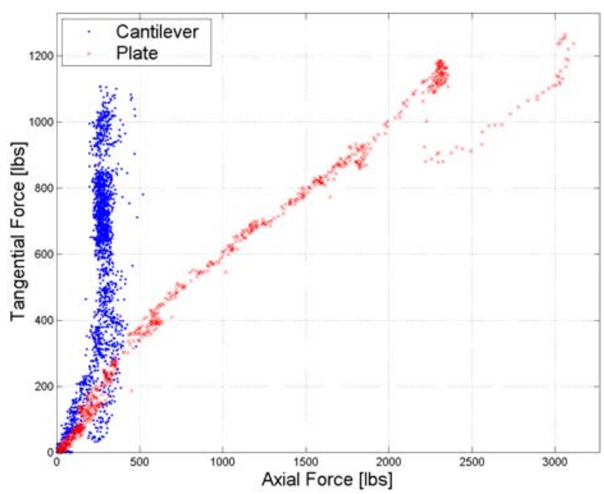

Figure 3.52 – Single-Cutter Test - WOB vs. Torque – Different Mounting
(Tests 7058B and 7074B-Catoosa-Polished-Water-10BR-9000psi-0.075DOC)

These trends are also evident in Figure 3.53. As seen, other parameters, such as ∂(∂(Torque)/∂(WOB))/∂(WOB), could be useful because the slope of ∂(Torque)/∂(WOB) to WOB is changed from positive to negative around 500 lbs, which is the beginning of the balling. Figure 3.5 shows torque versus WOB for the full-scale test, and different regions show different trends. For example, the balling region shows a trend with a much bigger slope, ∂(Torque)/∂(WOB), (C-D region) compared to the trend at the clean drilling (S-A) or limited cleaning regions (A-B). These trends are also evident in Figure 3.54. As shown in both previous figures, this parameter looks too eratic to be an ideal, conclusive diagnostic. A hypothetical explanation is given in Section 3.4.7.8.4.

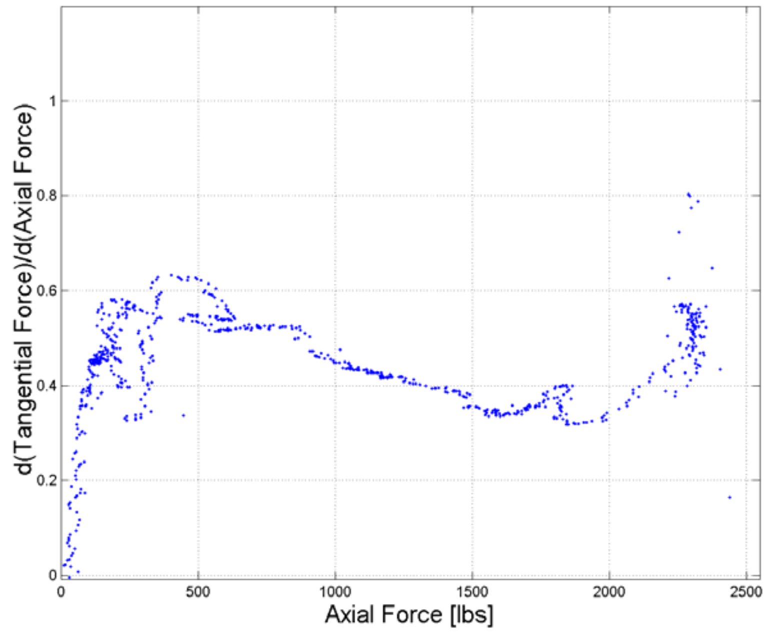

Figure 3.53 – Single-Cutter Test - WOB vs. d(Torque)/d(WOB)
(Test 7074B-Catoosa-Polished-Plate-Water-10BR-9000psi-0.075DOC)
(Regression over 100 points of data)

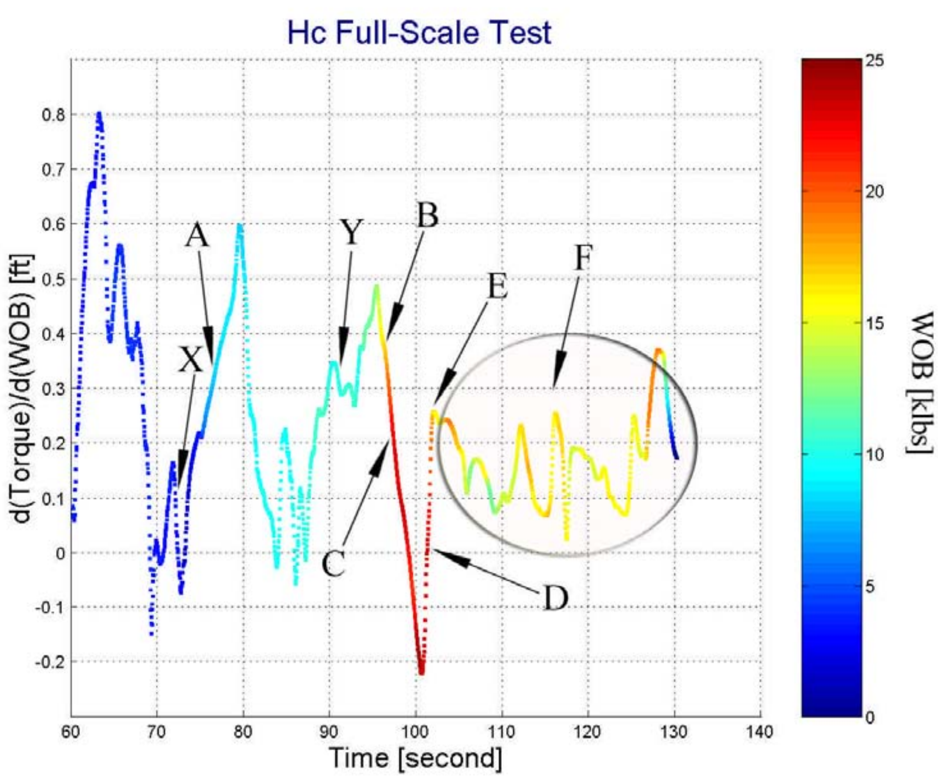

Figure 3.54 - Full-Scale Test - WOB vs. d(Torque)/d(WOB) (Regression over 4 second)

3.4.7.8.4. Explanation for Inaccurate Noisy Results

These parameters should logically be useful parameters. However, meaningful calculations of these parameters require a significant change in the numerator and denominator of the derivative because using a small change in both the upper and lower parts of the equations gives very inaccurate, erratic or noisy results. For example, as shown for the arbitrary variables X and Y in Figure 3.55, when calculating ∂Y/∂X with a regression over a longer range for X and Y (example A), the value is more accurate. However, if a smaller range is selected, the result may be very misleading, as shown in Example B. Mathematically, the derivative can be written like Equation 3.8, and then if X_{Noise} is larger than ΔX, and Y_{Noise} is larger than ΔY, the value of the derivative is not accurate. The practical use of these other possible parameters needs further study for conclusive evaluation.

$$\frac{\partial Y}{\partial X} \approx \frac{\Delta Y \pm Y_{Noise}}{\Delta X \pm X_{Noise}} \quad \text{(3.8)}$$

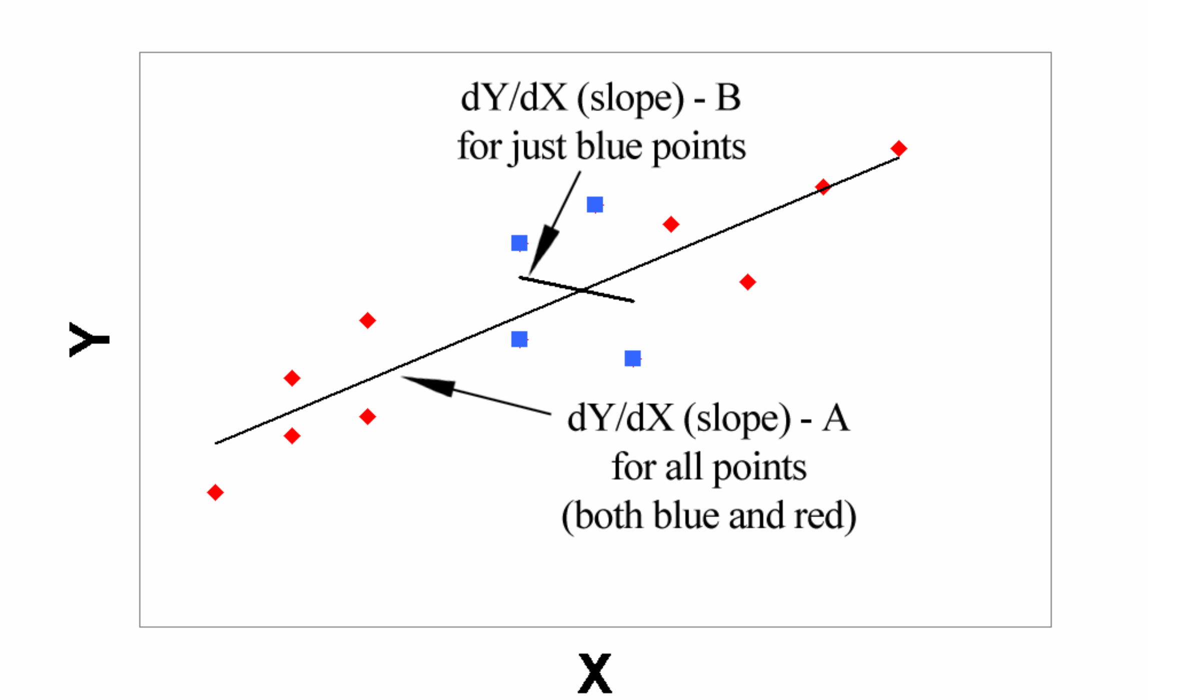

Figure 3.55 - Explanation for Inaccurate Noisy Results

3.5. Summary

Multiple potential diagnostic parameters for distinguishing the cause of a change in bit performance were evaluated based on single-cutter tests and one full-scale bit test. Values of each parameter were calculated and compared for several different known conditions: a clean bit drilling in shale, a balled bit in shale, and a bit drilling in strong rock. The qualitative magnitude and the sign of each parameter was compared between tests to determine whether a consistent relationship exists between the value and the drilling condition. The method of processing and organizing data for each parameter is detailed in Appendix VIII. ROP for single-cutter tests is based on cutting area. ROP for the full-scale test was calculated using the slope of the bit position versus time over a 0.5 second period. Torque and WOB were instantaneous measured values for all tests. All derivative parameters, such as ∂(Torque/WOB)/∂(WOB), were calculated using slope determined with a linear regression over 100 points of data for single-cutter tests and over 4 seconds for full-scale test. These ranges for regressions were selected based on visual observation of the minimum number of points to give a reasonably consistent value for the derivative.

A summary of diagnostic parameters are shown in Table 3.4. A combination of the main diagnostic parameters can be used to distinguish between different situations. As seen in the table for a clean bit drilling in shale, the ROP/WOB ratio has a large value, the torque/WOB ratio has a large value, the torque/ROP ratio has an intermediate value, the ∂(Torque/WOB)/∂(WOB) ratio generally has a large negative value, but can also be positive and the ∂(ROP/WOB)/∂(WOB) ratio has a large negative value.

As seen in the table for severely balled bit in shale, the ROP/WOB ratio has a small value, which is very small compared to the value for clean drilling, the torque/WOB ratio has a small value compared to the value for clean drilling, the torque/ROP ratio has an intermediate to large value larger than the value for clean drilling, the ∂(Torque/WOB)/∂(WOB) ratio has a small negative value compared to the value for clean drilling, and the ∂(ROP/WOB)/∂(WOB) ratio has a small negative value compared to the value for clean drilling..

Drilling a strong rock, the ROP/WOB ratio has a small value compared to the value for clean drilling, the torque/WOB ratio has a small to intermediate value compared to the value for clean drilling, the torque/ROP ratio has a large value compared to the value for clean drilling, the ∂(Torque/WOB)/∂(WOB) ratio has a positive value compared to the value for clean drilling, and the ∂(ROP/WOB)/∂(WOB) ratio has a positive value compared to the value for clean drilling.

Now if the drilling a strong rock and severe balling in the shale are compared, the ROP/WOB ratio has a similarly small value when drilling in both cases. The torque/WOB ratio has a small to intermediate value in drilling in a stronger rock and a small value for severely balled bit in shale, causing a potential overlap in the values of these ratios for the two different situations. The torque/ROP ratio has a large value in drilling in a strong rock and an intermediate to large value in severely balled bit in shale, causing a potential overlap between values of these ratios for these two different situations. The ∂(Torque/WOB)/∂(WOB) ratio has a positive value when drilling in a strong rock and a small negative value in severely balled bit in shale, so it can be seen that this parameter may distinguish between these two different situations. The ∂(ROP/WOB)/∂(WOB) ratio has a positive value in drilling in a strong rock and a small negative value in severe balling in shale, so it can be seen this parameter may also be useful to distinguish between these two different situation. Therefore, ∂(Torque/WOB)/∂(WOB), and ∂(ROP/WOB)/∂(WOB) are potentially conclusive on distinguishing between severe balling in shale and a strong rock.

Table 3.4 – Summary			
Parameter	Shale (Cleaner Bit)	Shale (Severely Balled)	Siltstone (Stronger Rock)
Torque/WOB	Large	Small	Small to Intermediate
Torque/ROP	Intermediate	Intermediate to Large	Large
ROP/WOB	Large	Small	Small
∂(Torque/WOB)/∂(WOB)	Large Negative	Small Negative	Positive
∂(ROP/WOB)/∂(WOB)	Large Negative	Small Negative	Positive
Torque Parameter B	Low value	High value	Low value

3.6. Nomenclature

ROP = Rate of Penetration, ft/hr

RPM = Rotary Speed, rev/min

Time = Time, Second

WOB = Weight on Bit, lbs

Cutting Area = Cutting Area, in^2

Axial Force = Axial Force, lbs

Tangential Force, Tangential Force, lbs

Torque = Torque, ft-lbs

E_S = Specific Energy, psi

DOC = Depth of Cut, in/rev

Diameter of the Path = Diameter of the Path, in

Width of PDC = Width of PDC, in

α = Torque Friction Coefficient, (ft for full-scale test) (dimensionless for single-cutter tests)

β = Torque Cutting Coefficient, (lbs-hr for full-scale test) (lbs/in^2 for single-cutter tests)

A = Torque Diagnosis Parameter A, (ft/hr/lbs for full-scale test) (in^2/lbs for single-cutter tests)

B = Torque Diagnosis Parameter B, (1/hr/lbs for full-scale test) (in^2/lbs for single-cutter tests)

4. FIELD DATA

4.1. Introduction

The problem of slow drilling rate in shale impacts drilling costs in deep, over-pressured wells in many areas of the world, so improving field drilling performance is an important goal for economic success.[2,29] Identifying and determining the cause of less than optimum bit performance are critical steps in being able to deliver improved performance. In this chapter, the diagnostic parameters identified in Chapter 3 are evaluated for different situations occurring in the field that cause changes in bit performance.

4.2. Data Description and Calculations

4.2.1. Description of the Data

The field data used in this study was provided by a project sponsor for the deep-hole intervals, below 10000 ft, of two wells, A and B. The data frequency is one set of recorded parameters every two seconds. The Well A data covers an interval of about 2600 ft from XX110 ft to XZ700 ft, and the average rate of penetration is between 5 to 15 ft/hr. In addition to the drilling operating parameters, gamma ray, sp, and resistivity logs were provided for this well. The Well B data covers an interval of about 2900 ft from XX400 ft to XZ300 ft, and the average rate of penetration is between 30 to 40 ft/hr. In addition to the drilling operating parameters, gamma ray and resistivity logs and mud logs were provided for this well. A list of the drilling data parameters recorded in each data set is given Appendix VI.

4.2.2. Calculation of Rate of Penetration

Conventional rate of penetration instrumentation measures the progress of the downward motion of the block or drill line travel. However, the drill-string is subject to variation of length due to elastic deformations, so the motion of the block is not exactly the same as the motion of the bit. For this study, Lubinski's[57] and Kerbart's[60] methods of calculating rate of penetration are considered to draw more accurate, rapid conclusions about bit performance. The calculated Kerbart's elasticity coefficient was found to be erratic, giving results that are often very low or very high compared to the calculated drill-string elasticity coefficient used in Lubinski's method. This is probably a result of the assumptions required in Kerbart's method, which are that lithology does not change and that the rate of penetration remains constant over a long time, being hard to satisfy. Therefore, Lubinski's method was used for all of the ROP calculations for the field data. Figure 4.1 shows that using Lubinski's method during periods when the weight on bit is changing is beneficial.

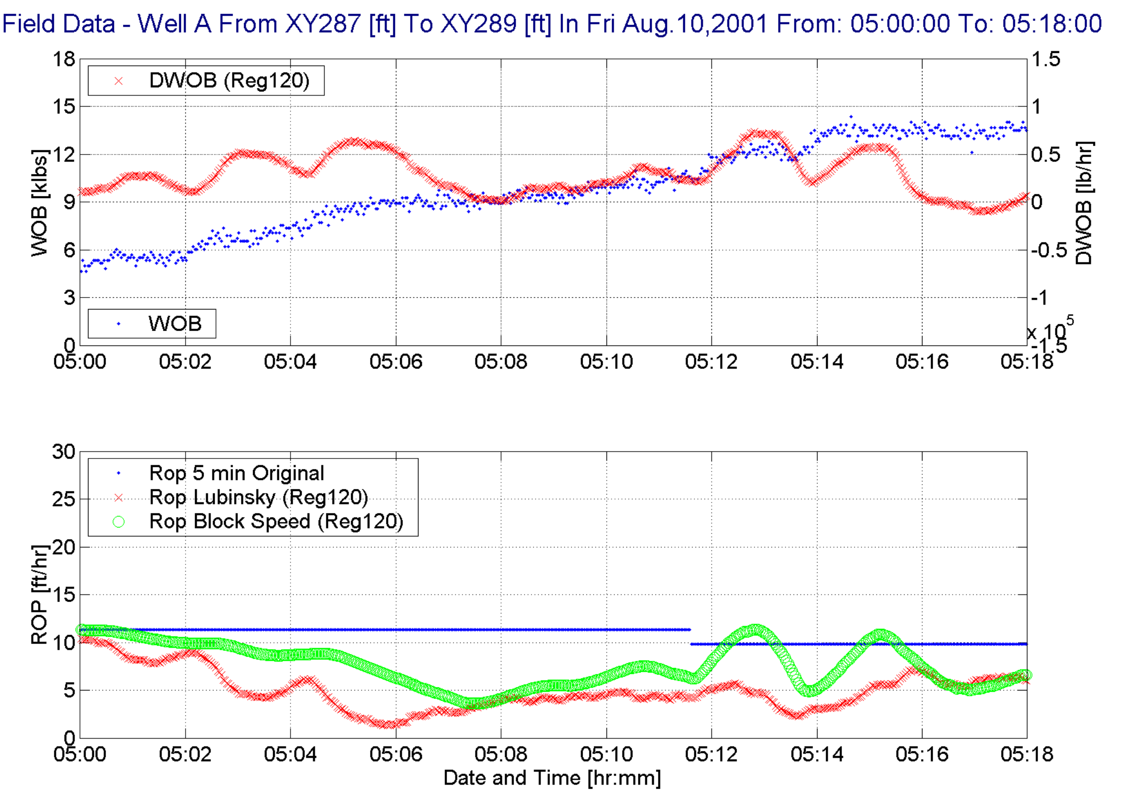

Figure 4.1 – ROP Comparison
(DWOB is ∂WOB/∂Time, calculated over 120 seconds, lbs/hr)

This method gives a significantly different ROP than either a simple running average over the same 120 seconds or an interval average over longer period of time as origainally reported in the drilling data log. Specifically, it also provides a much earlier and more accurate understanding of how the ROP is changing with the WOB, as shown by the rapid decrease in the red curve, ROP Lubinsky, in Figure 4.1 at 5:03. Furthermore, it can help avoid incorrect interpretations that increased WOB is increasing ROP, when the ROP is actually constant, even though the block is moving faster (e.g. 5:07 to 5:12).

4.2.3. Correction of the Depth

Because the depth recorded by sponsors in both wells is recalibrated for each connection, the measured depths just prior to and after connection are different, by about three feet. In order to compare the diagnostic parameters with log response in the same formations, a correction was required to the recorded depths. For this reason, the depth just after the connection is assumed to be correct, and all of the depths from the previous connection to the current connection are corrected, using Equation 4.1.

$$Depth = Depth_{Last} + \left[\frac{(Depth_{Measured} - Depth_{Last})(Depth_{After} - Depth_{Last})}{(Depth_{Before} - Depth_{Last})} \right] \quad (4.1)$$

Depth is the corrected depth, $Depth_{Last}$ is the depth recorded at the previous connection, $Depth_{Before}$ is the depth recorded just before the current connection, $Depth_{After}$ is the depth after the current connection, and $Depth_{Measured}$ is the recorded depth at each point in time.

4.3. Evaluation of Diagnostic Parameters for Distinguishing between Different Situations

Five primary diagnostic parameters are chosen to be evaluated for distinguishing between different situations encountered in Well A. Each is quantitatively compared to its value during routine drilling to imply the cause of any change in its values. The first steps are to find the limits (maximum and minimum) from previously drilled formations and then to identify a baseline value for each, based on routine drilling in shale. Then the maximum and minimum scale values are set to match the range for the diagnostic parameters on a given graph. Furthermore, distinguishing the causal effect for each event is attempted by comparing whether each diagnostic parameter is higher or lower than baseline for each situation encountered.

Torque and WOB are recorded data, but the ROP is calculated over a specified period (all results here in over 120-second intervals), and the two derivative parameters are calculated over another specified period (here in 30-second intervals). In this chapter, the events are separated into different patterns, and each pattern indicates a physical phenomenon in field situations. Then, for each individual pattern, comparisons of the main diagnostic parameters to their baselines are discussed. Finally, the results of other possible parameters, of which future study is still needed, are introduced. More detail about calculating the diagnostic parameters is included in Appendix VIII.

4.3.1. Pattern 1: Shale (Baseline)

The majority of the footage drilled in oil and gas wells is shale. Therefore, baseline values are selected in an interval of relatively high ROP over a long shale section. The selection is essentially arbitrary. However, using a high, but consistent trend will help in identifying decreases from that trend, the related changes in diagnostic parameters, and the best opportunity to make correction to maintain ROP at a relatively high level. The range limits on each plot are changed so that all parameters in each plot overlay along on baseline on the plot. As seen in Figure 4.2, all parameters on each of the three middle plots fall on the same line because curves are matched intentionally from the previously drilled formations. Thus, this pattern is the base pattern for comparison to other patterns. The interval shown is shale based on the gamma ray and SP logs, which can be confirmed by referring to the elative log section in Appendix VII. Table 4.1 simply summarizes that all diagnostic parameters are at their baseline.

Table 4.1 – Shale (Baseline)				
First Diagnostic parameter Group			Second Diagnostic parameter Group	
Torque/WOB	Torque/ROP	ROP/WOB	$\partial\left(\frac{Torque}{WOB}\right)/\partial(WOB)$	$\partial\left(\frac{ROP}{WOB}\right)/\partial(WOB)$
In Baseline	In Baseline	In Baseline	In Baseline	In Baseline

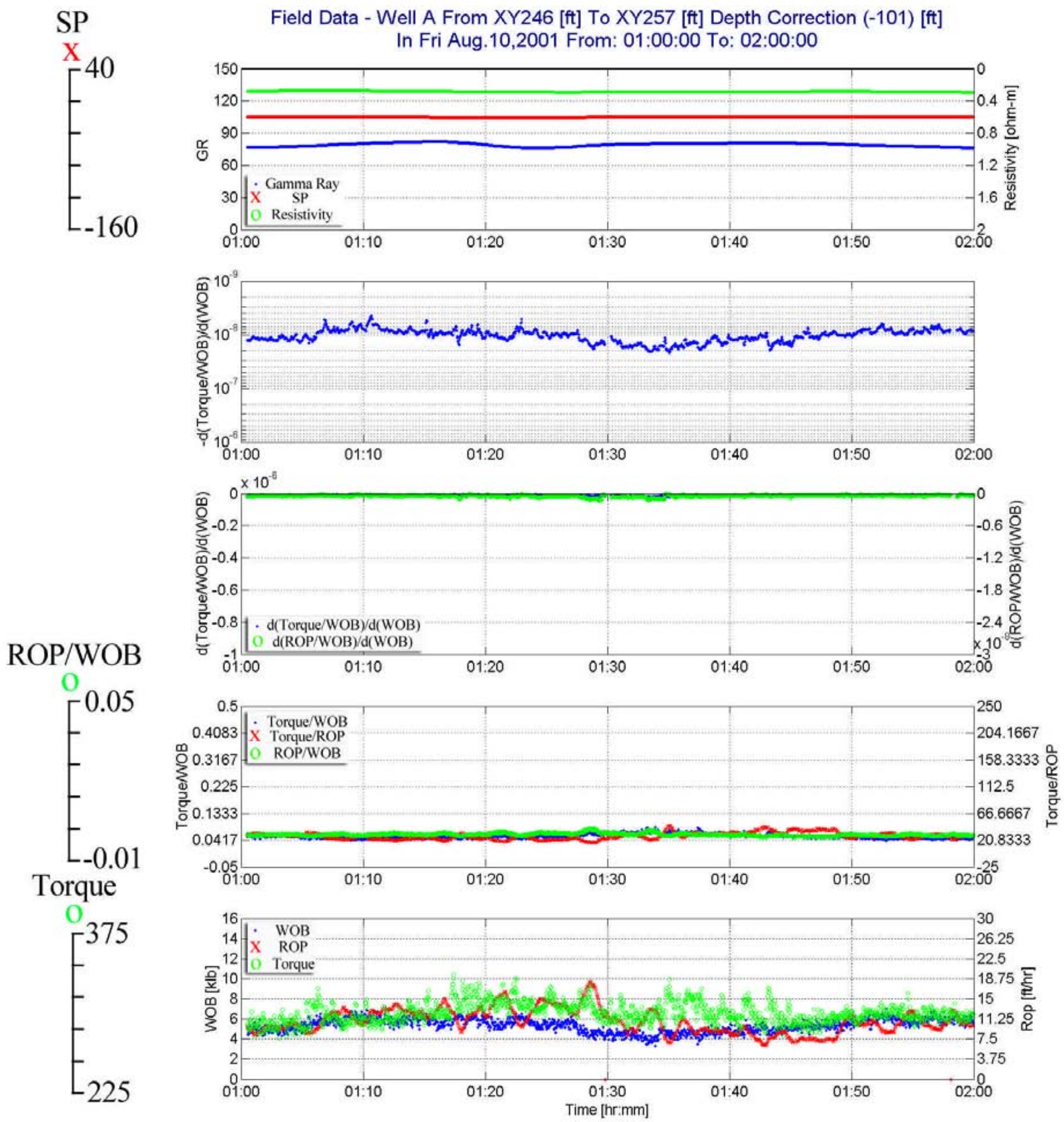

Figure 4.2 – Drilling in Shale (Baseline)

4.3.2. Pattern 2: Sand

The interval that is primarily sand was drilled from XY410 ft to XY530 ft in well A. The lower gamma ray and higher SP values versus the shale confirm that this interval is sand. The interval from XY450 to XY462 was selected from within the overall sand as most likely containing drilling that is representative of a clean bit drilling in a clean sand. The comparison of the diagnostic parameters with the base line within the selected interval is shown in Table 4.2 and Figure 4.3. Referring to Appendix VII, relative effects can be seen: the formation is sand because 1) the formation is drilled with a high ROP at a very small WOB, 2) gamma ray is lower than baseline, which indicates less shale, 3) resistivity is low, which indicates higher porosity and water saturation, and 4) SP is a larger negative value, which indicates permeability. Discussion about diagnostic parameters and validating the pattern are introduced in the following paragraphs.

a) ROP/WOB

The value of this parameter is larger than baseline for drilling because sand can be drilled quickly, so the ROP is larger than baseline ROP at the same WOB. Thus, the ROP/WOB ratio in sand is much larger than the baseline value.

b) Torque/ROP

As mentioned in Chapter three, Section 3.4.7.3, the observed torque/ROP ratio is highly influenced by rock properties, especially strength. This ratio varies from being just less than to being about double the baseline value. Given that sandstones vary widely in strength, sometimes even within a given formation, such variation in this ratio may be expected.

Table 4.2 – Sand				
First Diagnostic parameter Group			Second Diagnostic parameter Group	
Torque/WOB	Torque/ROP	ROP/WOB	$\partial\left(\frac{Torque}{WOB}\right)/\partial(WOB)$	$\partial\left(\frac{ROP}{WOB}\right)/\partial(WOB)$
Larger	Varies	Larger	Larger Negative	Larger Negative

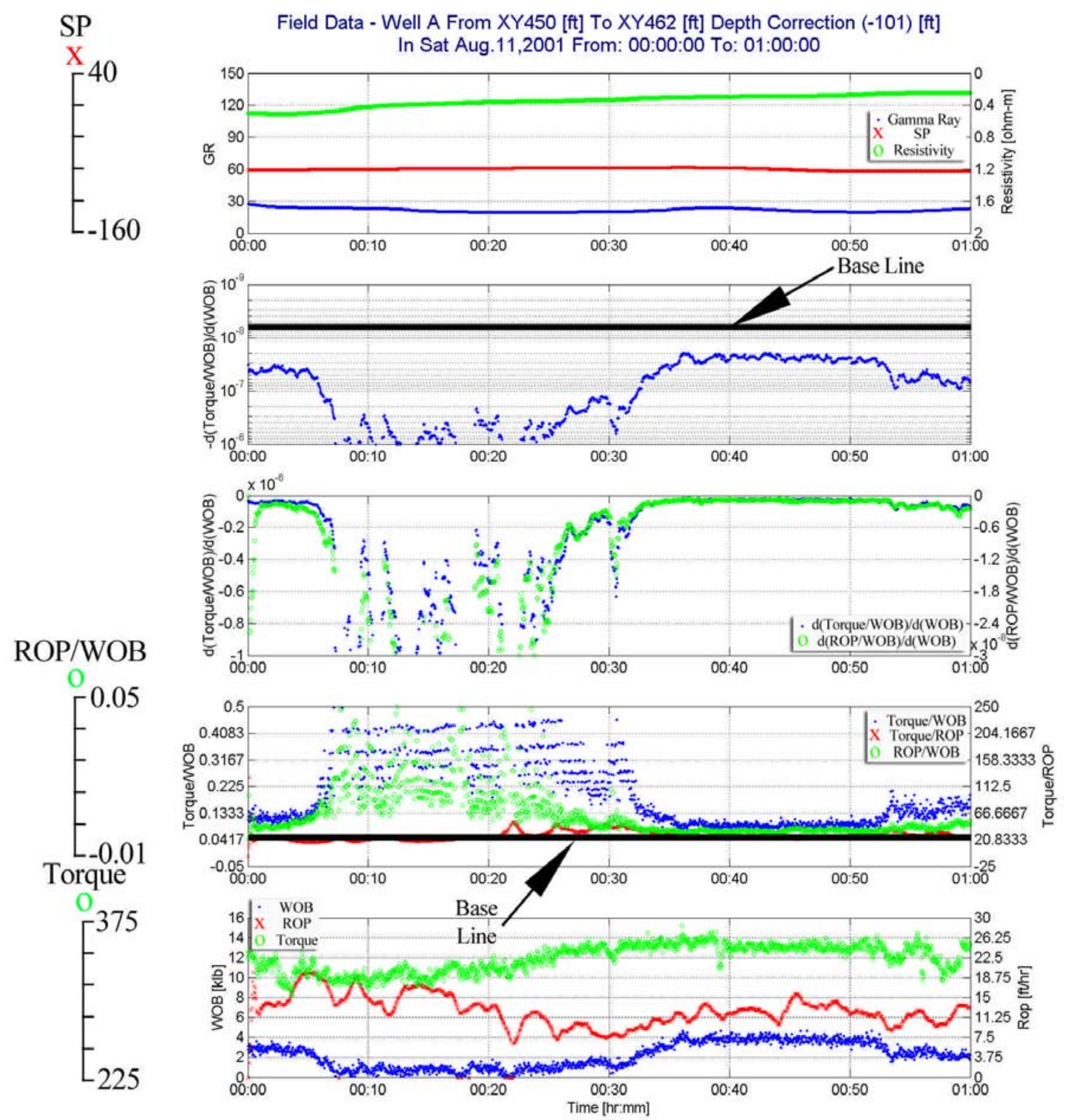

Figure 4.3 – Drilling in Sand

c) Torque/WOB

As mentioned in Chapter three (Section 3.4.7.4), the torque/WOB ratio is expected to be larger in a clean, weak formation, more like sand than the baseline ratio because the ROP is large. Therefore, $\text{torque}_{\text{BreakingRock}}$ is likely to be increased compared to the baseline value, which increases the torque/WOB ratio for a relatively constant or decreasing WOB, as was used in this interval.

d) ¶(ROP/WOB)/¶(WOB)

The drill-string effect is causing inaccuracy in measuring and calculating ROP and WOB representative of down-hole conditions. Similar to the cleaning limited region, the expected effect described in Section 3.4.7.5 can be observed in field data. The derivative parameter ∂(ROP/WOB)/∂(WOB) shows a larger negative value than the baseline value over the entire sand interval.

e) ¶(Torque/WOB)/¶(WOB)

Similar to the cleaning limited region, the expected effect described in Section 3.4.7.6 can be observed in field data. The derivative parameter ∂(Torque/WOB)/∂(WOB) shows a larger negative value than the baseline value over the entire sand interval.

4.3.3. Pattern 3: Shale (Performance Implying Cleaner Bit)

Referring to Appendix VII, relative effects can be seen: the lithology in this interval is shale, as evidenced by the gamma ray, resistivity, and SP being essentially identical to the baseline, as seen in the Figure 4.4. The comparison of the diagnostic parameters with the baseline within the selected interval is shown in Table 4.3 and Figure 4.4. In the following, discussion about diagnostic parameters and validating the pattern are introduced in the following paragraphs.

a) ROP/WOB

The value of this parameter is larger than baseline for drilling shale in the clean drilling and cleaning limited regions, as described in Section 3.4.7.3. Thus, the ROP/WOB ratio in this section is somewhat larger than the baseline value.

Table 4.3 – Shale (Cleaner Bit)				
First Diagnostic parameter Group			Second Diagnostic parameter Group	
Torque/WOB	Torque/ROP	ROP/WOB	$\partial\left(\frac{Torque}{WOB}\right)/\partial(WOB)$	$\partial\left(\frac{ROP}{WOB}\right)/\partial(WOB)$
Larger	Same	Somewhat Larger	Larger Negative	Larger Negative

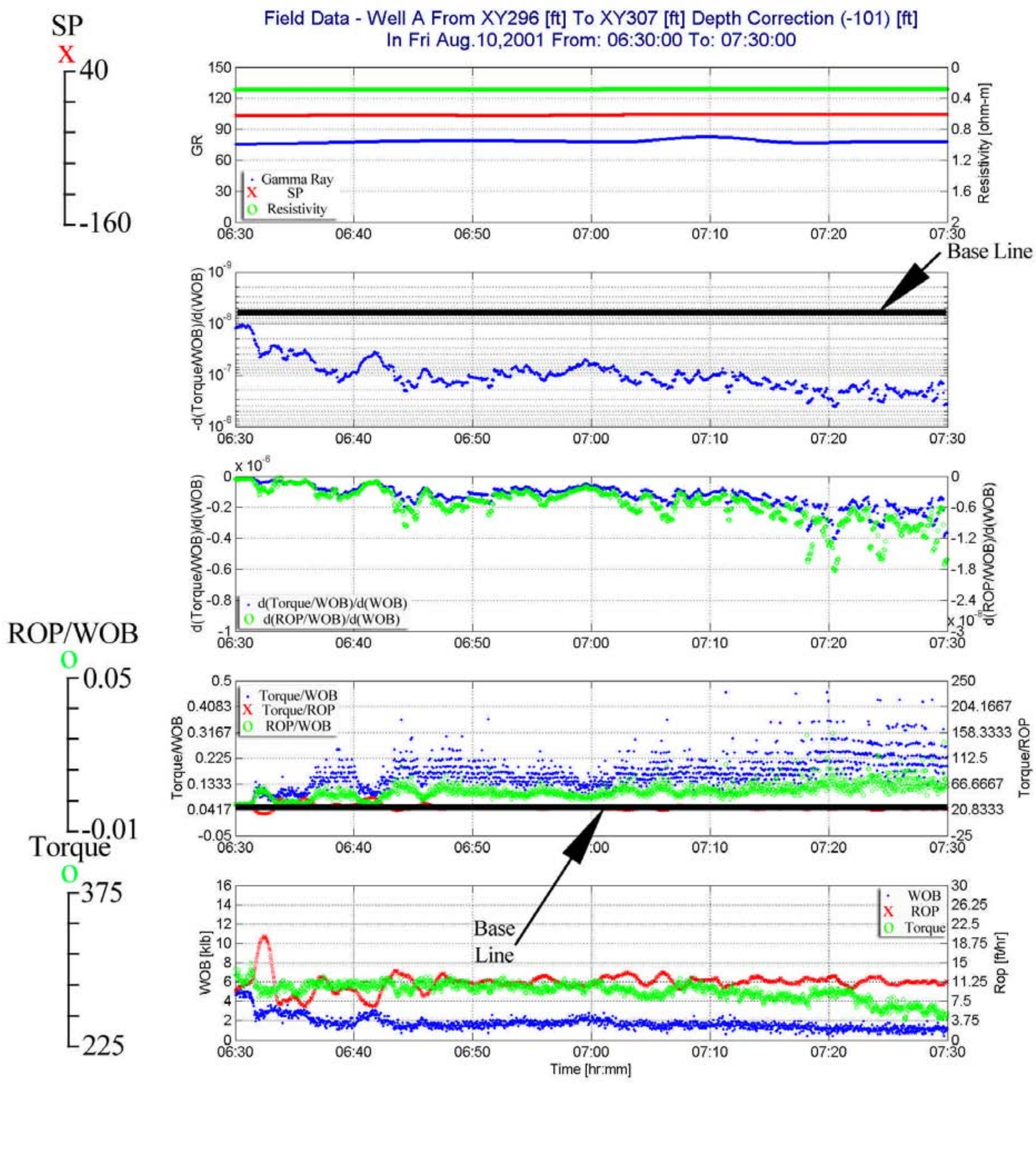

Figure 4.4 – Drilling in Shale (Cleaner Bit)

b) Torque/ROP

As mentioned in Chapter three, Section 3.4.7.3, the observed torque/ROP ratio is highly influenced by rock properties, especially strength. Similar to the clean bit and cleaning limited regions described in Section 3.4.7.3, it can be observed in field data that the torque/ROP ratio is close to the baseline value.

c) Torque/WOB

As mentioned in Chapter three (Section 3.4.7.4), the torque/WOB ratio is expected to be larger in the clean drilling and cleaning limited regions in shale due to low WOB, which can be observed in field data.

d) ¶(ROP/WOB)/¶(WOB)

Similar to the cleaning limited region, the expected effect described in Section 3.4.7.5 can be observed in field data. The derivative parameter ∂(ROP/WOB)/∂(WOB) shows a larger negative value than the baseline value over the entire interval.

e) ¶(Torque/WOB)/¶(WOB)

Similar to the cleaning limited region, the expected effect described in Section 3.4.7.6 can be observed in field data. The derivative parameter ∂(Torque/WOB)/ ∂(WOB) shows a larger negative value than the baseline value over the entire sand interval.

4.3.4. Pattern 4: Severe Balling in Shale

Referring to Appendix VII, relative effects can be seen: the lithology in this interval is shale, as evidenced by the gamma ray, resistivity, and SP being essentially identical to the baseline, as seen in the Figure 4.5. The comparison of the diagnostic parameters with the baseline within the selected interval is shown in Table 4.4 and Figure 4.5. Discussion about diagnostic parameters and validating the pattern are introduced in the following paragraphs.

Table 4.4 – Shale (Balling)				
First Diagnostic parameter Group			Second Diagnostic parameter Group	
Torque/WOB	Torque/ROP	ROP/WOB	$\partial\left(\frac{Torque}{WOB}\right)/\partial(WOB)$	$\partial\left(\frac{ROP}{WOB}\right)/\partial(WOB)$
Slightly Smaller	Larger	Slightly Smaller	Much Smaller Negative	Noisy / Inconclusive

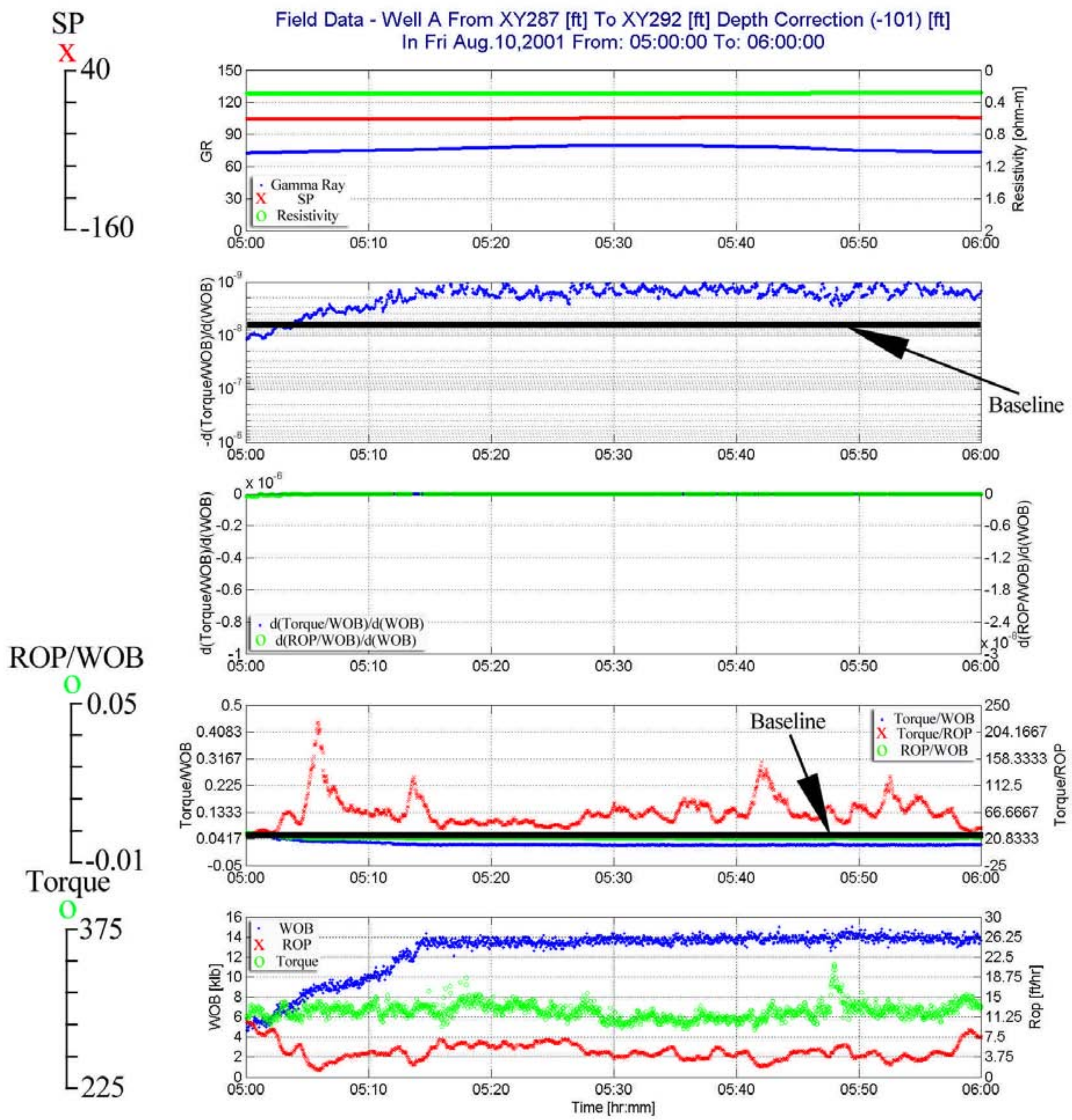

Figure 4.5 – Drilling in Shale (Balling)

a) ROP/WOB

The value of this parameter is smaller than baseline for drilling shale in the balling region, as described in Section 3.4.7.3. Thus, observed in field data, the ROP/WOB ratio in this section is smaller than the baseline value.

b) Torque/ROP

There is a difference between laboratory and field situation for this parameter, possibly because of additional torque due to drill-string (no proof, but there is possibility). The situation of balling usually happens in high WOB in-field situation, and the ROP is decreased because of the WOB higher than the flounder point, so $torque_{BreakingRock}$ is decreased because of a low ROP while $torque_{Friction}$ and $torque_{Drill\text{-}String}$ are possibly increased because of high WOB. Thus, because other components of torque are increased compared to $torque_{BreakingRock}$, the numerator is increased, the denominator is decreased, and the ratio is increased. However, in addition to what is described in Section 3.4.7.3 for the balling region, it can be observed in field data that the torque/ROP ratio is increased more in the field than in the laboratory compared to the baseline value.

c) Torque/WOB

As mentioned in Chapter three, Section 3.4.7.4, the torque/WOB ratio is expected to be smaller in the balling region in shale. But, it can be observed in field data the change is slightly smaller, possibly because of following reasons. The ratio is already low at baseline conditions because the bit is not fully clean. Total torque includes the drill-string which tends to obscure change in the torque of the bit.

d) ¶(ROP/WOB)/¶(WOB)

Similar to the balling limited region, the expected effect described in Section 3.4.7.5 can be observed in field data. The derivative parameter ∂(ROP/WOB)/∂(WOB) shows a smaller negative value than the baseline value over the entire interval. Inaccuracy in measuring and calculating the ROP and WOB may also result in this diagnostic parameter being less accurate in field situations than in the laboratory situation. So because the ratio is small in this situation, reaching a good conclusive comparison to the baseline value is not possible due to amount of noise, and in many field situations, use of this diagnostic parameter may be misleading.

e) ¶(Torque/WOB)/¶(WOB)

Similar to the balling region, the expected effect described in Section 3.4.7.6 can be observed in field data. The derivative parameter ∂(Torque/WOB)/∂(WOB) shows a smaller negative value than the baseline value over the entire sand interval.

f) Overview

The situation observed in Figure 4.5 is increasingly severe balling in shale because of the following. The formation was drilled at a baseline ROP with a moderate WOB, and after the WOB is increased, the ROP is reduced. Increasing the WOB causes an increase in torque/ROP, which is equivalent to an increase in specific energy, despite the formation being the same. These are two of the main symptoms of balling identified in the literature. The gamma ray, resistivity, and SP are the same as the baseline values, which indicates an impermeable, shale formation, of approximately the same strength as the baseline shale. Therefore, the changes in diagnostic parameters can be concluded to be caused by less efficient drilling, which is caused by balling.

4.3.5. Pattern 5: Stronger Rock

The interval from approximately XY406 to XY417 ft was selected as potentially representing a strong rock, based on the log response. The relatively low gamma ray values indicate much less clay content than the baseline shale, and the very slight increase in SP implies low permeability. The increase in resistivity means the porosity is also less than in the surrounding shales. Therefore, this zone apparently has a low porosity, low permeability siltstone or sandstone. Consequently, although no sonic log or cores are available to confirm formation strength, this is almost certainly stronger rock than the other sand and shale in Well A. The comparison of the diagnostic parameters over this interval with the baseline values is shown in Table 4.5 and Figure 4.6. Discussion about diagnostic parameters and validating the pattern are introduced in the following:

a) ROP/WOB

The ROP/WOB ratio is a little smaller than baseline value. As mentioned in Chapter three, Section 3.4.7.3, this parameter is expected to be smaller than baseline value in strong rocks. At about 20:16, the ratio is actually much larger than the baseline value, but it decreases rapidly to the baseline level by about 20:25. The interval from 20:16 to 20:25, which could be sand, was drilled more quickly than the immediately adjacent shales or stronger rocks and is excluded from this analysis. The lower gamma ray and slightly higher SP values versus the shale confirm the likelihood that this interval is sand.

b) Torque/ROP

The torque/ROP ratio is much higher than the baseline value throughout most of this interval. This is expected in a stronger rock. Note that the ratio returns to near baseline values between 20:16 and 20:25.

c) Torque/WOB

The torque/WOB ratio falls approximately on the baseline over most of this interval but is noticeably lower than it is in the adjacent shales. As mentioned in Chapter three, Section 3.4.7.4, the ratio is expected to increase in a strong rock that needs more energy and more torque to be drilled. However, the only interval where this ratio increases significantly is from 20:16 to 2:25.

Table 4.5 – Stronger Rock				
First Diagnostic parameter Group			Second Diagnostic parameter Group	
Torque/WOB	Torque/ROP	ROP/WOB	$\partial\left(\frac{Torque}{WOB}\right)/\partial(WOB)$	$\partial\left(\frac{ROP}{WOB}\right)/\partial(WOB)$
Slightly Larger or Close	Larger	Slightly Smaller or Close	Same or Slightly Larger Negative	Noisy / Inconclusive

d) ¶(ROP/WOB)/¶(WOB)

The derivative, ∂(ROP/WOB)/∂(WOB), is essentially constant at the baseline value except for the interval from about 20:6 to 2:25. The value close to the baseline is expected as described in Section 3.4.7.5. So because the ratio is small in this situation, reaching a good conclusive comparison to the baseline value is not possible due to amount of noise, and in many field situations, use of this diagnostic parameter may be misleading.

e) ¶(Torque/WOB)/¶(WOB)

The derivative, ∂(Torque/WOB)/∂(WOB), is also close to the baseline value and is typically just a slightly smaller negative value, which is also less negative than the immediately adjacent shales. This is the same tendency described in Section 3.4.7.6. The negative derivative has a much larger negative value from 20:16 to 20:25.

f) Review and Comments

Rock that is apparently relatively strong was drilled from 19:40 to 20:10 and 20:25 to 20:43 in the subject well. The torque/WOB ratio in this example does not increase as much relative to the value in shale as observed in laboratory data or other sections of possibly stronger rock in Well A, such as the one in XZ500 ft (can be seen in Appendix VII). In these two stronger rocks, the torque/WOB ratio is very close to the baseline value. These formations may not be as strong as the laboratory siltstone or other possibly stronger rock in the Well A, but they are stronger than the shale in Well A. The other indications of stronger rock are observed in the well, but there is no log response to verify that expectation, maybe because these stronger formations are thinner than the resolution of the log. These possibly stronger rocks could be seen for example at XX900, XY920, and XY500.

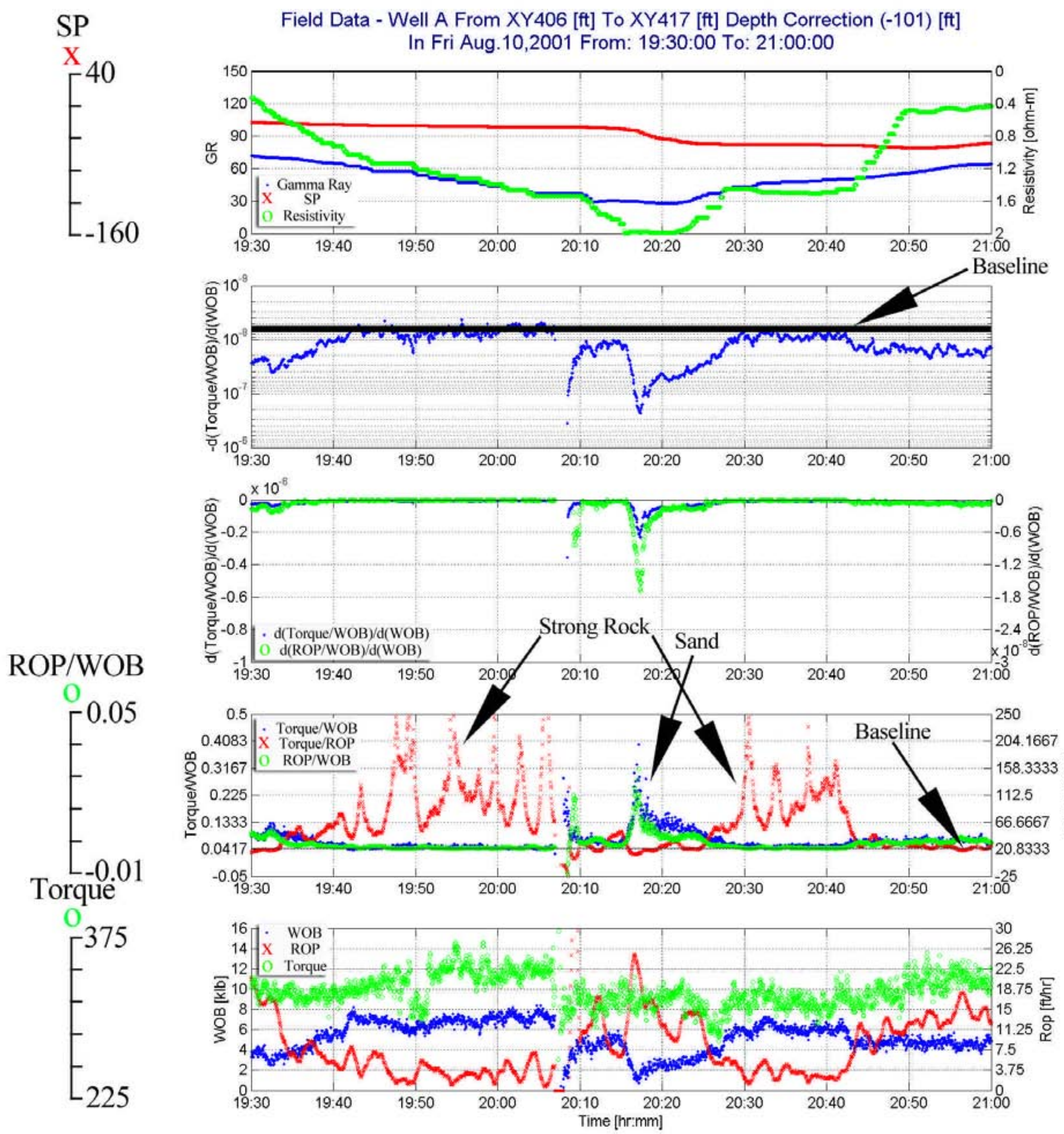

Figure 4.6 – Drilling in Stronger Rock

4.4. Discussion about Other Possible Parameters

4.4.1. The Torque Parameters, A and B

As mentioned in Chapter three, Section 3.4.7.7, two diagnostic parameters, A and B, are evaluated for laboratory situations. However, Equation 3.3 may not be valid anymore in field situations because surface torque is influenced by friction on the drill-string as well as the friction and cutting coefficients. As the results in Figure 4.7 show both parameters, A and B, are very noisy, and the second parameter (B) is very sensitive to WOB and usually increases just with WOB. The increase in B from about 10 to 20 at 5:01 to 5:02 to an average of 45 to 50 after 5:22 parallels both the increase in WOB and the trends in torque/WOB and ∂(Torque/WOB)/∂(WOB) shown in Figure 4.5 for the same interval. Another example is shown in Figure 4.8 for a stronger rock, the same interval of Figure 4.6, and it could be seen that the shape of the B-parameter is similar to the WOB.

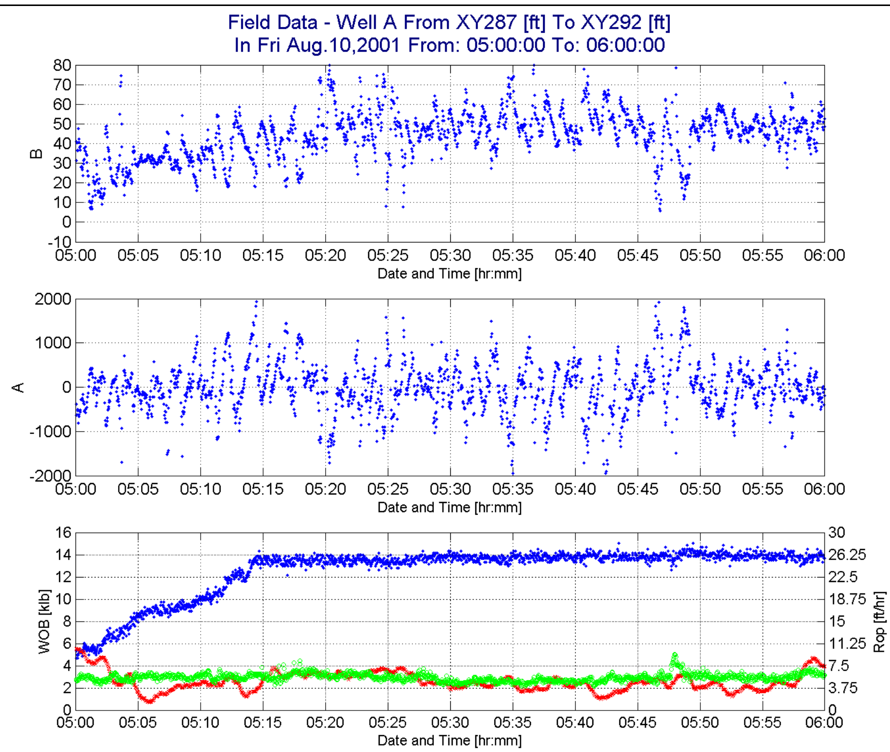

Figure 4.7 – A and B parameters - Drilling in Shale (Balling)

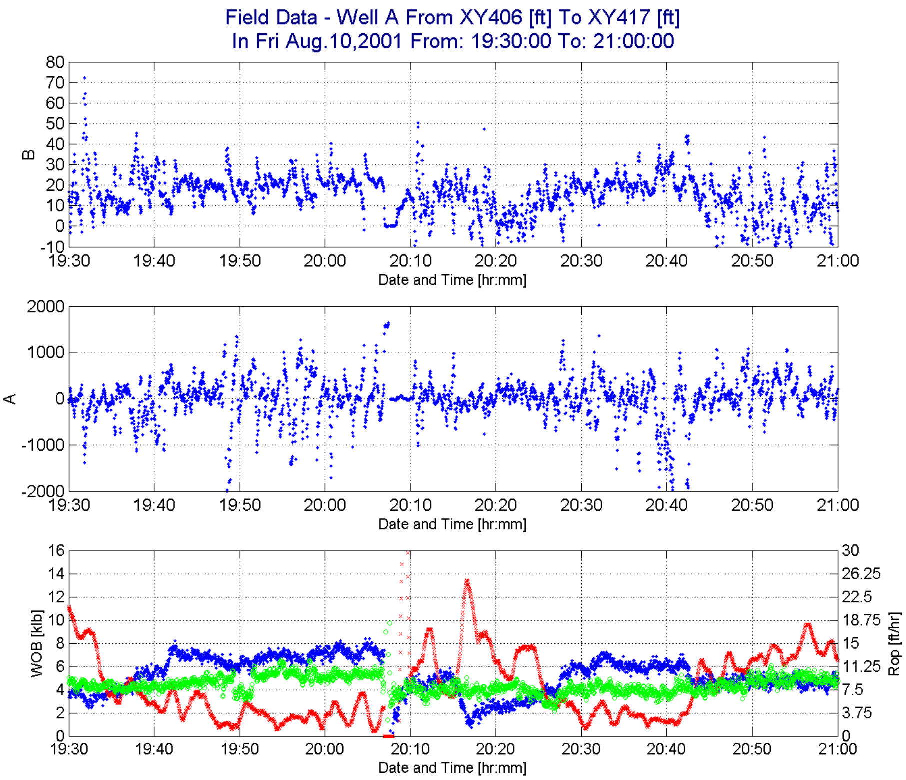

Figure 4.8 – A and B parameters - Drilling in Stronger Rock

4.4.2. Other Possible Diagnostic Parameters

Other possible parameters, such as King's parameters, ∂(ROP)/∂(WOB) (which are similar to King's main parameters), ∂(Torque)/∂(WOB), and ∂(Torque/∂(ROP) should be logically useful parameters. However, meaningful calculations of these parameters need a significant change in the numerator and denominator of the derivative, as described in Chapter three, Section 3.4.7.8.4. Using these kinds of diagnostic parameters probably requires intentionally changing the WOB over a bigger range than exists in the available data. An example of the noisy values of these parameters is shown in Figure 4.9 for the same interval as Figure 4.5, which shows severe balling in shale. More study of these parameters and methods for controlling WOB during their measurement will be required for a conclusive evaluation of their utility.

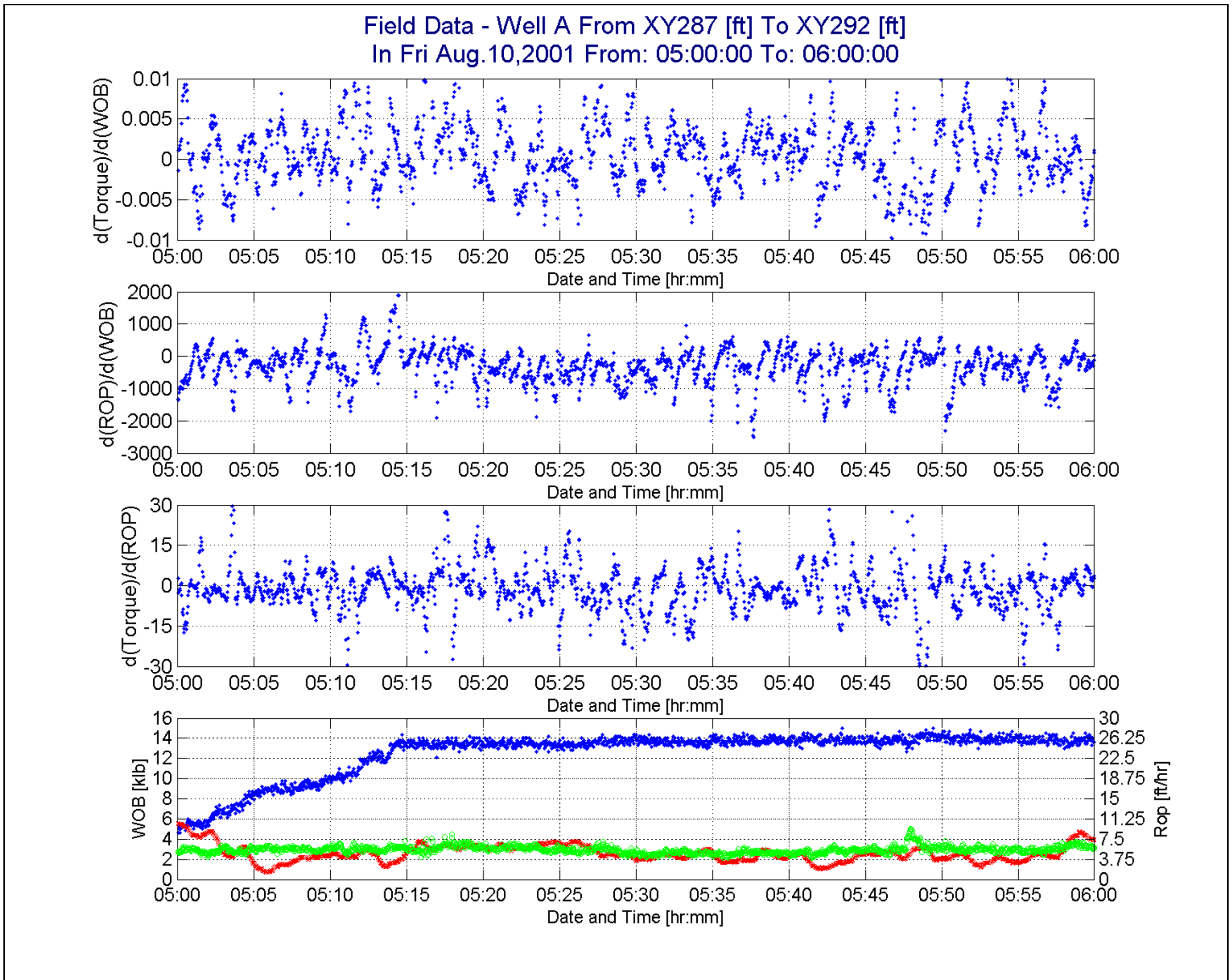

Figure 4.9 – Other Possible Parameters - Drilling in Shale (Balling)

4.4.3. Normalized Values for the Diagnostic Parameter Group

As mentioned in Chapter three, three main diagnostic parameters were used in previous research studies. These normalized parameters can be calculated by only changing the units of the torque parameter and including the effect of rotary speed and conversion constant, as appropriate. The only major difference between normalized parameters and diagnostic parameters are the range values of each parameter. The first conversion is torque, which is measured in amps, and should be converted to ft-lb (using in Figures 4.10 (low gear) and 4.11 (high gear)). Because there is no record of whether the rotary was used in low or high gear, calculations were done for both.

The second step is using equations from the previous research studies: Equations 2.16 (force ratio), 2.14 (specific energy), and 2.7 (FORS). Table 4.6 shows the maximum and minimum observed amps and equivalent of ft-lb in Well A. For the change of other torque between these maximum and minimum, a linear function between these two points is selected. Table 4.7 shows the scale of normalized parameters for Figures 4.2 to 4.6 if these parameters are used. Maximum represents conditions resulting in maximum value for the actual field data. (For force ratio and FORS the values at XT440 ft and for specific energy the values at XY410 ft are used) Minimum represents minimum on the scale in the plots (Figures 4.2, 4.3, 4.4, 4.5, and 4.6) and the values of the scale are used (values are negative because minimum scale values are chosen as negative value). For force ratio and specific energy, drill-string torque probably influences the values, so the very large number could be seen in the table.

Table 4.6 – Minimum and Maximum Observed Torques in the Well A

		Torque [amp]	Torque [ft-lb]
Low Gear	Minimum	225	3637
	Maximum	375	7694
High Gear	Minimum	225	2056
	Maximum	375	4403

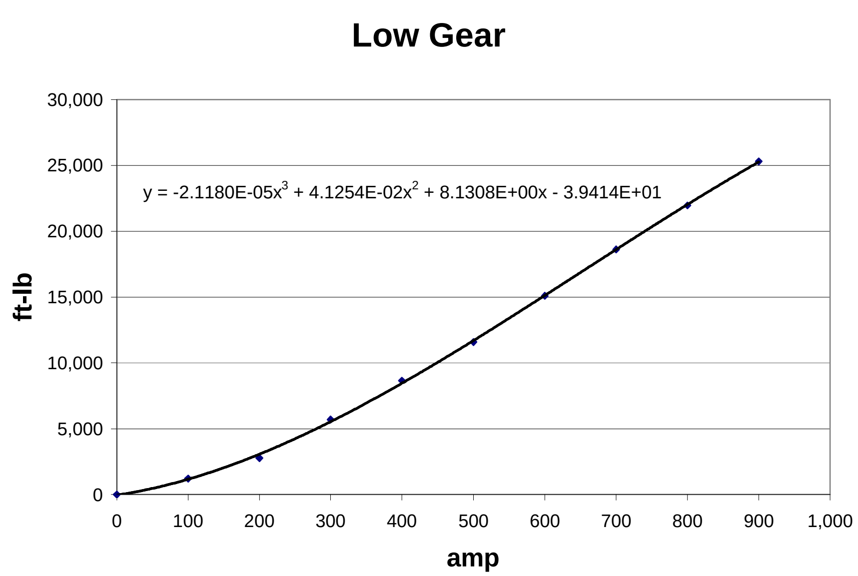

Figure 4.10 – Converting Torque from amp to ft-lbs (Low Gear)

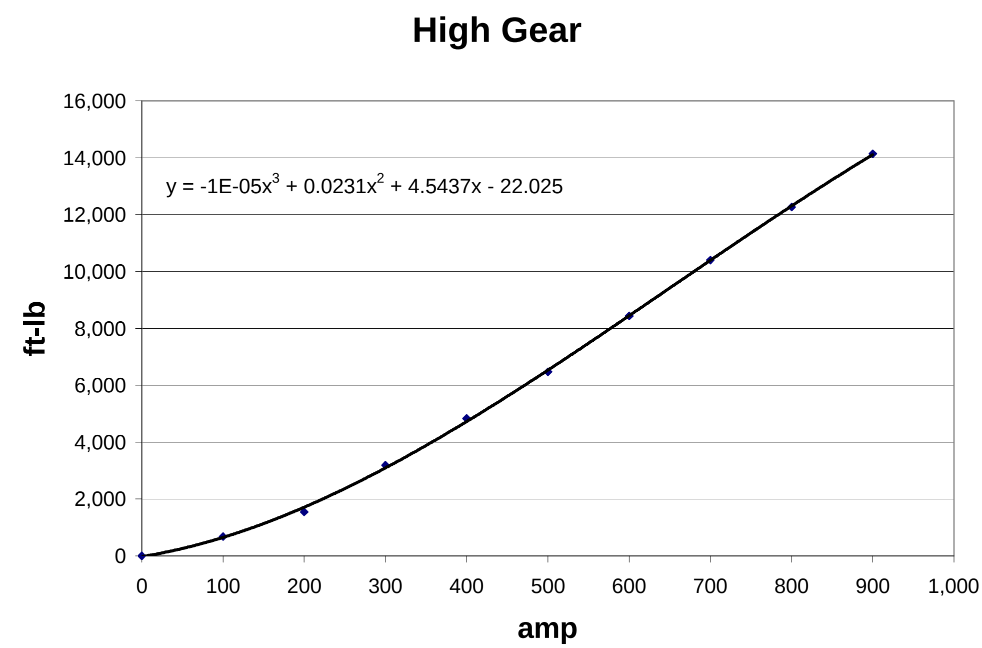

Figure 4.11- Converting Torque from amp to ft-lbs (High Gear)

Table 4.7 – Scale for Normalized Parameters

		R_f (~Torque/WOB)	E_S [psi] (~Torque/ROP)	$1/FORS$ [1/psi] (~ROP/WOB)
Low Gear	Minimum	-6	-3.67E5	-1.63E-4
	Maximum	75	4.66E6	8.13E-4
High Gear	Minimum	-3.4	-2.08E5	-1.63E-4
	Maximum	43	2.67E6	8.13E-4

4.5. Summary

Comparison of the diagnostic parameters with the baseline can help to distinguish between different situations causing changes in bit performance to detect balling. Table 4.8 shows the response of each diagnostic parameter to a particular drilling condition or situation observed in a well. Balling could be most conclusively detected by using the ∂(Torque/WOB)/∂(WOB) parameter. This parameter is a smaller negative number near zero when compared to the baseline value of this parameter only in the situation of balling. Other different situations, such as strong sand, other lithologies, bit wear, etc., and more data for confirmation, such as sonic logs, are not available in the existing field data, so adding those situations to the list without any confirming evidence is not appropriate or relevant.

Table 4.8 – Summary of Observed Field Response of Diagnostic Parameters					
First Diagnostic Parameter Group				Second Diagnostic Parameter Group	
Situations	Torque/WOB	Torque/ROP	ROP/WOB	$\partial\left(\frac{Torque}{WOB}\right)/\partial(WOB)$	$\partial\left(\frac{ROP}{WOB}\right)/\partial(WOB)$
Shale (baseline)	In Baseline	In Baseline	In Baseline	In Baseline	In Baseline
Sand	Larger	Varies	Larger	Larger Negative	Larger Negative
Shale (Cleaner Bit)	Larger	Same	Somewhat larger	Larger Negative	Larger Negative
Shale (Severely Balled)	Slightly Smaller	Larger	Slightly Smaller	Much Smaller Negative	Noisy / Inconclusive
Stronger Rock	Slightly Larger or Close	Larger	Slightly Smaller or Close	Same or Slightly Larger Negative	Noisy / Inconclusive

4.6. Nomenclature

ROP = Rate of Penetration, ft/hr

Time = Time, hr:min

WOB = Weight on Bit, klbs

Torque = Torque, amp

Depth = Depth, ft

A = Torque Diagnosis Parameter A, ft/hr/lbs

B = Torque Diagnosis Parameter B, 1/hr/lbs

RPM = Rotary Speed, rev/min

5. RESULTS AND DISCUSSION

5.1. Introduction

The main diagnostic parameters proposed in the two previous chapters must be compared to determine whether the responses are consistent for similar field and laboratory situations. In addition to the discussion about the main proposed diagnostic parameters, other possible parameters in both the field and laboratory situations are described. Finally, field results are compared with existing wire-line logs, and the final procedure is validated.

5.2. Discussion about Main Diagnostic Parameters in Field and Lab Data

5.2.1. ROP/WOB

As mentioned in Chapter three (Section 3.4.7.2) and Chapter four (Sections 4.3.2, 4.3.3, 4.3.4, and 4.3.5), and summarized in Table 5.1 for all laboratory and field situations, this parameter is smaller than the baseline value in situations of balling and drilling a strong rock and larger than the baseline value when drilling weak sand or shale at clean bit. The only difference between laboratory and field situation is in the accuracy of the ROP, which is more accurate in laboratory tests. The observation is similar to previously published research,[29,61] which was done for 1/FORS.

Table 5.1
ROP/WOB

	Cleaner Drilling in Weak Rock (Sand or Shale)	Shale (Severely Balled)	Strong Rock
Laboratory	Large	Small	Small
Field (vs. shale baseline)	Larger	Slightly Smaller	Slightly Smaller or Close

5.2.2. Torque/ROP

As mentioned in Chapter three (Section 3.4.5.3) and Chapter four (Sections 4.3.2, 4.3.3, 4.3.4, and 4.3.5), and summarized in Table 5.2, this parameter is the same as the baseline value in the situation of drilling sand or shale at low WOB. In the situation of drilling a strong rock, the ratio has a larger value for both laboratory and field situations. As mentioned before in Chapters three and four, the additional torque due to drill-string friction creates a difference between this ratio for laboratory and field situations. For both conditions the ratio is larger than the baseline but in field situations the ratio is increased more. The observation is similar to previously published research,[1,2,8,9,29,41,61] in which specific energy is increased in situations of balling and strong rock.

Table 5.2
Torque/ROP

	Cleaner Drilling in Weak Rock (Sand or Shale)	Shale (Severely Balled)	Strong Rock
Laboratory	Intermediate	Intermediate to Large	Large
Field (vs. shale baseline)	Same, Varies in Sand	Larger	Larger

5.2.3. Torque/WOB

As mentioned in Chapter three (Section 3.4.5.4) and Chapter four (Sections 4.3.2, 4.3.3, 4.3.4, and 4.3.5), and summarized in Table 5.3, for all laboratory and field situations, this parameter is smaller than the baseline value in situations of balling, a little larger than the baseline value in situations of drilling a strong rock, and larger than the baseline value when drilling weak sand or shale at clean bit. The observation is similar to previously published research,[1,2,8,9,29,41,61] in which force ratio is decreased in situations of balling.

Table 5.3
Torque/WOB

	Cleaner Drilling in Weak Rock (Sand or Shale)	Shale (Severely Balled)	Strong Rock
Laboratory	Large	Small	Small to Intermediate
Field (vs. shale baseline)	Larger	Slightly Smaller	Slightly Larger or Close

5.2.4. ¶(ROP/WOB)/¶(WOB)

A summary of the observations of this derivative parameter is shown in Table 5.4. Because the drill-string effects add inaccuracy in measuring and calculating ROP and WOB, a difference between field and laboratory situations is the accuracy of the diagnostic parameter, which is less accurate in field situations. All discussion about the diagnostic parameter is in Chapter three (Section 3.4.5.5) and Chapter four (Sections 4.3.2, 4.3.3, 4.3.4, and 4.3.5). This parameter has a smaller negative value than the baseline value in situations of balling, the same or a little larger negative than the baseline value in situations of drilling a strong rock, and a larger negative value than the baseline value when drilling weak sand or shale at clean bit. But as stated in Chapter four, because the ratio is small in the situations of both severe balling and drilling a strong rock, and due to erratic values, reaching a good diagnostic conclusion is not possible.

Table 5.4
∂(ROP/WOB)/∂(WOB)

	Cleaner Drilling in Weak Rock (Sand or Shale)	Shale (Severe Balling)	Strong Rock
Laboratory	Large Negative	Small Negative	Positive
Field (vs. shale baseline)	Larger Negative	Noisy / Inconclusive	Noisy / Inconclusive

5.2.5. ¶(Torque/WOB)/¶(WOB)

A summary of the observations of this derivative parameter are shown in Table 5.5. All discussion about the diagnostic parameter is in Chapter three (Section 3.4.5.6) and Chapter four (Sections 4.3.2, 4.3.3, 4.3.4, and 4.3.5). This parameter has a smaller negative value than the baseline value in situations of balling, the same or a little larger negative value than the baseline value in situations of drilling a strong rock, and larger negative value than the baseline value when drilling weak sand or shale at clean bit. As mentioned before in Chapters three and four, the additional torque due to drill-string friction creates a difference between this ratio for laboratory and field situations.

Table 5.5 ∂(Torque/WOB)/∂(WOB)			
	Cleaner Drilling in Weak Rock (Sand or Shale)	Shale (Severe Balling)	Strong Rock
Laboratory	Large Negative	Small Negative	Positive
Field (vs. shale baseline)	Larger Negative	Much Smaller Negative	Same or Slightly Larger Negative

5.3. Discussion about Normalized Parameters

Equations 2.14, 2.15, 2.16, and 2.17 define normalized parameters analogous to the diagnostic parameters used herein. However, in addition to ROP, torque, and WOB, other factors such as borehole area, bit diameter, and RPM are used in calculating parameters, particularly force ratio and specific energy. Using normalized parameters and making values meaningful need more research for the following reasons. Validating the parameters needs data for different situations. For example, evaluating the effect of the bit diameter on force ratio requires that data for different bit diameters should exist. In our research, only one bit diameter is used in full-scale test and field data, and in single-cutter tests only diameter is used. In addition, for the effect of RPM of specific energy, much data for different RPMs is needed, which does not exist in our research. Comparing a dimensionless parameter, such as force ratio, should ideally be done by comparing it to other dimensionless parameters, but other good dimensionless parameters are not introduced by previous research studies; therefore, a dimensionless force ratio is usually compared with a dimensional parameter, such as ROP, specific energy, etc. Correlating different wells to each other or finding the best RPM for better performance adds other factors into the calculation, and it increases the complication of the project, which is already complicated enough.

5.4. Overall Comparison of the Diagnostic Parameters with Logs

Appendix VII is a plot of the diagnostic parameters and the wire-line logs on a common depth basis. Over the range of 2600 ft of existing data, the diagnostic parameters imply the lithology and drilling conditions consistent with wire-line logs. Sands can be seen over depths of XX450-XX480 and XY410-XY530 where low gamma ray, high SP, and low resistivity validate these as water-saturated, porous, permeable formations with low clay content. At depth of XY410, a strong rock formation is observed in which low gamma ray, low SP, and high resistivity validate the possibility of a strong rock formation. Other apparently strong rock formations are indicated by the proposed diagnostic parameters. Because these are thin, log response is not observable. In addition, the lack of a density log and/or sonic log prevents any strong conclusions about rock strength, and the lithology cannot be validated. Several instances of severe balling can be observed at depths XX120, XX190, XX350, XX890, XY290, etc., in which the high gamma ray and low sp, and low resistivity indicate formations are weak shale. In each case, WOB is increased, ROP is decreased, force ratio is decreased, and specific energy is increased, which are three common symptoms of balling per Smith.[1,2,8,9] Overall, these parameters can be measured with good depth resolution of less than one foot, which is much better than conventional wire-line logs. Therefore, they are potentially valuable for identifying lithology and formation boundaries for thinly-bedded formations.

5.5. A Potential Procedure

A potential procedure for causing changes in bit performance, especially detecting the onset of, or an increase in the severity of balling or using diagnostics to maximize bit performance is proposed:

1) Find the baseline value for all diagnostic parameters from previously drilled data based on the long-term trend of best ROP in shale. Shale intervals may be inferred directly from low ROP and

small negative values of the derivative parameter, ∂(Torque/WOB)/∂(WOB). Shale intervals may also be implied by correlation to offsets or confirmed by cuttings.

2) Make sure other important parameters, e.g., RPM, flow rate, pump pressure, mud properties, etc., are relatively constant.

3) If any of the diagnostic parameters change, use Table 5.6 to determine the probable cause so that the appropriate action may be recommended for the situation. Table 5.6 is based on trends in the diagnostic parameters observed in field data as described in Chapter four. For example, reduce the WOB if balling is becoming more severe, or increase the WOB if the ROP is low in a strong rock.

4) Update the baseline as needed for change in depth, RPM, flow rate, the bit, etc.

Table 5.6 – Summary of Observed Field Response of Diagnostic Parameters Compared to a Shale Baseline, Based on Well A

First Diagnostic parameter Group				Second Diagnostic parameter Group	
Situations	Torque/WOB	Torque/ROP	ROP/WOB	$\partial\left(\frac{Torque}{WOB}\right)/\partial(WOB)$	$\partial\left(\frac{ROP}{WOB}\right)/\partial(WOB)$
Shale (baseline)	In Baseline	In Baseline	In Baseline	In Baseline	In Baseline
Sand	Larger	Varies	Larger	Larger Negative	Larger Negative
Shale (Cleaner Bit)	Larger	Same	Somewhat Larger	Larger Negative	Larger Negative
Shale (Severe Balling)	Slightly Smaller	Larger	Slightly Smaller	Much Smaller Negative	Noisy / Inconclusive
Stronger Rock	Slightly Larger or Close	Larger	Slightly Smaller or Close	Same or Slightly Larger Negative	Noisy / Inconclusive

6. SUMMARY AND CONCLUSIONS

6.1. Summary

A detailed analytical model of bit mechanics and performance, including bit balling, has never been accomplished by the petroleum industry because of the very complicated drilling system and many unknowns. In this research, some physical concepts were applied to existing data to try to diagnose what happened and to find the cause without analyzing why and how it happened in detail. Therefore, using conceptual causes and effects, the changes in possible diagnostic parameters were observed when balling or a change in rock type occurred, and distinctions between these parameters for the different causal conditions were identified.

6.2. Conclusion

1) Changing drilling operational parameters is an opportunity to reduce bit-balling, to avoid problems, and to optimize performance that requires rapid diagnosis of real-time drilling data. This knowledge was gained from previous research.[1,2,8,9]

2) The basic surface drilling parameters, measured on nearly all rigs, show a response to conditions that can cause a change in bit performance.

3) There are characteristic relationships between the set of diagnostic parameters defined in this study and the specific conditions that can cause a change in bit performance.

4) Using the trend of data to define and assess diagnostic parameters is more useful than considering only single-point data. The trend is a useful for defining a baseline, identifying derivations from the baseline, and defining values of derivatives that have distinctive meanings.

5) High noise in drilling parameters measured in strong rocks in the laboratory implies that this may be a good means of identification of these rocks in field drilling, provided data acquisition frequency is high and noise is not overly dampened by the drill-string.

6) Existing conventional drilling monitoring parameters, such as ROP and surface torque, and normalized parameters, such as force ratio, specific energy, and parameters similar to FORS or "apparent formation strength", are widely accepted as being useful measures for characterizing bit performance. However, they are typically not conclusive for diagnosing the cause of a decrease in the ROP. Specifically, they are not conclusive for distinguishing an increase in balling severity from encountering a strong rock.

7) The proposed diagnostic parameters do provide distinctive characteristics to differentiate between causes for changes in bit performance that are shown to be consistent in both laboratory and field situations.

8) The best diagnostic parameter to distinguish balling in shale from strong rocks is $\partial(\text{Torque/WOB})/\partial(\text{WOB})$. The value of this parameter is a smaller negative number compared to the baseline value for balling, as observed in single-cutter, full-scale laboratory, and field data. It is a larger negative number comparing the baseline for strong rocks, as observed in both single-cutter and field data.

6.3. Recommendations

1) Intentionally changing a drilling operational parameter in field situations and observing the result can be beneficial for diagnosing bit performance. For example, having a larger ΔWOB increases the accuracy of derivative relative to the ΔWOB, and it gives an opportunity to uses other potential diagnostic methods, such as King's method, which has reported successful use of high ΔWOB in the field.

2) Comparing MWD and surface data for a given interval of well or wells should be used to assess the accuracy and utility of using surface data instead of data measured at the bit. These

parameters could then be applied and evaluated for range of field conditions. This would be a logical project to follow the current project.

3) An instrument or method for measuring noise, specifically variations in torque and WOB, transmitted by the drill-string should be investigated as a possible means of identifying strong rocks.

4) Detailed analysis or simulation of drill-string dynamics should be evaluated as a means to improve accuracy of estimating bottom-hole parameters from surface data, and as a means of improving the utility of surface data in general. This analysis will probably require a separate project to be initiated to focus on this opportunity.

5) Additional laboratory test data for different rock types, RPM, fluid types, WOB, ROP, bit sizes and types, would probably be beneficial for validating and improving diagnostic methods. This data should be used to address the utility of and possible methods of defining fully normalized or dimensionless parameters.

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APPENDIX I

KING'S METHOD[66,69,70]

This method uses multi-variable linear regression on weight of bit (WOB) and rate of penetration (ROP) to find the relationship between ROP and WOB.[66,69,70] Using ten second averages of data with five records per second data resolution, the method finds the relationship of WOB and ROP by performing multi-linear regression analysis over four minutes of drilling. Equation I.1 is shown in the form used for the regression, with t indicating 10 second averaged data and ROP_{t-1} and ROP_{t-2} designating the ROP averaged over the two previous 10 second periods.

$$ROP_t = a + b_1 ROP_{t-1} + b_2 ROP_{t-2} + b_3 WOB_t \quad \text{(I.1)}$$

As shown in Equations I.2 and I.3, because ROP should be constant in that specific formation drilling steady-state, in times t, t-1, and t-2. "Target bit weight is calculated by setting ROP to the target bit rate of penetration (preselected ROP) and solving Equations I.2 or I.3." [69] "Then the bit weight will bring ROP to the target bit rate of penetration"[69] "Then, the system uses a drilling model to determine a target weight on bit to produce an optimum rate of penetration."[69] After that, regression apply to data to recalculate new target WOB again. Thus, knowing the optimum ROP, the method calculates the optimum WOB for that situation. Furthermore, the method continuously determines an optimum weight on bit based upon measured conditions and maintains it at the optimum level during relatively constant formation characteristics. As measured conditions change while drilling, the method updates the determinations of optimum WOB.[66,69,70]

$$WOB_t = \frac{ROP_t - a - b_1 ROP_{t-1} - b_2 ROP_{t-2}}{b_3} \quad \text{(I.2)}$$

$$WOB = \frac{ROP(1 - b_1 - b_2) - a}{b_3} \quad \text{(I.3)}$$

APPENDIX II

ARTHUR LUBINSKI'S MEHTOD[57]

Because the length of the drill-string due to elastic deformations is affected by change in forces, this approach assumed that the change in the drill-string length is equal to a linear function of the change in forces (due to a change in weight on the bit) in the string,[57] and that the drill-string behaves as a perfect spring. It means that the speed of the drill-string at the bit is equal to the sum of the change in length of the drill-string, which is proportional to the change in the WOB and the elasticity coefficient of the drill-string, as well as the block speed at surface. Consequently, if we use the linear regression in the time interval between block positions and times, the slope of the line is block speed (Equations II.1 and II.2 and Figure II.1):

$$\text{Block position} = a * Time + b \quad \text{(II.1)}$$

$$\rightarrow ROP_{Surface} = a = \frac{dD_S}{dt} \quad \text{(II.2)}$$

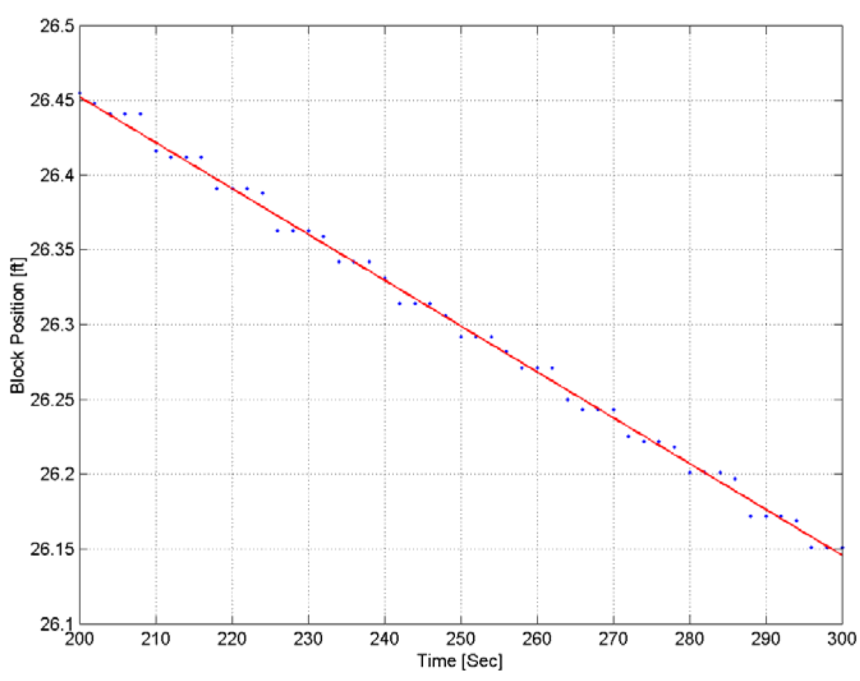

Figure II.1 – Block Speed Slope

If it is assumed that the system is in a steady-state condition (no acceleration and wave transmission), block speed includes two length changes: Firstly, the real rate of penetration and secondly, the change in drill-string length due to a change in forces so that:

$$\text{ROP} = \text{Block Speed at Surface} - \text{Decrease in Drill-String Length} \quad \text{(II.3)}$$

$$\text{Block Speed at Surface} = \frac{dD_S}{dt} \quad \text{(II.4)}$$

$$\text{Change in Drill-String Length} = \text{Elasticity Coefficient of Drill-String} * \text{Change in Forces} \quad \text{(II.5)}$$

$$\text{Decrease in Drill-String Length} = K\frac{dW}{dt} \quad \text{(II.6)}$$

$$ROP = \frac{dD_s}{dt} - K\frac{dW}{dt} \quad \text{(II.7)}$$

When using Lubinski's method, the elasticity coefficient is needed, this can be found in any textbook concerning mechanic of material:

$$K\left[{ft}/{lb}\right] = \frac{L[ft]}{144\left[{in^2}/{ft^2}\right]E\left[{lb}/{in^2}\right]A\left[ft^2\right]} \quad \text{(II.8)}$$

Because pipe includes both drill-string and drill-collar:

$$K = \frac{L_{Col}}{144EA_{Col}} + \frac{L_{Drill-string}}{144EA_{Drill-string}} = \frac{1}{144E}\left(\frac{L_{Col}}{A_{Col}} + \frac{L_{Total} - L_{Col}}{A_{Drill-string}}\right) \quad \text{(II.9)}$$

The length of the pipe can be assumed equal to the depth:

$$L_{Total} \approx Depth \quad \text{(II.10)}$$

$$\rightarrow K = \frac{1}{144E}\left(\frac{L_{Col}}{A_{Col}} + \frac{Depth - L_{Col}}{A_{Drill-string}}\right) \quad \text{(II.11)}$$

APPENDIX III

YVES KERBART'S METHOD[60]

One other simple method, which elaborates Arthur Lubinski's method,[57] is Kerbart's method.[60] Because there is friction between the drill-string and the well wall, using the known elasticity coefficient of the drill-pipe is not necessarily realistic. Thus, the method used in Lubinski's equation (Equation III.1) but with a different elasticity coefficient, which calculates using a statistical model of previous drilling operation data, assumes that the lithology does not change and the rate of penetration remains constant.

$$ROP = \frac{dD_s}{dt} - K\frac{dW}{dt} \quad \text{(III.1)}$$

For the larger time interval, if we assume the ROP remains constant and the limited change in forces, ΔW/Δt is reduced, because K is a small value, then:

$$\Delta t_L >> 0 \,\&\, K \equiv e \rightarrow K\frac{dW}{dt} = K\frac{\Delta W}{\Delta t} \approx 0 \quad \text{(III.2)}$$

Δt_L is the time of that long interval, so Arthur Lubinski's equation is changed to:

$$ROP_L = \frac{dD_s}{dt} \quad \text{(III.3)}$$

ROP_L is the average ROP in Δt_L (long interval), then in that long interval, because we assume ROP is constant:

$$ROP_L = \frac{dD_s}{dt} - K\frac{dW}{dt} \rightarrow ROP_L - \frac{dD_s}{dt} = -K\frac{dW}{dt} \quad \text{(III.4)}$$

ΔROP is the different between current ROP and ROP_L (long time average)

$$\Delta ROP = ROP_L - \frac{dD_s}{dt} \quad \text{(III.5)}$$

Then elasticity coefficient can be found using linear regression in a longer time interval:

$$\rightarrow \Delta ROP = -K_{Kerbert} \frac{dW}{dt} \quad \text{..} \quad (III.6)$$

ROP can be calculated in the shorter interval using Arthur Lubinski's formula:

$$ROP = \frac{dD_s}{dt} - K_{Kerbert} \frac{dW}{dt} \quad \text{..} \quad (III.7)$$

APPENDIX IV

LABORATORY TESTS DETAIL

Single Cutter Tests

	Test Name	Confining Pressure [psi]	Rock Type	Depth of Cut [in/rev]	Fluid Type	Cutter Type	Mounting Type	Back Rake [Degree]	Saturation
1	Test 7058F	300	Catoosa	0.075	Water	Polished	Cantilever	10	FALSE
2	Test 7058G	1000	Catoosa	0.011	Water	Polished	Cantilever	10	FALSE
3	Test 7058K	1000	Catoosa	0.075	Mineral oil	Polished	Cantilever	10	FALSE
4	Test 7058E	1000	Catoosa	0.075	Water	Polished	Cantilever	10	FALSE
5	Test 7058S	1000	Catoosa	0.075	Water	Polished	Cantilever	10	TRUE
6	Test 7058M	1000	Catoosa	0.075	Water	Polished	Cantilever	10	TRUE
7	Test 7058P	1000	Catoosa	0.075	Water	Polished	Chip Break	10	FALSE
8	Test 7058H	1000	TC Siltstone	0.011	Water	Polished	Cantilever	10	FALSE
9	Test 7052C	3000	Catoosa	0.033	Water	15 Bevel	Cantilever	20	FALSE
10	Test 7058D	3000	Catoosa	0.075	Water	Polished	Cantilever	10	FALSE
11	Test 7058C	6000	Catoosa	0.075	Water	Polished	Cantilever	10	FALSE
12	Test 7074G	9000	Catoosa	0.006	Mineral oil	Polished	Plate	10	FALSE
13	Test 7074K	9000	Catoosa	0.006	Water	Polished	Plate	10	FALSE
14	Test 7074I	9000	Catoosa	0.011	Mineral Oil	Polished	Plate	10	FALSE
15	Test 7057A	9000	Catoosa	0.011	Water	Polished	Cantilever	5	FALSE
16	Test 7058A	9000	Catoosa	0.011	Water	Polished	Cantilever	10	FALSE
17	Test 7059A	9000	Catoosa	0.011	Water	Polished	Cantilever	20	FALSE
18	Test 7074A	9000	Catoosa	0.011	Water	Polished	Plate	10	FALSE
19	Test 7060B	9000	Catoosa	0.011	Water	Standard	Cantilever	10	FALSE
20	Test 7075A	9000	Catoosa	0.011	Water	Standard	Cantilever	20	FALSE
21	Test 7058L	9000	Catoosa	0.075	Mineral oil	Polished	Cantilever	10	FALSE
22	Test 7059C	9000	Catoosa	0.075	Mineral oil	Polished	Cantilever	20	FALSE
23	Test 7074F	9000	Catoosa	0.075	Mineral oil	Polished	Plate	10	FALSE
24	Test 7060D	9000	Catoosa	0.075	Mineral oil	Standard	Cantilever	10	FALSE
25	Test 7060C	9000	Catoosa	0.075	Mineral oil	Standard	Cantilever	10	FALSE
26	Test 7058J	9000	Catoosa	0.075	Oil & water	Polished	Cantilever	10	FALSE
27	Test 7074D	9000	Catoosa	0.075	Oil & water	Polished	Plate	10	FALSE
28	Test 7061B	9000	Catoosa	0.075	Water	15 Bevel	Cantilever	5	FALSE
29	Test 7057C	9000	Catoosa	0.075	Water	Polished	Cantilever	5	FALSE
30	Test 7057B	9000	Catoosa	0.075	Water	Polished	Cantilever	5	FALSE
31	Test 7058R	9000	Catoosa	0.075	Water	Polished	Cantilever	10	TRUE
32	Test 7058B	9000	Catoosa	0.075	Water	Polished	Cantilever	10	FALSE
33	Test 7058N	9000	Catoosa	0.075	Water	Polished	Cantilever	10	TRUE
34	Test 7059B	9000	Catoosa	0.075	Water	Polished	Cantilever	20	FALSE
35	Test 7058O	9000	Catoosa	0.075	Water	Polished	Chip Break	10	FALSE
36	Test 7074B	9000	Catoosa	0.075	Water	Polished	Plate	10	FALSE
37	Test 7060A	9000	Catoosa	0.075	Water	Standard	Cantilever	10	FALSE
38	Test 7074J	9000	Pierre	0.075	Mineral Oil	Polished	Plate	10	FALSE
39	Test 7074H	9000	Pierre	0.075	Mineral oil	Polished	Plate	10	TRUE
40	Test 7058T	9000	Pierre	0.075	Water	Polished	Cantilever	10	TRUE
41	Test 7074C	9000	Pierre	0.075	Water	Polished	Plate	10	TRUE
42	Test 7058I	9000	TC Siltstone	0.011	Water	Polished	Cantilever	10	FALSE
43	Test 7058Q	9000	TC Siltstone	0.033	Water	Polished	Cantilever	10	FALSE
44	Test 7058U	9000	TC Siltstone	0.075	Water	Polished	Cantilever	10	FALSE

Full-scale Test

Test Name	Confining Pressure [psi]	Rock Type	Bit Type	Bit Model	Bit Size [in]	Mud Type	Mud Density [ppg]
BAL0101F	6000	Catoosa	PDC	HC-DP0553	8.5	WBM: CLS-FW	9.5

APPENDIX V

CUTTING AREA CALCULATION

Cutters dimension shows in figures V.1, V.2, and V.3

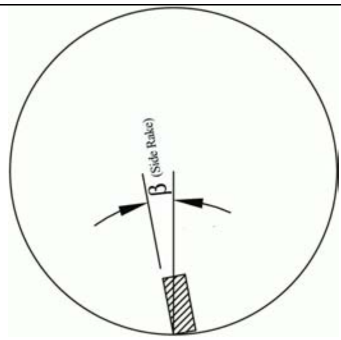

Figure V.1 – Single Cutter

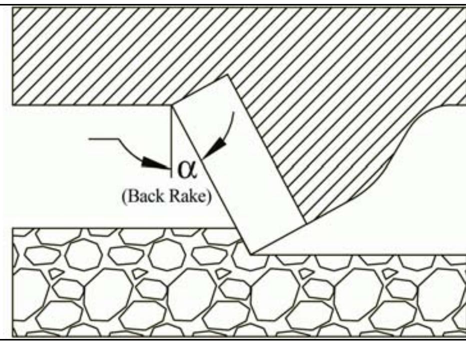

Figure V.2 – Cutter

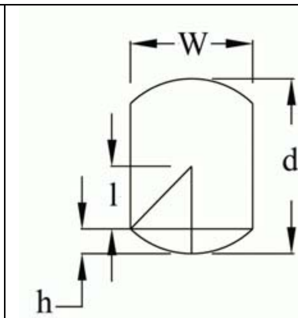

Figure V.3 – Cutter

If we assume no back rake and no side rake for simple calculation, we have $\boldsymbol{a} = 0, \boldsymbol{b} = 0$ .We also know $w = 0.34''$ and $w = 70\%d \Rightarrow d = w/0.7 \approx 0.53''$

From figure V.3:

$$\left(\frac{d}{2}\right)^2 = \left(\frac{w}{2}\right)^2 + l^2 \Rightarrow l = \sqrt{\frac{d^2}{4} - \frac{w^2}{4}} = \frac{1}{2}\sqrt{d^2 - w^2} \quad \text{(V.1)}$$

$$h = \frac{d}{2} - l \;\Rightarrow h = \frac{d}{2} - \frac{1}{2}\sqrt{d^2 - w^2} \quad \text{(V.2)}$$

We have two situations as figures V.4 and V.5:

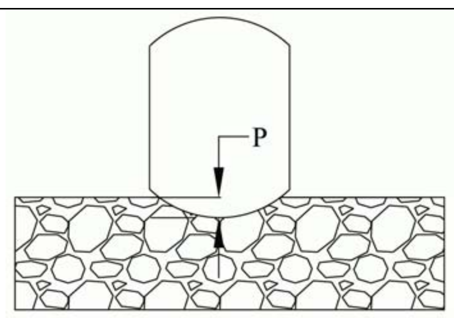

Figure V.4 - Situation One

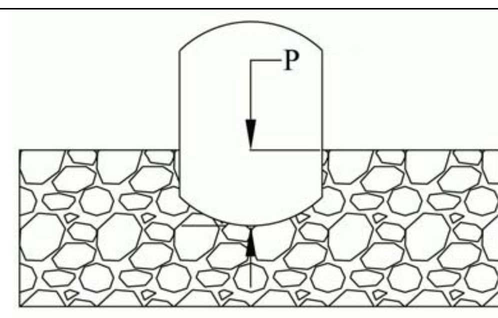

Figure V.5 - Situation Two

1. $p \leq h$

$$S_{total} = S_{curv} - S_{\Delta} \quad \text{(V.3)}$$

$$\left(\frac{d}{2}\right)^2=\left(\frac{d}{2}-p\right)^2+x^2 \Rightarrow x=\sqrt{\frac{d^2}{4}-\left(\frac{d}{2}-p\right)^2} \Rightarrow S_{\Delta}=\left(\frac{d}{2}-p\right)\sqrt{\frac{d^2}{4}-\left(\frac{d}{2}-p\right)^2} \text{ .... (V.4)}$$

$$Cosh=\frac{\frac{d}{2}-p}{\frac{d}{2}}=\frac{d-2p}{d} \Rightarrow h=Cos^{-1}\left(\frac{d-2p}{d}\right) \text{.................................. (V.5)}$$

$$S_{Curv}=\frac{pd^2}{4}\frac{2h}{2p}=\frac{hd^2}{4} \text{ .... (V.6)}$$

$$S_{total}=\frac{d^2Cos^{-1}\left(\frac{d-2p}{d}\right)}{4}-\left(\frac{d}{2}-p\right)\sqrt{\frac{d^2}{4}-\left(\frac{d}{2}-p\right)^2} \text{ .... (V.7)}$$

2. $p \geq h$

$$S_{total}=S_h+S_{box} \text{ .... (V.8)}$$

$$S_h=\frac{d^2Cos^{-1}\left(\frac{d-2h}{d}\right)}{4}-\left(\frac{d}{2}-h\right)\sqrt{\frac{d^2}{4}-\left(\frac{d}{2}-h\right)^2} \text{ .... (V.9)}$$

$$S_{total}=\frac{d^2Cos^{-1}\left(\frac{d-2h}{d}\right)}{4}-\left(\frac{d}{2}-h\right)\sqrt{\frac{d^2}{4}-\left(\frac{d}{2}-h\right)^2}+pw \text{ .... (V.10)}$$

So we calculated the area of contact between rock and cutter, cutting area, base on total area of current situation minus total area of previous revolution as figures V.6, V.7, and V.8:

$$S=S_{total}-S_{total\_Prv\_Rev} \text{ .... (V.11)}$$

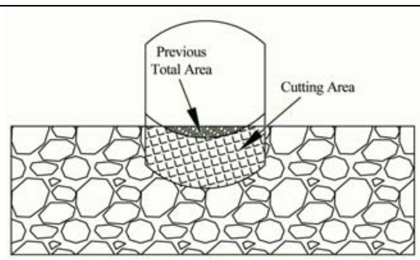	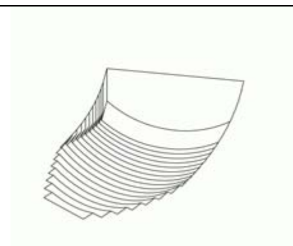	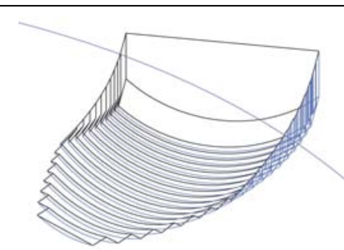
Figure V.6 – Cutting Area	Figure V.7- Cutting	Figure V.8- Cutting

APPENDIX VI

FIELD DATA INFORMATION

Name of the well	Well A	Well B
List of parameters	1. Time 2. Depth 3. Block Position 4. Hook Load 5. WOB 6. RPM 7. Torque 8. Pump Pressure 9. Pump Rate 10. Mud Motor 11. Casing Pressure 12. Pumps Strokes	1. Time 2. Depth 3. Block Position 4. Hook Load 5. WOB 6. RPM 7. Torque 8. Pump Pressure 9. Pump Rate 10. Mud Motor 11. Casing Pressure 12. Pits Volume 13. Total Gas 14. Flow Line 15. Flow In 16. Lag Time 17. Co2 & H2S 18. Temperature In & Out 19. Air PR In 20. A flow Out 21. WT In & Out 22. Total Gasm 23. Bit Tm On & Off 24. C1 & C2 & C3 & C4i &C4n &C5i &C5n & Acetylene 25. STD In & Out 26. SWAB Surge 27. CMPL Time 28. D Exp & EDC 29. Pumps Strokes 30. Diff HKLD 31. ACC Volume 32. Ton Miles 33. Diff PVT 34. ACC Reserve 35. Delta Pressure 36. PVT GL RAT

APPENDIX VII

THE DIAGNOSTIC PARAMETERS LARGE FIGURE

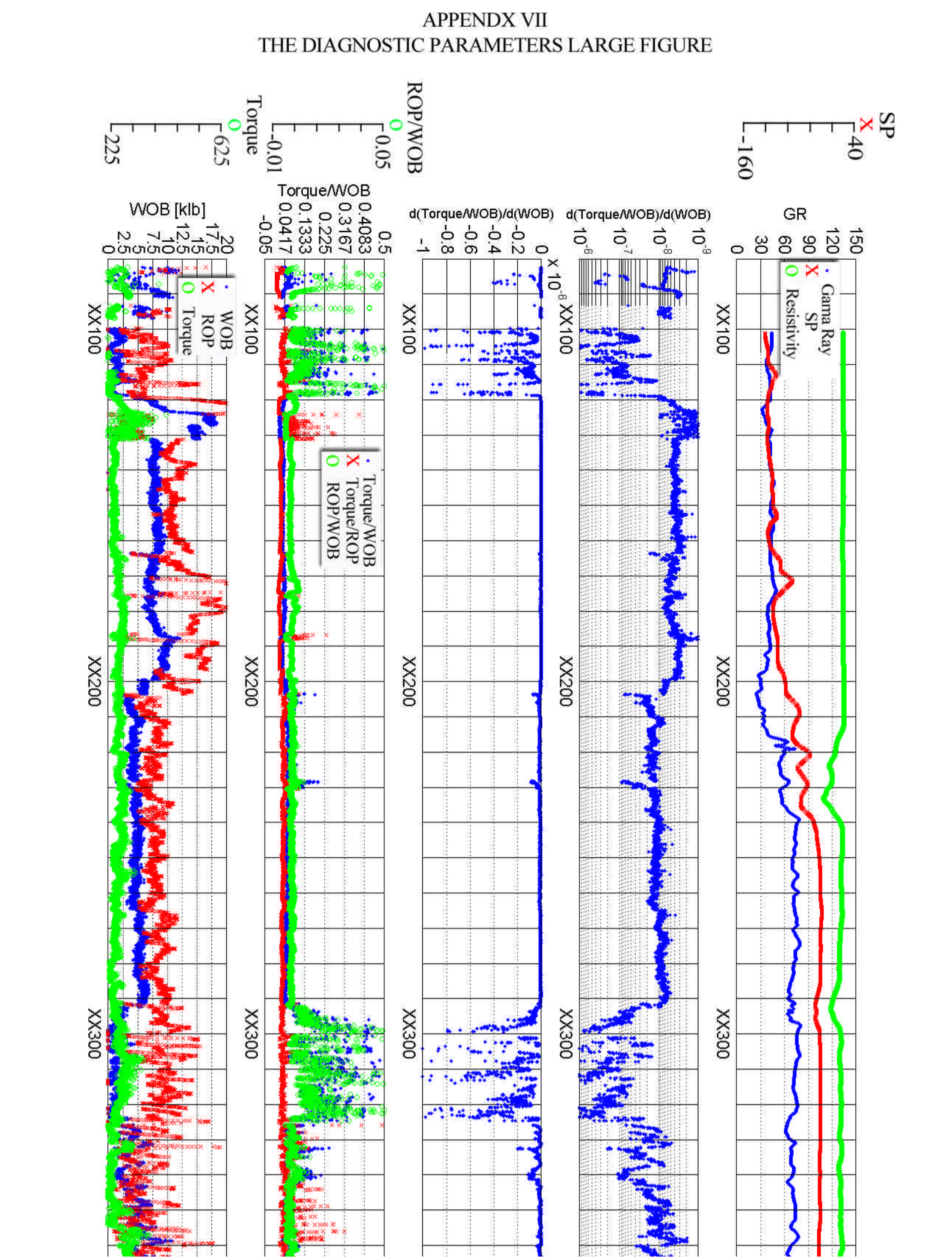

Figure VII.1 – The Diagnostic Parameters Large Figure

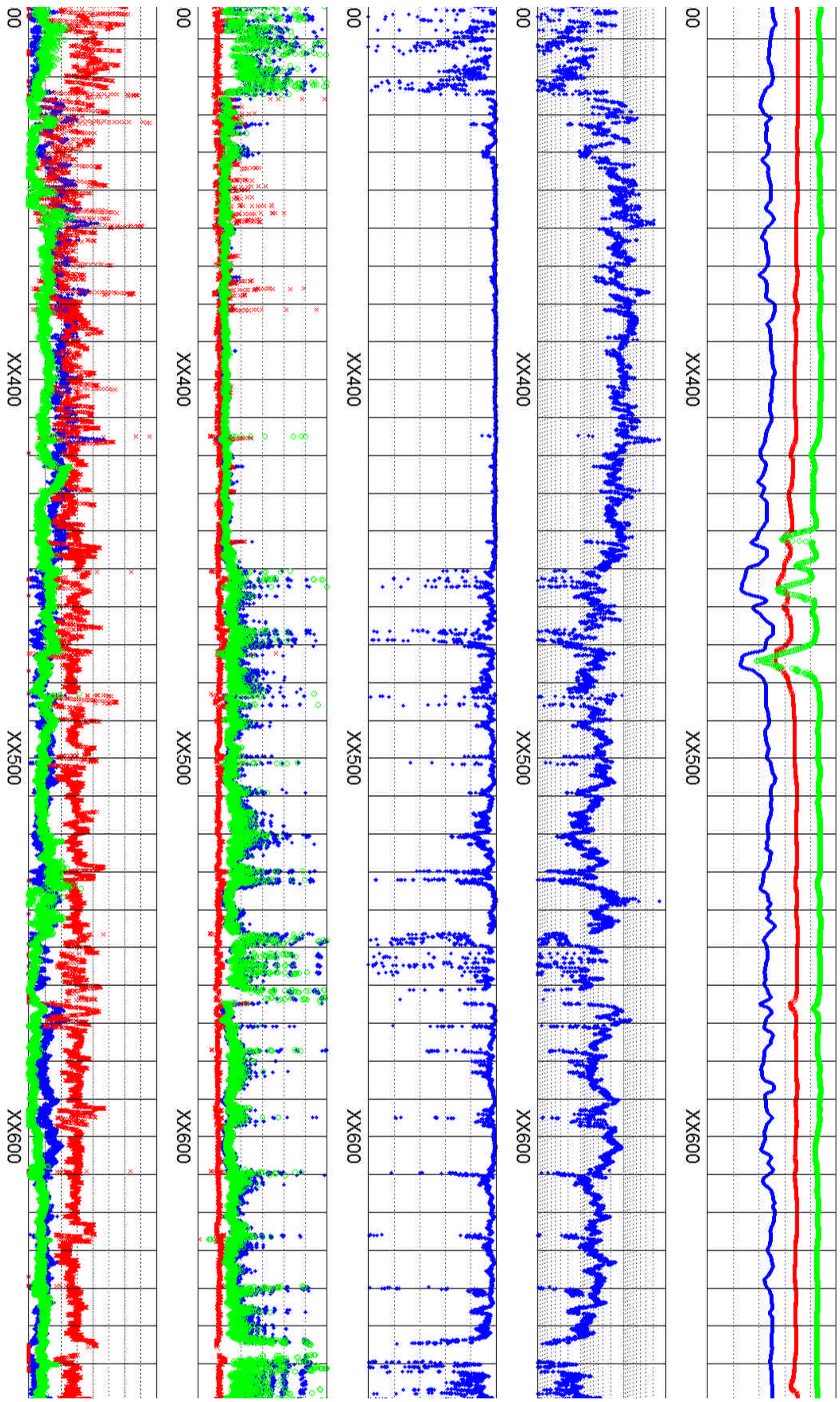

Figure VII.1 – The Diagnostic Parameters Large Figure – Continue

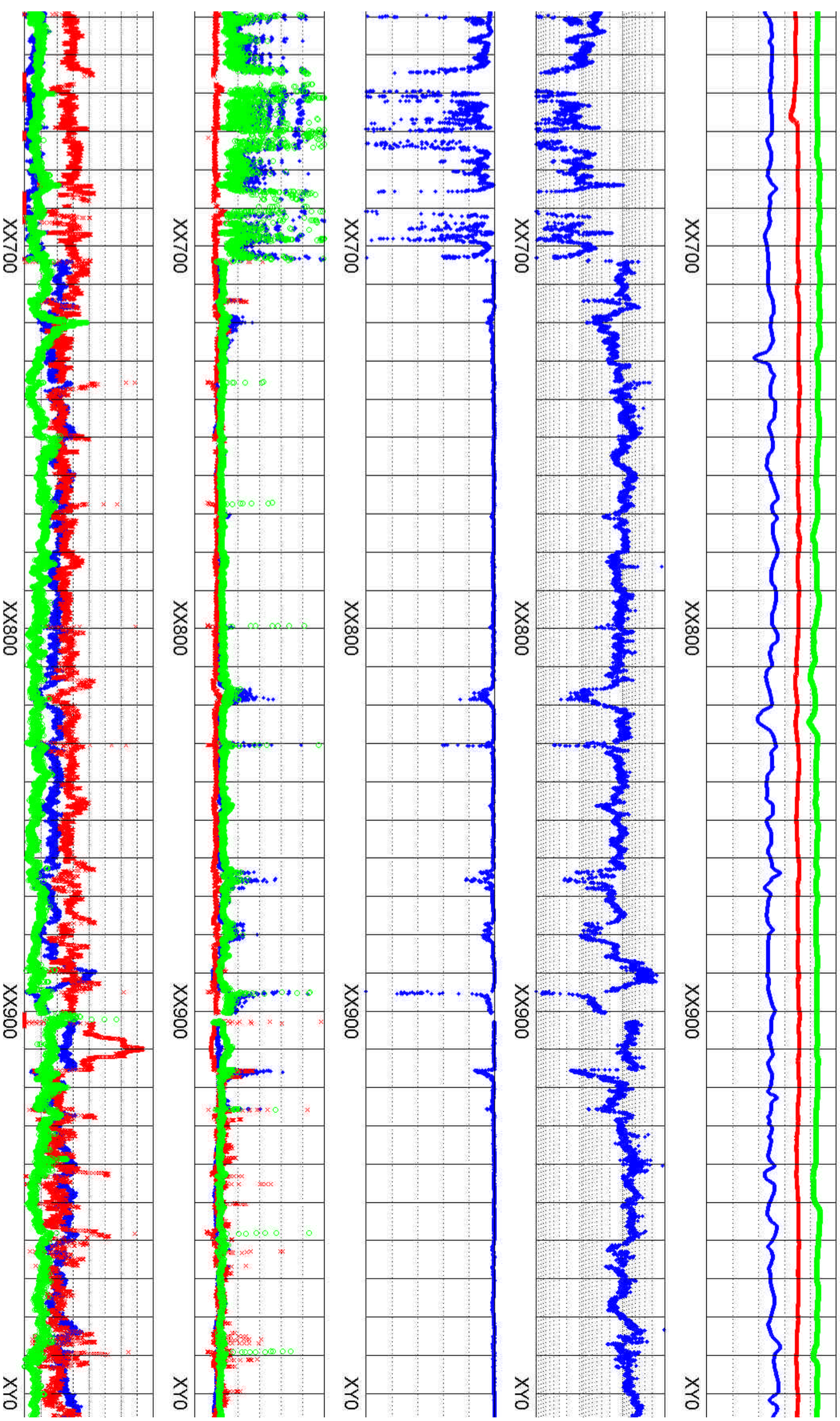

Figure VII.1 – The Diagnostic Parameters Large Figure – Continue

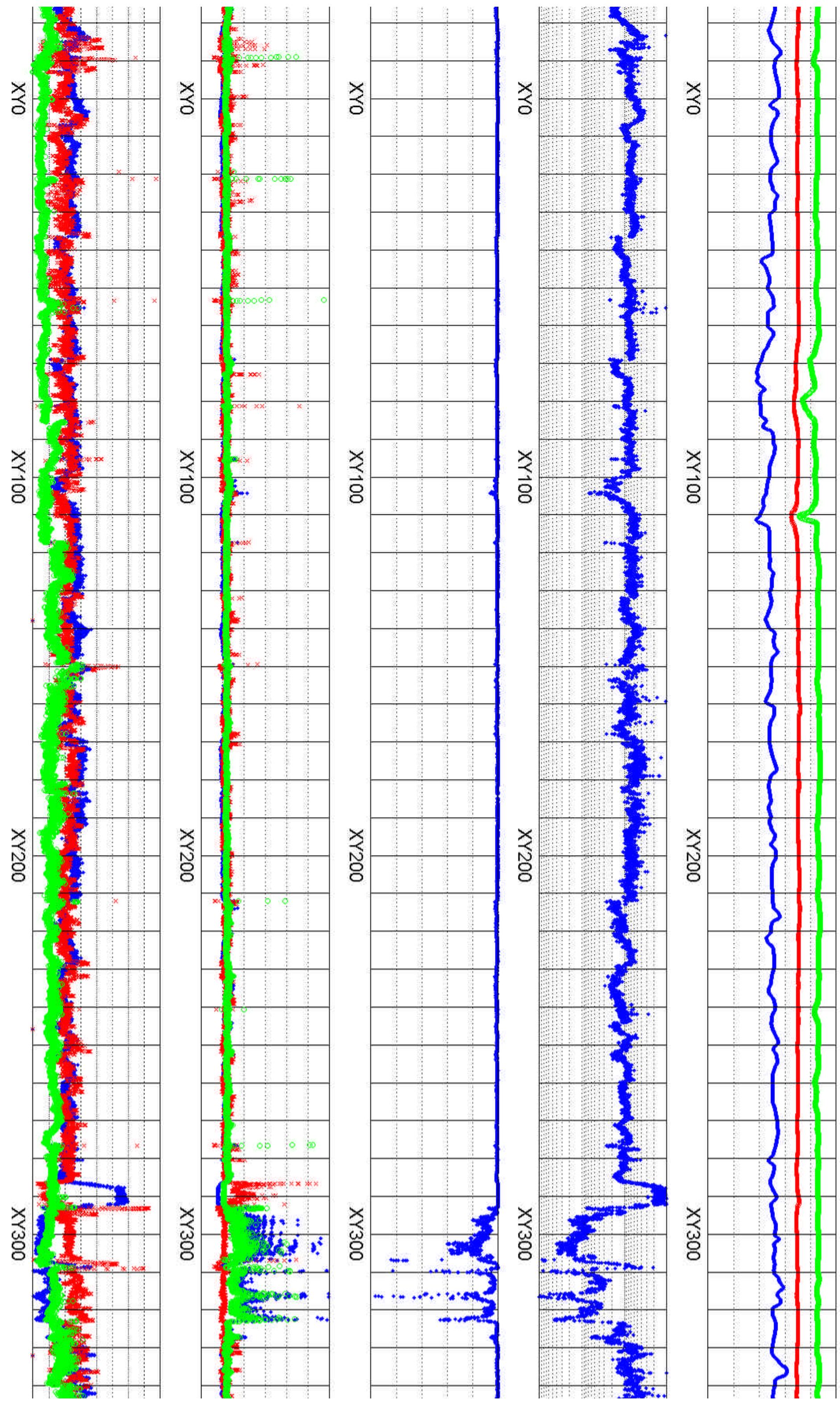

Figure VII.1 – The Diagnostic Parameters Large Figure – Continue

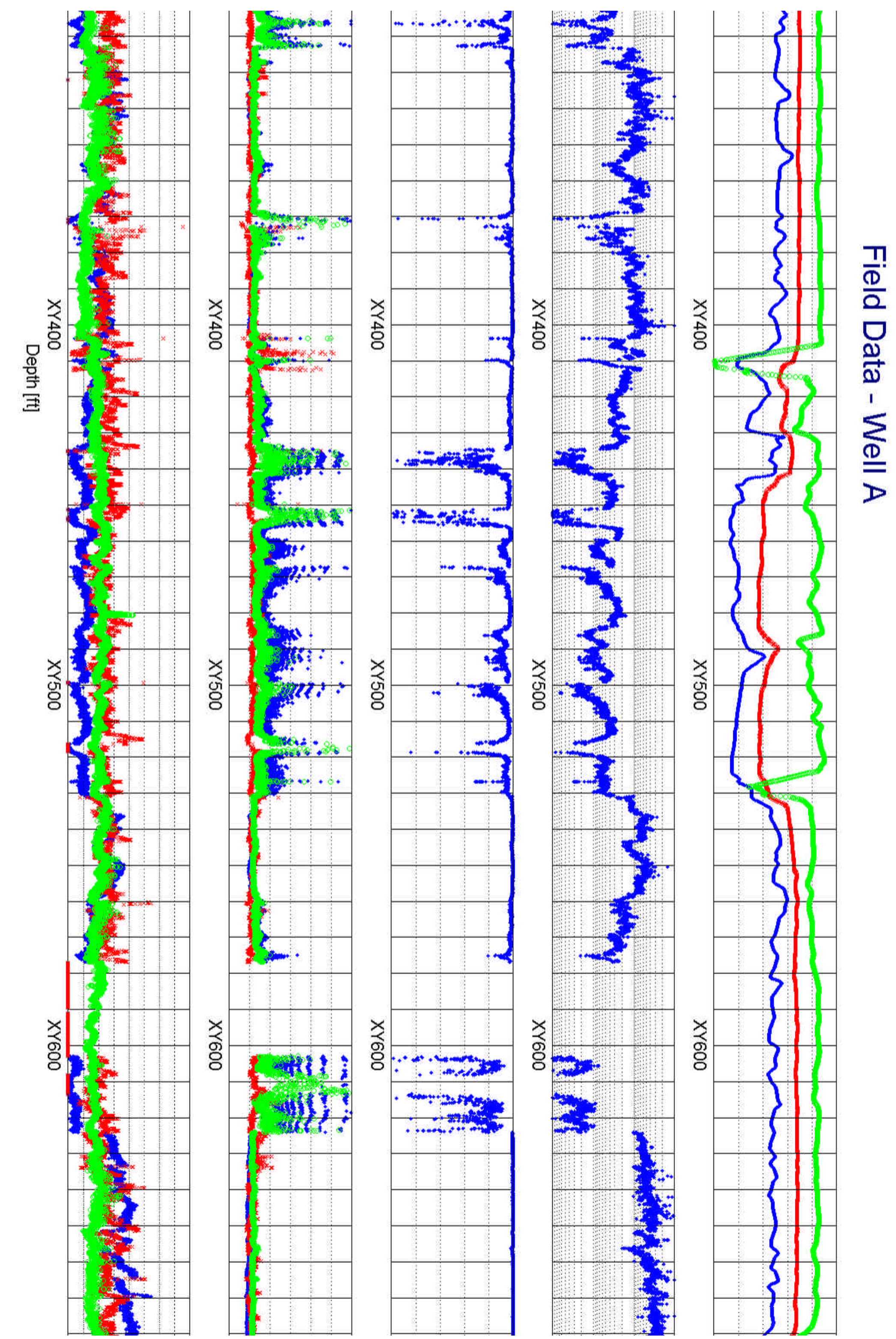

Figure VII.1 – The Diagnostic Parameters Large Figure – Continue

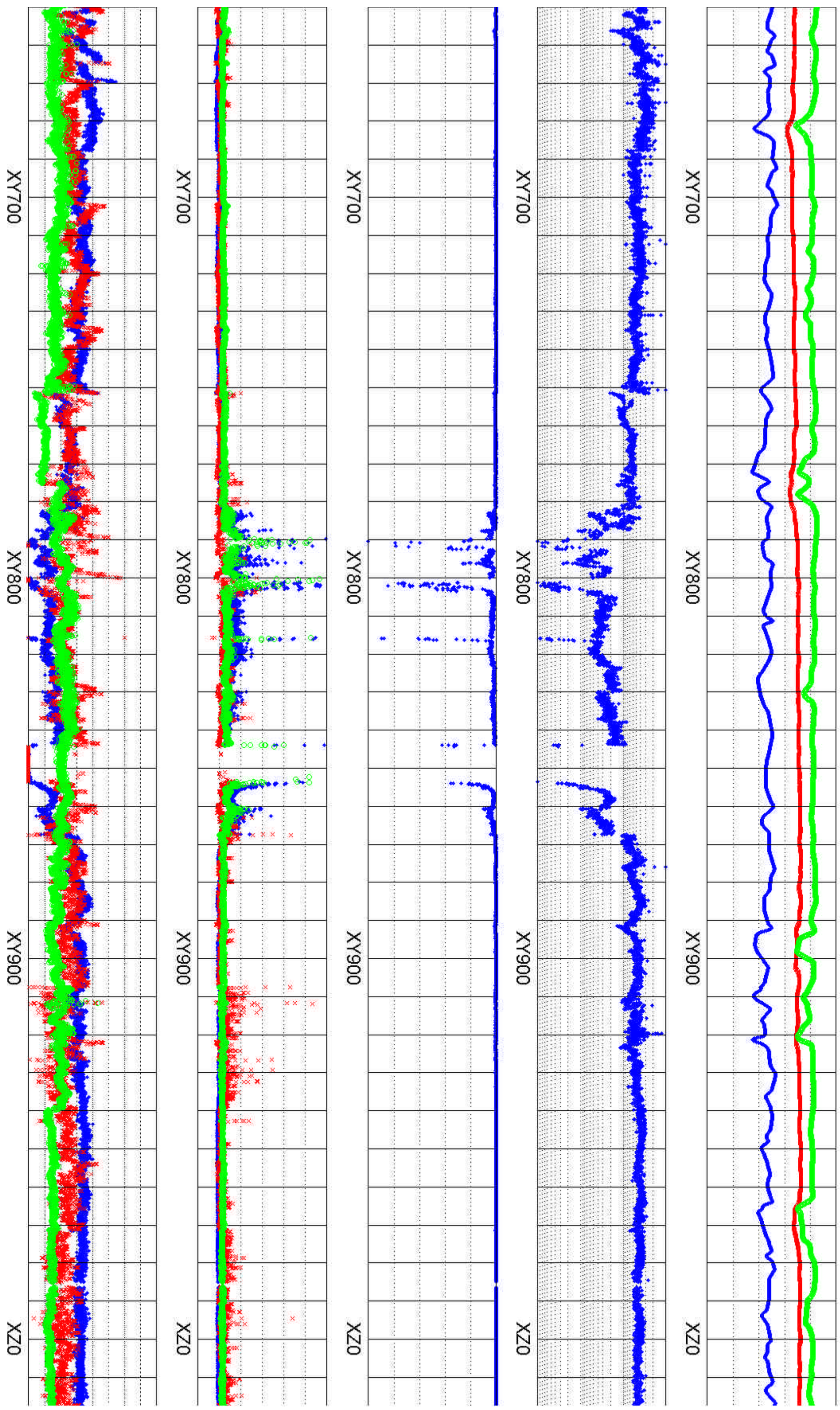

Figure VII.1 – The Diagnostic Parameters Large Figure – Continue

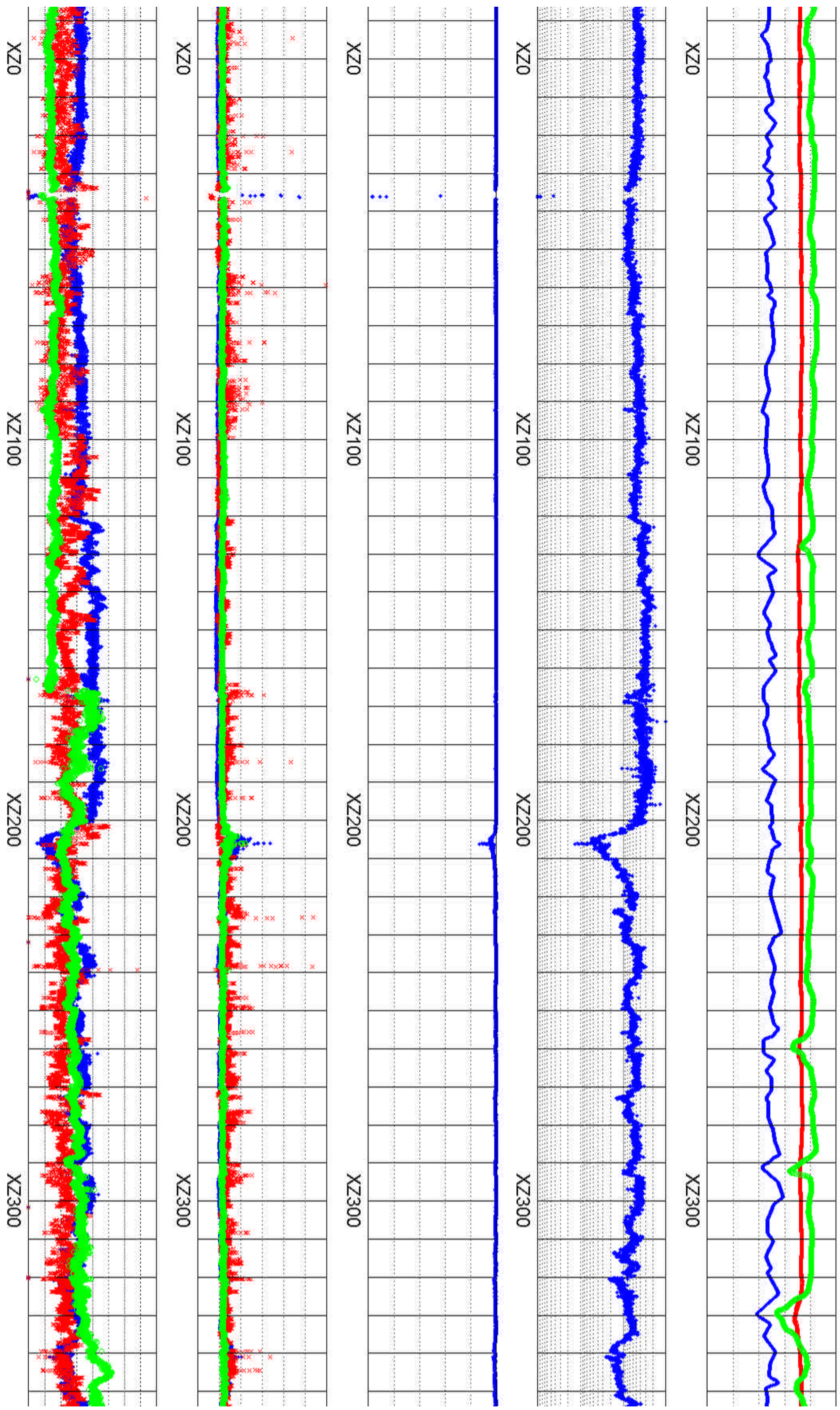

Figure VII.1 The Diagnostic Parameters Large Figure – Continue

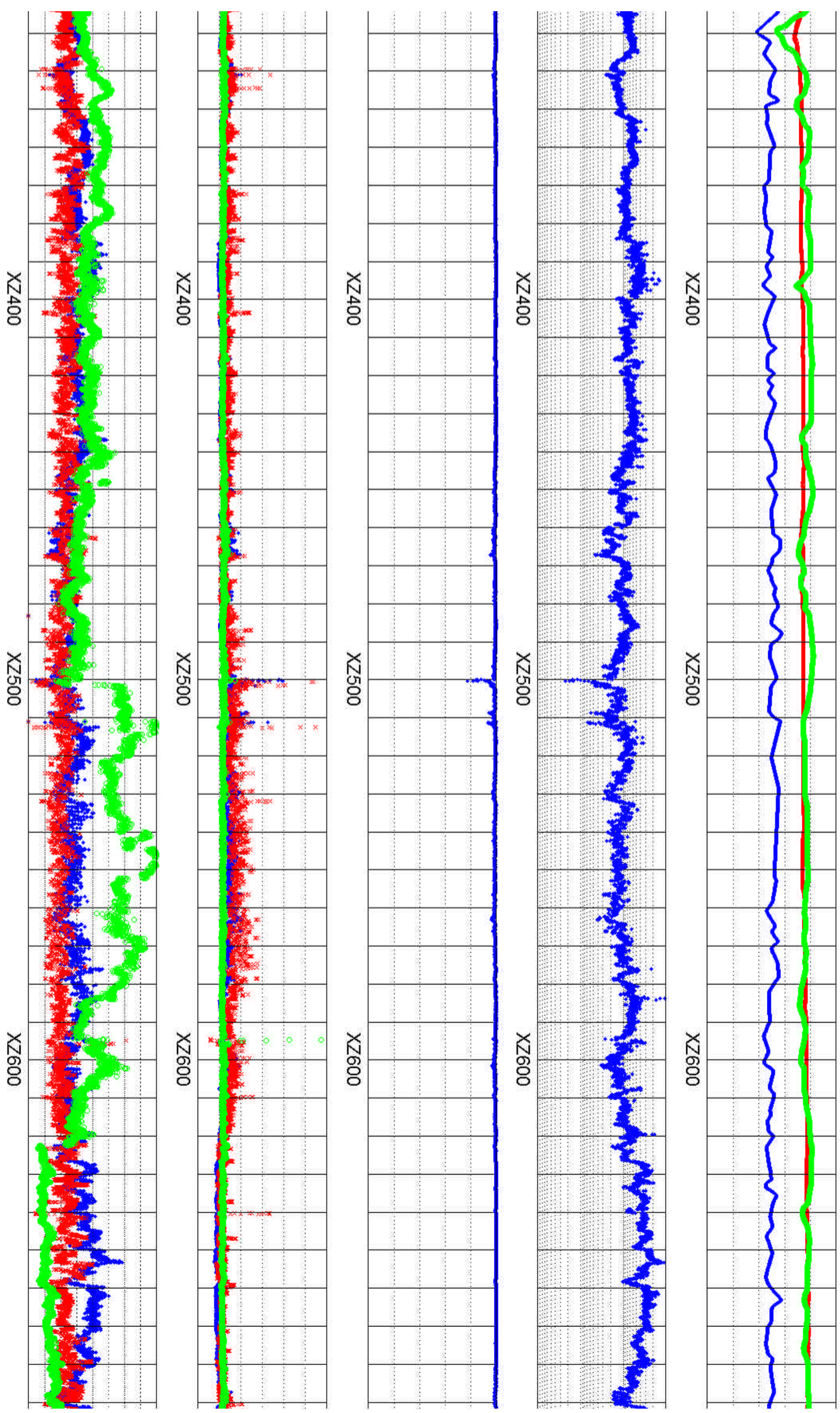

Figure VII.1 – The Diagnostic Parameters Large Figure – Continue

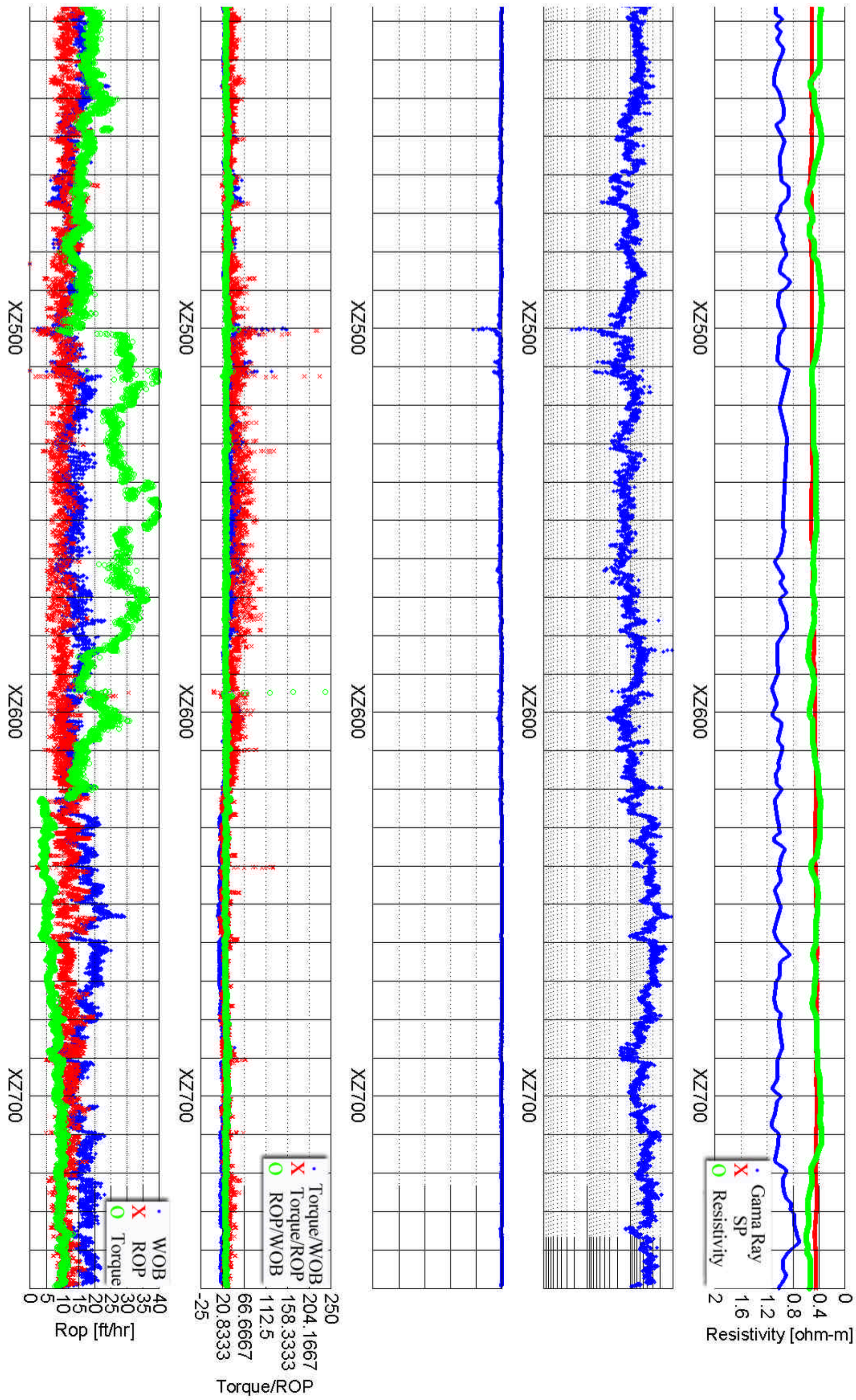

Figure VII.1 – The Diagnostic Parameters Large Figure – Continue

APPENDIX VIII

CALCULATION METHOD FOR DIAGNOSTIC PARAMETERS

1. The Field

1) Data is imported into MATLAB from database.

2) In each time over the specified time interval (in our examples, last 120 seconds of each time), block speed (slope of the block position versus time) and the first derivative of WOB versus time are calculated (slope of the WOB versus time). Using Equation 2.1, ROP from Lubinski's method is calculated for each time.[57]

3) After finding the previous connection and current connection, using Equation 4.1, the depths between these two connections for each time are corrected.

4) The torque/WOB ratio is calculated from the measured torque and WOB in each point.

5) The torque/ROP and ROP/WOB ratios are calculated from ROP found by Lubinski's method over last 120 seconds before the current point in time and the measured torque and WOB for each point.

6) Other derivative parameters, such as A, B, ∂(ROP/WOB)/∂(WOB), ∂(Torque/WOB)/∂(WOB), ∂(Torque)/∂(WOB), ∂(Torque)/∂(WOB), ∂(Torque)/∂(ROP), ∂(ROP)/∂(WOB) are calculated using a linear regression of the actual measured torque and WOB for the previous 30 seconds and the calculated ROP as in the previous step.

7) Wire-line logs are converted from depth to time.

8) The data is cleaned to remove data during connection times.

9) The cleaned data is saved into the database.

10) If King's Parameters are needed:

a) WOB and ROP (over last 120 seconds) are averaged over last 10 seconds

b) Using Equation I.1, multi-linear regression is applied to the 10-second averaged data over the last 120 seconds of each point.

2. Single-Cutter Tests

1) Data is imported into MATLAB from the database.

2) Using Equations V.7 and V.10, the total area of cutters and the rock is calculated from cutter and test configuration data and block position.

3) Cutting area is calculated from differences of contact area of cutter and the rock at each point, and previous rotation.

4) The (tangential force)/(axial force), (cutting area)/(axial force), and (tangential force)/(cutting area) ratios are calculated from measured data and calculated cutting area for each point.

5) Over last 100 points of data, other parameters, such as A, B, ∂(ROP/WOB)/∂(WOB), ∂(Torque/WOB)/∂(WOB), ∂(Torque)/∂(WOB), ∂(Torque)/∂(WOB), ∂(Torque)/∂(ROP), ∂(ROP)/∂(WOB) are calculated using actual measured torque and WOB for each point and cutting area.

3. The Full-Scale Test

1) Data is imported into MATLAB from database.

2) In each time over the specified time interval (in our examples, the last 0.5 second of each time), ROP (same as block speed which is slope of the block position versus time) is calculated.

3) The Torque/WOB, ROP/WOB, and Torque/ROP ratios are calculated from the measured data and calculated ROP (over 0.5 second) for each point.

4) Other derivative parameters, such as A, B, ∂(ROP/WOB)/∂(WOB), ∂(Torque/WOB)/∂(WOB), ∂(Torque)/∂(WOB), ∂(Torque)/∂(WOB), ∂(Torque)/∂(ROP), ∂(ROP)/∂(WOB) are calculated using a linear regression of the actual measured torque and WOB for the previous 4 seconds and the calculated ROP as in the previous step.

APPENDIX IX

PERMISSION FROM HUGHES CHRISTENSEN

From: "Ledgerwood, Roy" <Roy.Ledgerwood@hugheschris.com>
To: <aaghassi@softhome.net>
Cc: "Marvel, Tim" <Tim.Marvel@hugheschris.com>
Sent: Wednesday, October 30, 2002 8:09 AM
Subject: RE: Permission for HC full-scale test provided for LSU

Arash:

We give you permission to use in your thesis plots of the data we sent you.

Tim and I are trying to determine whether we will be able to attend your defense. Thank you for inviting us. We will let you know soon.

In looking at your graphs, we are wondering whether we ever described to you the test sequence. For example, all of the data with negative depths represent data taken while the bit was rotating above the rock, before the test began. Also, the test sequence consisted of incrementing the WOB in 5KIP increments. When the WOB reached 15KIPS, the bit balled. When this occurred, at about 13 inches depth, the control system of the test machine momentarily overshot. After about six seconds, the WOB dropped to the neighborhood of the set point of 15 KIPS. We presume that the letters on your graph may refer to text which explains some of these details. If you need any more information about the test, please feel free to call us.

Roy Ledgerwood
Drilling Mechanics Group Leader
Hughes Christensen Research
(281) 363-6602

-----Original Message-----
From: Marvel, Tim
Sent: Tuesday, October 29, 2002 4:10 PM
To: Ledgerwood, Roy
Subject: FW: Permission for HC full-scale test provided for LSU

Regards,

Tim Marvel
Hughes Christensen
The Woodlands, TX
77380
281-363-6359
tim.marvel@hugheschris.com
-----Original Message-----
From: Arash Aghassi [mailto:aaghassi@softhome.net]
Sent: Monday, October 28, 2002 11:12 AM
To: Tim.Marvel@hugheschris.com
Cc: John Rogers Smith
Subject: Permission for HC full-scale test provided for LSU

Dear Mr.Marvel

I used the full-scale test data set that you provided to John Rogers Smith at LSU in my thesis. The data was from a PDC bit test showing the effect of balling.

As per your original transmittal, I need and am hereby requesting your (HCC) permission to use plots based on the data in my thesis. I need this permission before submitting the thesis to LSU in early November. The data itself will not be in the thesis, but I am attaching the original data file for your reference. The graphs that I will use that include data from the tests are attached. The graphs and their description acknowledges that the data was provided by Hughes Christensen. Although I intend to restrict access to the thesis initially, it will become a public document, and I do desire to publish professional papers based on the thesis.

I am also sending you an invitation to attend the presentation describing my research and defending my thesis.

We really appreciate your support.
Sincerely

Arash Aghassi

Fig IX.1 – Original E-Mail

Arash:

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Regards,

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Sincerely

Arash Aghassi

VITA

Arash Aghassi was born to Fereidoon Aghassi and Shahla Sheikholeslami in Tehran, Iran, on September 9, 1970. Arash received his primary and secondary education in various private and public schools in Tehran, Iran. He subsequently graduated from the University of Tehran with a Bachelor of Science degree in mechanical engineering in May 1993. Arash worked for one year at Belal Manufacturing Co., Tehran, Iran, as an engineer, designing mechanical parts for the electro motors. He later became a computer programmer, database manager, and project manager at Farayan Consultant Co., Tehran, Iran, from 1995 to 2000.