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Extending BHA Life with Multi-Axis Vibration Measurements

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Abstract

Extending motor, bit, MWD, and BHA component life is of primary importance to the drilling process. Frequently downhole vibrations can cause anywhere from minor to catastrophic failure in any of the components of a typical BHA.

Some types of vibrations are more detrimental to various components of the BHA. Most vibrations can be controlled with the alteration of surface parameters such as weight-on-bit and rotary speed in conjunction with downhole measurement tools such as downhole weight-on-bit and downhole torque as well as BHA alteration. The problem has always been knowing which parameters to alter without adversely affecting total drilling performance.

Recent advances in MWD technology have provided a means of measuring downhole vibration in *multiple* axes. This information, provided in real-time, allows the driller to control the proper parameters to minimize specific vibration effects thereby maximizing BHA life and total drilling performance.

Introduction

Attempts to drill vertical holes with 30/60 pendulum assemblies (MWD and straight-hole mud motors) or 60/90 pendulums (in rotary mode with only MWD) had met with catastrophic failures in the past year. Mud motors had been "twisting off" and several MWD failures resulting in junked electronics were common.

On the first case well, using a 30/60 pendulum assembly, the mud motor was twisted off at the AKO sub and the MWD failed. The MWD collar was even torn open. The MWD dump of the standard MWD shock counter revealed very high shocks. After this run, two rotary runs were made with only MWD and 60/90 pendulum assemblies. Both MWD tools failed. It was decided to employ the multi-axis vibration chassis to get a picture of what was happening downhole. The MVC data revealed violent episodes of mostly torsional and lateral vibrations characteristic of BHA whirl. These episodes occurred in hard, wet sands prevalent in this area. This MWD run failed as well.

On run five, the MWD was stabilized top and bottom. Using the MVC, the drillers were able to "see" the sands and adjust their weight-on-bit and rotary speeds to reduce vibrations to acceptable levels and prevent the BHA from going into a whirling state. Parameters were returned to normal in shales. All failures ceased. On run six a record BHA run for this area was recorded with the application of a straight-hole motor with a sleeve stabilizer and the MWD and LWD tools correctly stabilized. On two subsequent wells the assemblies were modified using straight-hole motors with sleeve stabilizers. The drillers duplicated their drilling practices of the previous well and both wells were drilled without failure.

Theory

Drilling requires energy. In drilling, this energy is obtained with three basic drilling parameters, weight on bit, RPM, and mud flow. Vibrations are always present during drilling in varying magnitudes and these detract from and re-direct some of the energy used for the drilling process. The usual primary goal in vibration detection and prevention is to minimize these vibrations in order to maximize ROP. In this field case, this statement has become secondary. The primary goal in this case is to prevent the destruction of critical components of the BHA in order to extend drilling life downhole.

To extend BHA life, it is critical to understand the mechanisms working against us and to be able to quantify their magnitude. With this knowledge, we can alter BHA construction as well as use surface drilling parameters to control these mechanisms. With a multi-axis vibration detection device we can identify the differing types of known mechanisms, measure their magnitude, and determine the effectiveness of our designs and efforts to control them. This case study will qualify these statements.

Vibration Theory. First, it is important to identify the dynamic motions that cause downhole shocks. These mechanisms can be coupled one being triggered by another resulting in what is normally called a parametric response. (Fig.1)

1. Bit Bouncing- This is defined as a resonant axial motion of the BHA. The bit repeatedly lifts off bottom and impacts the formation. This generally occurs in near vertical holes, when using tricone bits, when drilling out the shoe track, or in hard formations or stringers. It can also be the result of another shocking mechanism such as BHA whirl or slip/stick. The surface indicators may be top drive or kelly shaking axially and fluctuating WOB on the weight indicator. This mechanism can result in premature bit and BHA component failure and reduced ROP. Cures include reducing WOB and increasing RPM, changing bit design, and/or using a shock sub.
2. Slip/Stick- This is defined as an alternate slowing and acceleration of BHA rotation. The bit periodically stops rotating causing the drill string to intermittently torque up and spin free. It generally occurs in high angle wells, when aggressive PDC bits are used and in environments where the BHA to wellbore friction is high. Surface indications are ratty surface torque and fluctuating RPM. This mechanism can result in over torqued and damaged connections leading to washouts. The increased bit speed and side impact forces can remove cutters from PDC bits and teeth from roller cone bits. ROP will be adversely affected. Cures can be reduced WOB and RPM. Reduction in friction can be achieved with the use of roller reamers, smoother well profiles, and an increase in mud lubricity.
3. Bit Whirl- This is defined as an eccentric rotation of the bit. Instead of rotating around its geometric center, the bit rotates eccentrically as a result of its interaction with the wellbore. This generally occurs in near vertical wells, in interbedded soft and hard formations, and with PDC bits with aggressive side cutters. Surface detection is nearly impossible but the bit will have noticeable characteristics at the end of a run such as being out of gauge or out of round. Downhole detection is easier due to the presence of high downhole lateral shocks consistent with this mechanism. The high shocks induced by bit whirl can lead to premature BHA component failure, bit failure, and reduced ROP. Cures include the use of anti-whirl bits and correct drilling practices. Immediately after tagging bottom, increase RPM then bring up WOB.
4. BHA Whirl- This is defined as the eccentric rotation of the BHA around the wellbore. (Fig.2) This motion can be either in the same direction as the pipe rotation, in reverse, or chaotic. The BHA “walks” around the wellbore due to “gearing” of the stabilizers and tool joints when hitting the borehole walls. This generally occurs in near vertical wells, washed out boreholes, unstabilized BHA sections, pendulum assemblies, and when mud lubricity is not appropriate. Surface detection can be indirectly achieved when this mechanism induces bit bouncing or on drill string components after the run. One-sided wear on stabilizers and tool joints are typical signs of BHA whirl. A combination of high downhole lateral and torsional shocks is evident on multi-axis detection devices. These high shocks can easily result in bit and BHA component failure. Drillstring components are flattened on one side and subjected to extreme fatigue. Cures include the use of roller reamers and increasing mud lubricity, re-designing the BHA, and correct drilling practices. Any attempt to reduce this type of shock while drilling should start with stopping drilling to cut out resonance then changing both RPM and WOB.

It has been clearly demonstrated in a multitude of tests and publications that BHA resonance in a whirl state is a major contributor to the failure of BHA components. This presentation and its case histories graphically display multiple mechanisms amplified by resonant behavior.

Measurement Theory. The multi-axis vibration chassis is, in effect, a 4-axis shock measurement tool. The first axis of the system refers to the strain gauges and associated electronics used for torsional measurements. The remaining 3 axis refer to a system consisting of the vibration acquisition board and three off board accelerometers. This complete system is mounted on a special chassis in the MWD tool.

The 3 accelerometers are mounted in a mutually orthogonal arrangement along the centerline of the MWD tool. The vib_x sensor measures axial shocks while the vib_y and vib_z sensors measure lateral shocks in orthogonal directions. The mounting arrangement is designed to insure that the chassis experiences the same vibrations as the rest of the MWD tool.

The MWD vibration acquisition system measures the Root Mean Square (RMS) value of the tool acceleration and torque signals. The RMS amplitude of a time dependent signal, $V_{(t)}$, is defined as:

$$V_{rms} = SQRT[1/T_p \ V_{(t)}{}^2 \ dt]$$

where T_p is the signal’s period. Note that the expression inside the square root brackets is just the mean value of the signal squared. This equation is best suited for analytically calculating the RMS value of a simple waveform with a definite period. In order to handle arbitrary analog signals, the RMS-to-DC converters used for the acceleration measurements implement an implicit representation of the RMS averaging equation but the basic principle is the same as expressed in the previous equation.

Measurement Technique

Typically, an MWD crew will program the MWD to send up the calculated values for vib_tor (torsional), vib_lat (lateral), and vib_x (axial) from the MVC as well as a peak shock count measurement from the MWD. These values will be shown around the rig on displays in pertinent locations. The values are graphed in log format as well to display historical trends. The values are analyzed in themselves as well as in combination to determine the particular shock mechanisms, if any, affecting the BHA.

As previously stated, axial vibrations characterizing bit bouncing will be displayed by fluctuations in vib_x. Lateral vibrations will be indicated by the vib_lat value. It has been noted that if high lateral shocks are present, there will be an elevation in torsional shocks as well as the BHA interacts with the borehole wall. Often high lateral shocks accompanied by some degree of axial will characterize bit whirl. Torsional vibrations are indicated by the vib_tor variable and are a measure of the slip/stick phenomena. High torsional vibrations accompanied by high lateral vibrations indicate BHA whirl. The higher the amplitude and consistency of torsional and lateral vibration often indicate the level of BHA whirl. High amplitude and a consistent pattern usually indicate a forward whirl while sporadic bursts in torsional with some degree of elevation in lateral usually signals a reverse whirl. Massive elevations in both indicate a chaotic state. The peak shock counter will record shocks above a 25g threshold. As shocks grow more severe, this will mirror the pattern of the MVC sensors.

Background

In recent years, the operator has switched to drilling deep wells greater than 13,000 feet with oil-based mud and PDC bits. This combination has allowed for drilling vertical wells with ROP in excess of 200 ft/hr. especially in the 3,000-10,000 foot hole sections. However, maintaining angle at less than 5 degrees at these high rates has been a problem.

Drilling with a RPM in excess of 120 and with moderate bit weights of 5,000-15,000 pounds, the bit would “skip” off hard streaks in the sands and drastic formation changes indigenous to this area. After drilling several of these anomalies, the hole angle would be anywhere from 5-15 degrees in some wells. With the drilling of more of these straight, deep wells to smaller targets in these older, established fields, a method of keeping hole angle down was needed.

The decision was made to use straight-hole motors to keep WOB low and allow the mud motor to generate bit speed for the PDC bits. It was hoped that the low WOB would minimize the building tendency upon contact with formation anomalies.

The initial test of this philosophy was a success. The well was drilled to +15,000 feet in 15 days with less than 5 degrees of angle. The next four wells however, all experienced the same problems.

After setting surface casing and swapping out to oil-based mud, a PDC bit was run with a straight-hole motor and an MWD tool. (Fig.3) Each time a 2,500-4,000 foot run was made before it appeared that the motor would stall. After pulling off bottom, the assembly would not reach bottom again. Upon reaching the surface it was discovered each time that the motors had parted at the AKO sub leaving the lower part of the motor in the hole with the stator sticking up. (Fig.4) Fortunately, all of these “fish” were recovered on the first fishing attempt.

After recovery, it was also noted each time that the bits were “wrung out” with a 1” groove crosscut into the face. (Fig.5) The pattern was described as a whirl pattern. The theory at the time was that the bit had gone into some type of “whipping” action that eventually caused enough stress on the motor to break it at the weakest point, the AKO sub. (Fig.6)

Case Histories

These examples come from two of the actual wells drilled in the inland waters of Louisiana. They were selected to graphically display a before and after argument as to the benefits of the use of multi-axis vibration measurements in solving the operator’s problem. This solution also relates how the use of MVC data related to the reconstruction of the BHA’s which also contributed to success. Subsequent well data from this operator has proven to be relatively repetitive and unspectacular due to the application of this solution.

Example well 1. A similar BHA (Fig.7) was constructed for the initial run and performed with like results. After making 2,200 feet, the motor parted at the AKO and, peculiarly, the MWD was subjected to enough stress to tear it open at a weak point. After so many like failures, it was decided to abandon this BHA construction and use a 60/90 pendulum rotary assembly. (Fig.8)

The pendulum assembly was constructed with the first undergauge stabilizer over 30 feet above the MWD and the full gauge stabilizer another 30 feet plus above that. It was hoped that without the motor and with light bit weight that the assembly would not build angle and the bit would not be put into whirl state. Two runs were made with this type of assembly, the first 4,000 feet, the second, 150 feet. Both ended with MWD failures. These failures were catastrophic to the MWD electronics both resulting in “junked” tools. Another pendulum assembly was made up but this time it was decided to employ the MVC to discern what was taking place downhole.

The forth run revealed a massive and frequent combination of lateral and torsional shocks that easily indicate BHA whirl. Fig.9) The shocking mechanism was so severe that it even induced a relatively low level of axial shocks. It became obvious that the BHA had entered into a whirl state. The magnitude and frequency of the lateral and torsional shocks obviously show that the BHA is resonating around the borehole and has entered into a chaotic state. In an attempt to correct this mechanism the bit was pulled off bottom and the rotary was stopped for thirty seconds to eliminate the resonation. When drilling re-commenced the RPM was slowed and WOB was increased slowly. The run was extended to 1,000 feet until a massive and prolonged period obvious whirling behavior finally caused the MWD to fail.

After analyzing the data it was decided to change the BHA to a 30/60 pendulum (Fig.10) for run five. A drill collar was run below a set of full-gauge stabilizers bracketing the MWD tool. The result was an immediate and marked decrease in lateral and torsional shocks. (Fig.11) As drilling proceeded, some periods of high shocks were encountered. A strategy was developed to reduce RPM and vary WOB when these periods were recognized in order to reduce shock levels. If a whirling shock pattern was identified, the rotary was stopped to eliminate the resonation as before. The result was a 2,200 foot run in 54 on-bottom drilling hours. At this point it was decided to run a steerable positive displacement mud motor to correct the well as it had built angle to five degrees.

BHA 6 was an LWD run consisting of the 1¼ degree motor with a slightly undergauge sleeve stabilizer followed by another slightly undergauge stabilizer, the LWD tool, an in-line full gauge stabilizer, and finally, the MWD tool. There were few problems on this run as the RPM was kept relatively low. Some major sands before TD caused an elevation in torsional shocks that induced some axial bit bouncing. (Fig.12) This was indicative of stick/slip in the sands which was controlled by varying the WOB and RPM. The result was a 2,700 foot run in 167 on-bottom drilling hours.

Example 2. After analyzing the data from example one, the operator put the lessons learned to work on the next well. A BHA was constructed using a straight-hole motor with a full gauge sleeve stabilizer and bracketing the MWD with full gauge stabilizers. (Fig.13) The MWD crew was given instructions not to allow lateral vibrations to climb above 4g in combination with a torsional shock limit of approximately 800 rad/sec².

The run proceeded with relatively low shock levels throughout. (Fig.14) Some periods did display an increase in axial and lateral shocks (Fig.15) with a proportionally smaller increase in torsional shocks. This was diagnosed as bit whirl generated by the high-speed motor and the PDC bit as formation changes were encountered. The WOB was decreased in these intervals to suppress the shock levels. If these shocks continued and torsional shock level began to increase suggesting lateral resonance and/or BHA whirl, the bit was pulled of bottom and the rotary was stopped. The bit was then set back on bottom and the rotary speed was increased followed by a gradual increase in WOB back to normal levels. The MWD section of the well was completed in one 7,500 foot run which took only 64 on-bottom hours for an ROP of 117 ft/hr. The hole angle was maintained under ½ degree as well.

Conclusions

After these two case histories another well was drilled with the same methodology as example 2. The results were virtually identical. Subsequently, the MVC has been applied in both vertical and some directional wells for the operator where the drilling environment was known to be harsh in order to manage drilling vibrations.

MWD engineers are able to constantly monitor shock information and are able to converse with drilling personnel on methods of correcting or at least, reducing the shock levels affecting the BHA. They are able to monitor the individual shock types and determine the mechanisms at work on the BHA with multi-axis vibration sensitive tools. The MWD crew instructs the drillers and drilling foremen on their findings and relates this information to the data displays so that the drilling crew can watch the process and correct as needed. The data is simply diplayed and straightforward. With a short educational process, it is possible for any member of the drilling team to make quick corrective decisions.

It is also evident that multi-axis shock data, when properly analyzed, provides the drilling team with the necessary means to construct the proper BHA for drilling in difficult environments, maximizing time on bottom and ROP without excessively suffering the destructive effects of downhole shocks.

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Nomenclature

AKO	top sub on mud motor
BHA	bottom hole assembly
g	gravity
LWD	logging while drilling (tool)
MVC	multi-axis vibration chassis
MWD	measurement while drilling (tool)
PDC	polycrystalline diamond (bit)
RMS	root mean square
ROP	rate of penetration
RPM	revolutions per minute (rotary speed)
vib_lat	vibration lateral
vib_tor	vibration torsional
vib_x	vibration axial
vib_y	vibration y axis
vib_z	vibration z axis
WOB	weight on bit

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Figure 1

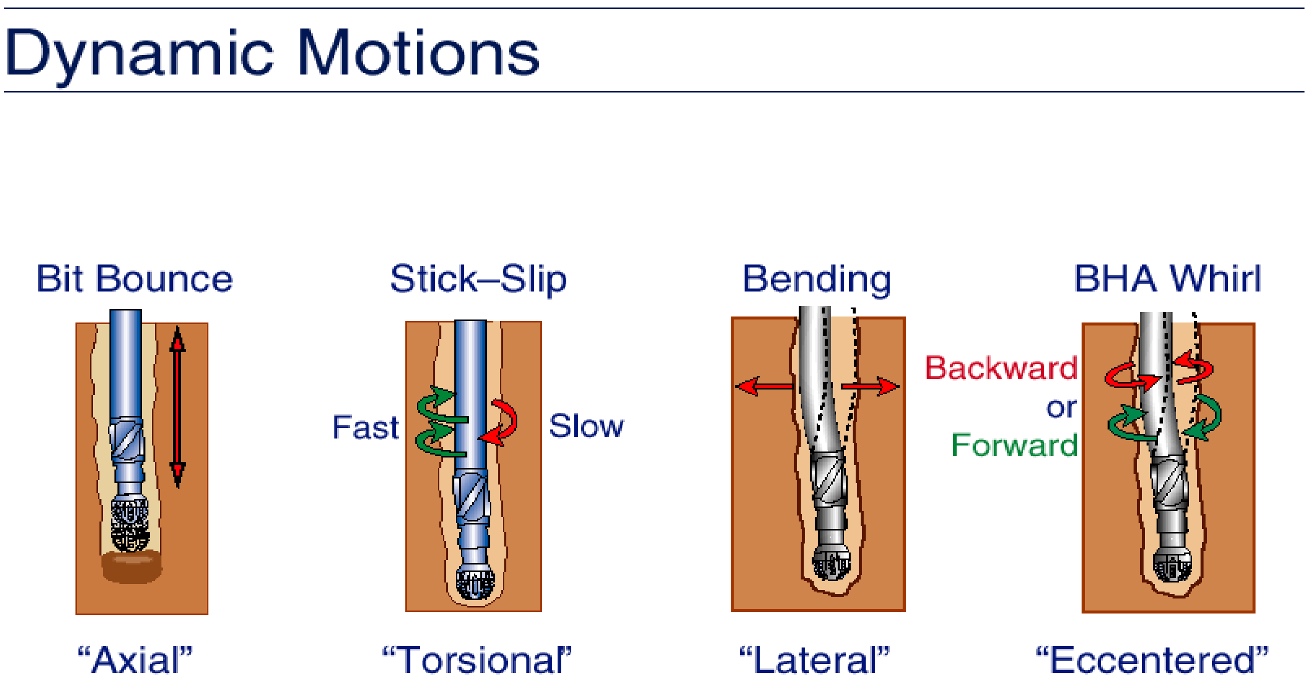


Figure 2

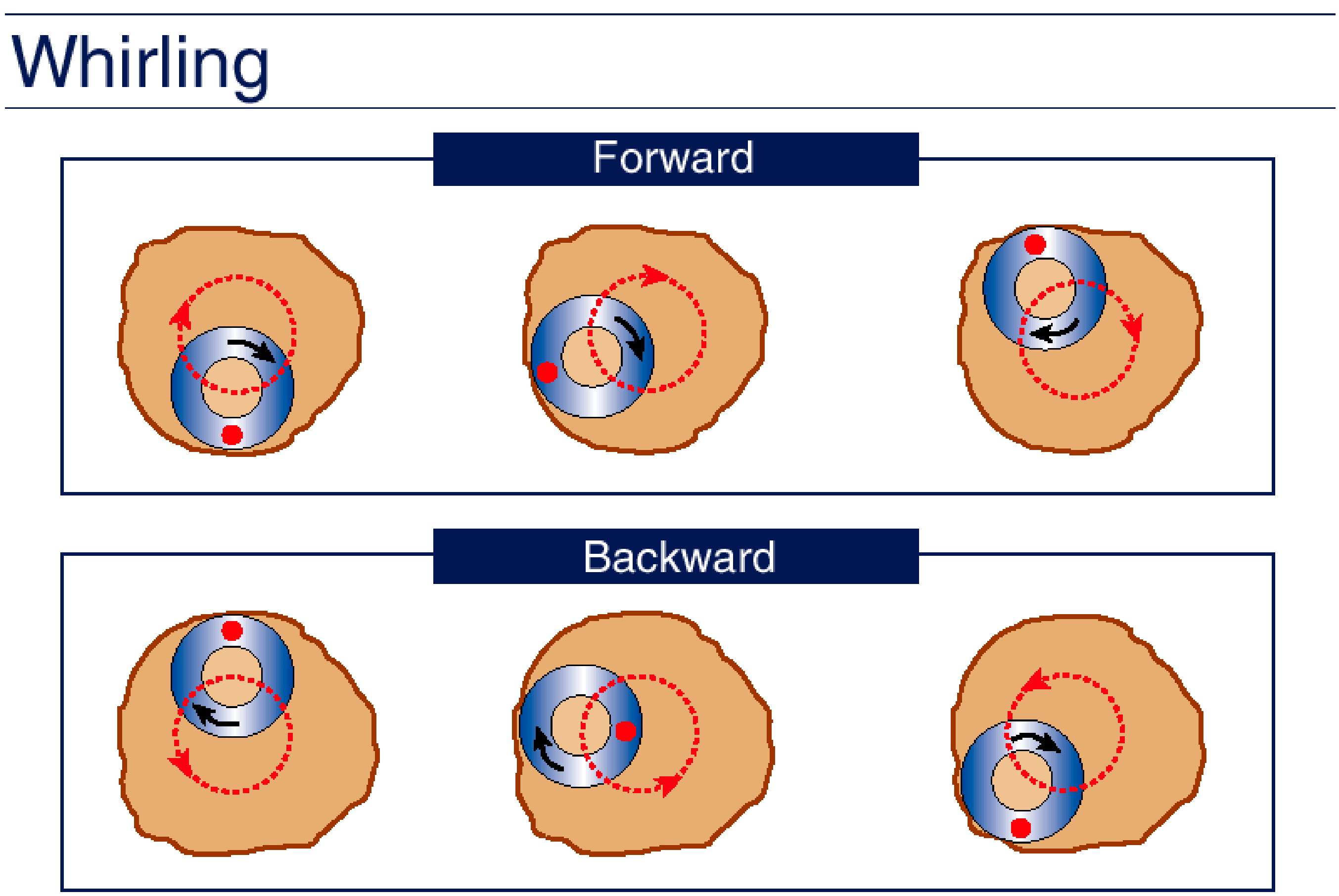


Figure 3

Figure 4

Figure 5

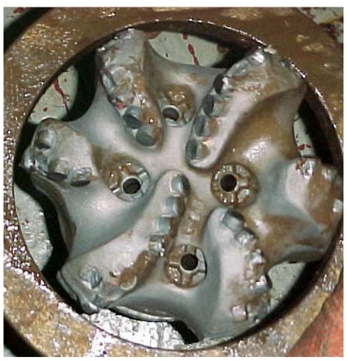
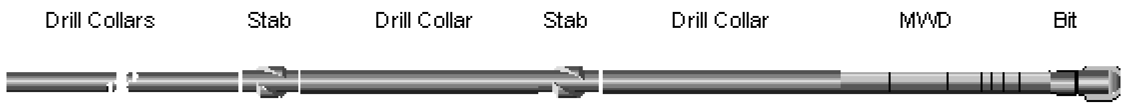


Figure 6

Figure 7

Figure 8



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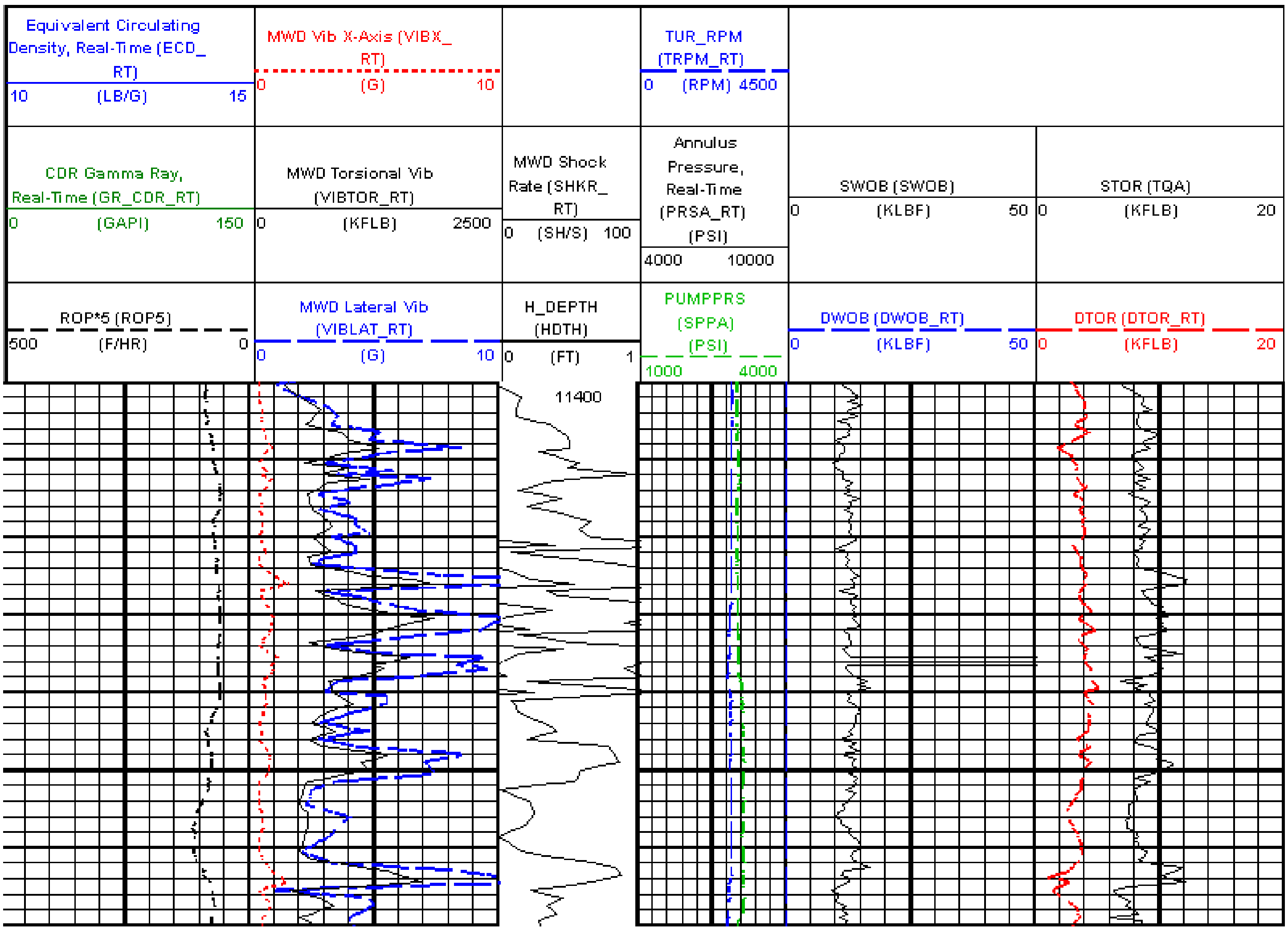


Figure 10

Figure 11

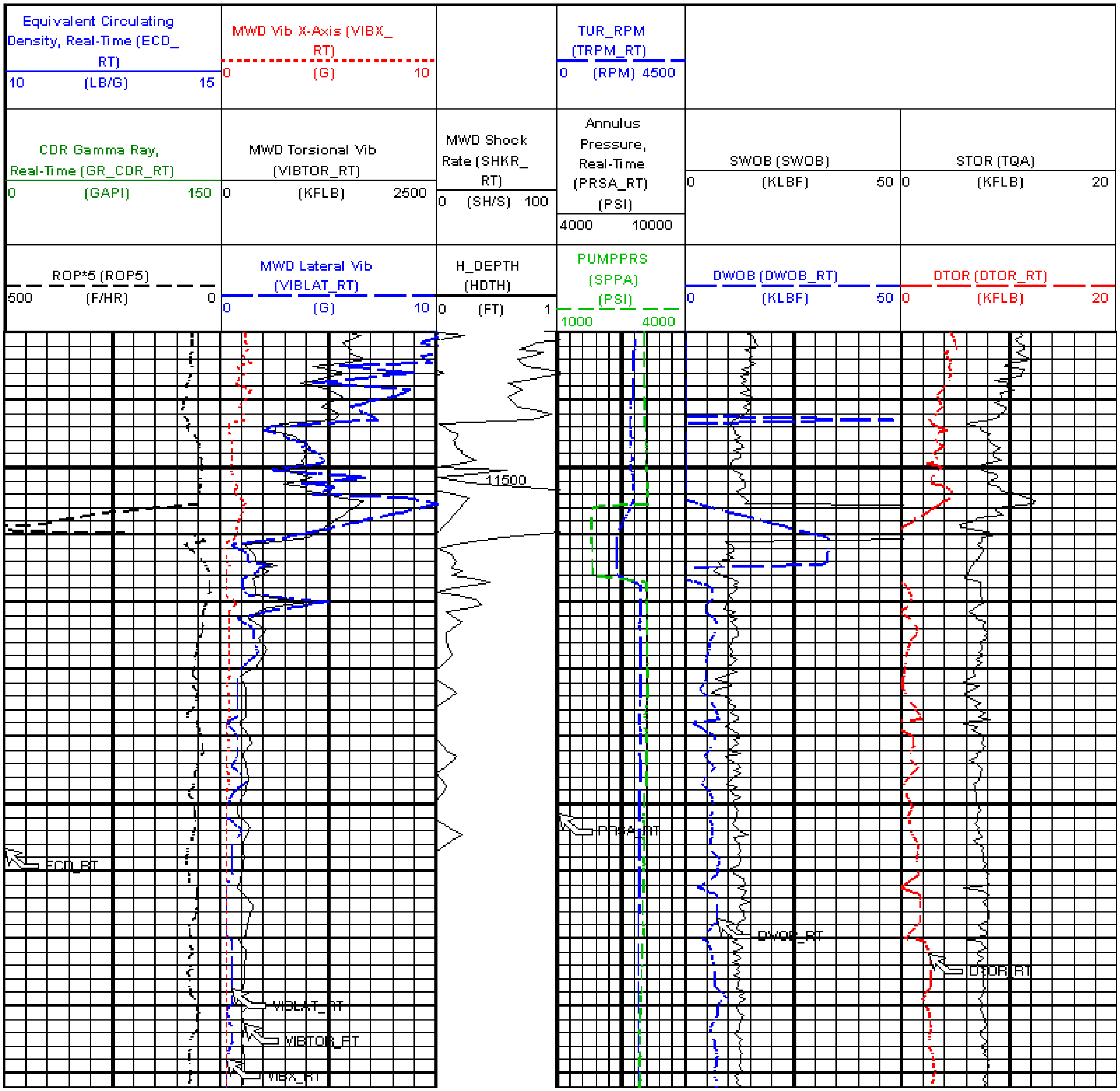
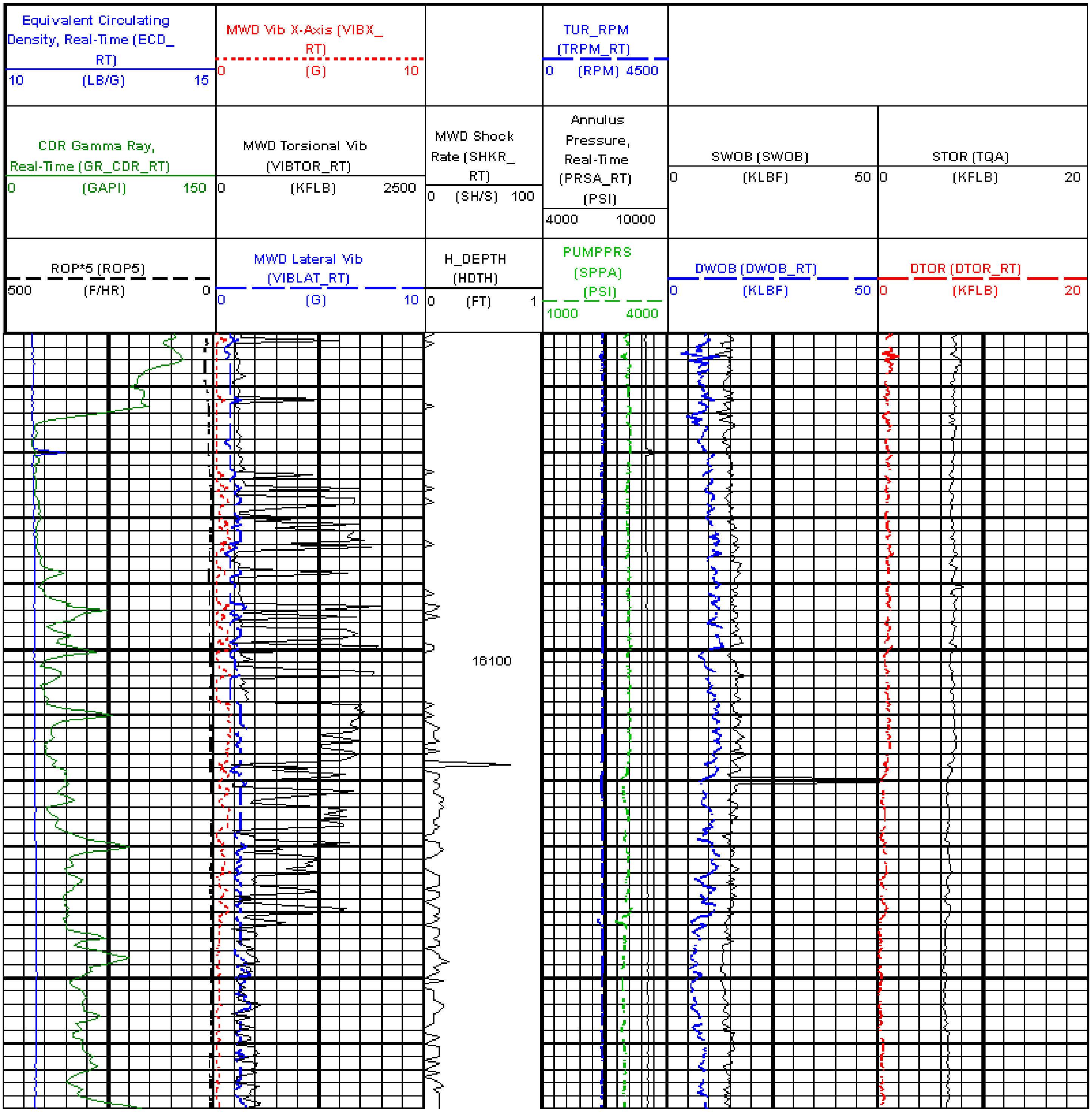


Figure 12


Equivalent Circulating Density, Real-Time (ECD_RT)
10 (LB/G) 15
MWD Vib X-Axis (VIBX_RT)
0 (G) 10
TUR_RPM (TRPM_RT)
0 (RPM) 4500
CDR Gamma Ray, Real-Time (GR_CDR_RT)
0 (GAPI) 150
MWD Torsional Vib (VIBTOR_RT)
0 (KFLB) 2500
MWD Shock Rate (SHKR_RT)
0 (SH/S) 100
Annulus Pressure, Real-Time (PRSA_RT) (PSI)
4000 10000
SWOB (SWOB)
0 (KLBF) 50
STOR (TQA)
0 (KFLB) 20
ROP*5 (ROP5)
500 (F/HR) 0
MWD Lateral Vib (VIBLAT_RT)
0 (G) 10
H_DEPTH (HDTH)
0 (FT) 1
PUMPPRS (SPPA) (PSI)
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DWOB (DWOB_RT)
0 (KLBF) 50
DTOR (DTOR_RT)
0 (KFLB) 20
16100

Figure 13

Figure 14

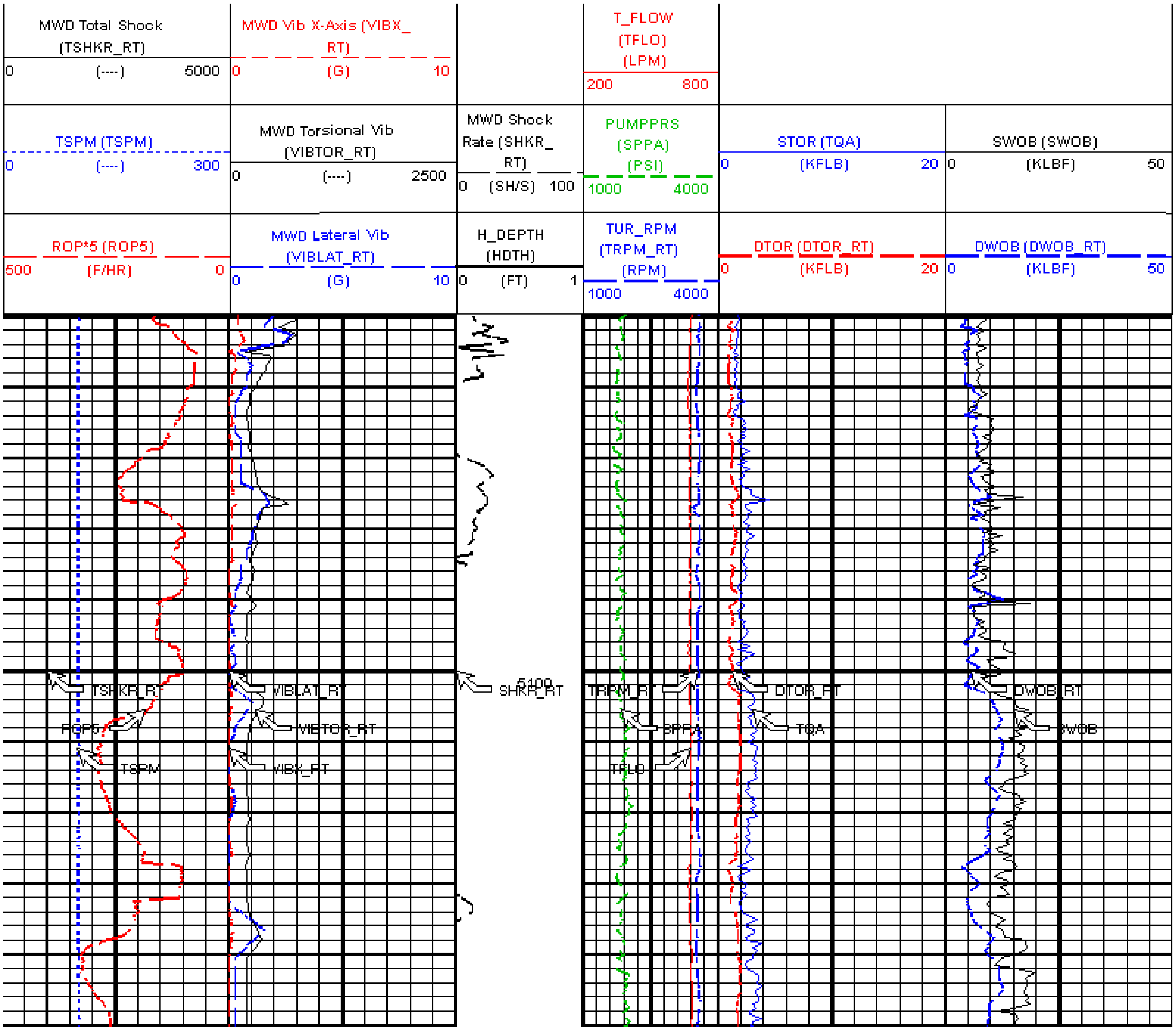
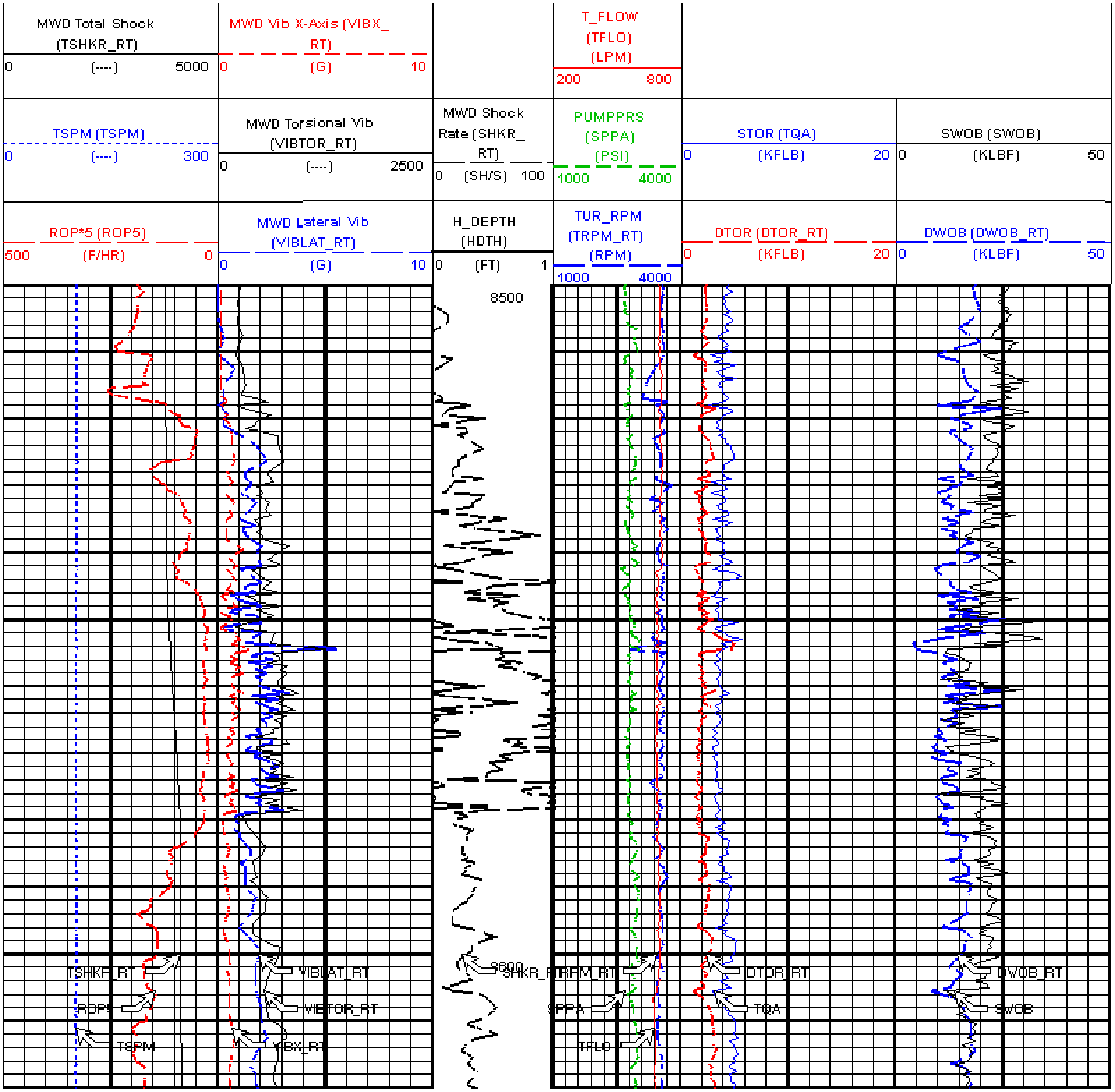


Figure 15


MWD Total Shock (TSHKR_RT)
0 (----) 5000
MWD Vib X-Axis (VIBX_RT)
0 (G) 10
T_FLOW (TFLO) (LPM)
200 800
TSPM (TSPM)
0 (----) 300
MWD Torsional Vib (VIBTOR_RT)
0 (----) 2500
MWD Shock Rate (SHKR_RT)
0 (SH/S) 100
PUMPPRS (SPPA) (PSI)
1000 4000
STOR (TQA)
0 (KFLB) 20
SWOB (SWOB)
0 (KLBF) 50
ROP*5 (ROP5)
500 (F/HR) 0
MWD Lateral Vib (VIBLAT_RT)
0 (G) 10
H_DEPTH (HDTH)
0 (FT) 1
TUR_RPM (TRPM_RT) (RPM)
1000 4000
DTOR (DTOR_RT)
0 (KFLB) 20
DWOB (DWOB_RT)
0 (KLBF) 50
8500
8600