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Revealing Causes of Restrictions by Signatures in Real-Time Hook Load Signals

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Abstract

Downhole restrictions are causing non-productive time, which represents large economic losses. Knowing the cause of the restriction in order to implement the correct remedies are crucial for preventing extensive cleaning activities or even stuck pipe. Using the hook load signal to find special signatures for the different causes of restriction could be a solution to quick recognition of restriction type.

In the wells studied it was found 22 cases of restriction, which could be divided into 5 main groups of causes; unstable wellbore, ledges, cuttings accumulation, differential sticking and local dogleg. One incident from each group was chosen for an extensive post-event analysis for the purpose of strengthening the hypothesis of the cause.

The results from the study has shown that it was necessary to simplify the analysis in to two main types of hook load restriction signatures; fixed and moveable. For the physical interpretation of the two signatures, fixed and moveable, hook load signals from ledge and cuttings bed were used respectively. These were assumed to be good representatives for the two main types, and the signals proved to coincide with the physical explanation valid for them. The two groups were created based on the clear differences in the hook load signals between ledges and cuttings accumulation visible in the post-event analysis. Both of these causes of restriction have a very clear physical explanation; when the drill string encounters a ledge it will stop moving and is thereby fixed to one position in the well. On the other hand, cuttings downhole is moveable and is able to move along with the drill string. It became clear that dividing signatures into groups based on causes of restrictions was not the best way to do it, but rather divide it into groups based on physical explanation such as fixed and moveable. From that point on causes of restrictions are related to one or two of the two main groups. The goal of distinguishing hook load signals from different causes of restrictions was reached to some extent. It was found that by recognizing if the restriction was fixed or moveable by looking at the hook load signal, 4 out of 5 causes of restrictions were distinguishable. This was possible because unstable wellbore was recognized by including both fixed and moveable restrictions and differential sticking was recognized by occurring at the beginning of a stand pulled.

Sammendrag

Nedihullsrestriksjoner forårsaker ikke-produktiv tid som representerer store økonomiske tap. Det er helt avgjørende å vite årsaken til restriksjonene for å motvirke omfattende hullrensningsaktiviteter eller til og med at borestrengen setter seg fast. Bruk av kroklast signalet for å finne spesielle signaturer til restriksjonsårsaker kan være løsningen på en rask gjenkjenning av restriksjonstype.

Det ble funnet 22 tilfeller av restriksjoner i brønnene som ble studert. Disse ble delt inn i følgende 5 hovedårsaksgrupper; ustabil brønn, 'ledges', borekaks akkumulering, 'differential sticking', lokal dogleg. En av tilfellene fra hver gruppe ble plukket ut til en utvidet post-hendelse analyse for å styrke påstanden om hva som forårsaket hendelsen.

Resultatene av studien viser at det måtte gjøres en forenkling ved å dele inn i to hovedtyper av signaturer for krok-last restriksjoner; fast og bevegelig. Krok-last signaler fra restriksjonene ledges og borekaks dyner ble brukt i en fysisk tolkning av hoved signaturene faste og bevegelige. Det ble antatt at disse var gode representater for de to hovedtypene av restriksjoner, og signalene viste seg å sammefalle med den fysiske forklaringen som var gjeldene for de to hovedtypene. Dannelsen av disse to hovedtypene var basert på klare forskjeller som ble funnet i kroklast signalet under post-hendelse analysen. Begge disse restriksjonsårsakene har en veldig klar fysisk forklaring; når borestrengen treffer en ledge vil den slutte å bevege seg og er derfor fast til en posisjon i brønnen. Borekaks derimot er bevegelig og vil kunne bevege seg med borestrengen nedihulls. Det ble klart at å dele signaturene inn i grupper basert på årsaker til restriksjonen ikke var den beste måten å gjøre det på, men heller dele de inn i grupper basert på den fysiske forklaringen av de slik som fast eller bevegelig. Deretter kan årsaker til restriksjoner relateres til en eller begge hovedtypene. Målet med å kunne skille mellom krok-last signalet for ulike restriksjonstyper ble nesten nådd. Resultatene viser at ved å kjenne igjen om det fast eller bevegelig restriksjon ved å se på krok-last signalet skal være mulig å skille mellom 4 av 5 årsaker til restriksjoner. Dette var mulig fordi ustabil brønn kunne gjenkjennes ved at den hadde både faste og bevegelige restriksjoner og 'differential sticking' ble gjenkjent ved at det skjer i begynnelsen av et stand som blir trukket ut.

Preface

This Master's thesis was written during the spring semester of 2013 at the Department of Petroleum Engineering and Applied Geophysics at the Norwegian University of Science and Technology, NTNU.

I would like to thank my supervisor Pål Skalle for his guidance and help throughout the process. I would also like to thank Statoil for providing the material for this study, including real-time data and daily reports, without it this study would not be possible.

I would also like to thank my fellow student Marit Innvær Agasøster for technical discussions regarding hook load restrictions, and Simon Josephsen for support in the report setup in LaTeX.

Hanne Bjerke
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1 | Introduction

Restrictions in the well could potentially cause stuck pipe and thereby non productive time (NPT), which represents large economic losses. In offshore operations NPT could represent a loss of $426,000 per day (offshore.no 2011). Early detection of the restrictions as well as knowing the cause of the restrictions are therefore crucial in the process of preventing extensive cleaning activities or even stuck pipe and loss of wellbore section. The main causes of restrictions are: cuttings plowing in relatively straight wellbores, cuttings plowing through washouts in the wellbore, swelling wellbore, creeping wellbore, cavings, ledges, local dogleg and differential pressure pipe sticking. All these restrictions could be visible with their own signature on the hook load (HKL) signal from the real-time drilling data (RTDD). The restrictions are mainly visible during tripping operation. Tripping is therefore the focus drilling activity.

Restrictions are seen on the HKL signal as a decrease in value when tripping-in and an increase when tripping-out, respectively 'took weight' and 'overpull'. These two main types of signals could have different signature for each of the cause of restriction groups. Some may only be visible when tripping in, e.g. a ledge with a sharp edge on top and smooth from bottom. Each of the restrictions has different methods of solving the problem and it therefore becomes crucial to know what type of restriction you are facing. The challenge is to identify HKL signals that are special for each particular group of restriction so that this can be used when decision of remedies are made.

There are some previous work on identifying different hook load signals and the cause of restriction. Cordoso et al. (1995) have created type curves for borehole closure, ledges and differential sticking in addition to normal type curves. These curves are useful for recognition of swelling wellbore and ledges, but for the rest of the mentioned causes no type curve is available.

The goal is to find a hook load signature for each of the restrictions that can be recognized on site while tripping. Before the signatures can be found an extensive post-event analysis on cases where restrictions were encountered have to be implemented. This analysis is important for the purpose of strengthening the final signature analysis. It is crucial to be confident with what caused the restriction before studying the hook load signal for signatures.

2 | Hook Load Variation

In order to work with the signal in real-time drilling data (RTDD) it is crucial to understand the physics of how HKL is measured and how it is influenced by restrictions. It is also important to know what is normal behavior and how the signal normally appears. These topics will be covered in this chapter.

2.1 General

The hook load is equivalent to the weight suspended in the hook and the weight depends on several factors. The main factors are the weight of the downhole tools together with the drill string minus the buoyancy. If the well is inclined some of the weight will be transferred to the borehole wall depending on the wellbore angle. In horizontal wells all the weight of the drill string in the horizontal section will be resting on the borehole wall. Under dynamic conditions friction has to be added or subtracted depending on the hoisting direction. When drilling, a part of the weight is set down on the bit at the bottom of the hole and is thereby reducing the hook load. When rotating the drill string, e.g. drilling or backreaming, friction in the axial direction of the hole is neglected. If restrictions are encountered the hook load will increase or decrease depending on the hoisting direction, respectively up or down. Generally the hook load is equal to the sum of all forces acting in the vertical direction.

Pseudo Mechanical Borehole Friction Factor

The pseudo mechanical borehole friction factor includes not only the theoretical friction factor dependent on the normal forces, but also other factors that influence the hook load. The measured hook load is a function of many parameters such as restrictions downhole. Examples of what is affecting it are listed below (Cordoso et al. 1995):

- Cuttings bed
- Ledges
- Partially close boreholes
- Bridges
- Hook load sensor error
- Measured depth sensor error
- Operational procedures during tripping
- Pulley friction
- Partially stuck pipe
- Drilling fluid properties and effects
- Irregular geometry (washouts)

2.2 Signature Plot

A signature plot for tripping is necessary when working with hook load signal analysis. The signature plot shows what is normal behavior of the weight while tripping one stand out. An example of a normal hook load signal while tripping is shown in Figure 2.1. The column to the left shows the block position, denoted as 'HK Height' and the middle column shows the hook load, denoted as 'WOH' (Weight on Hook). The column to the right shows the bit depth and hole depth both in meters Measured Depth (mMD), bit depth is also indicated in red numbers. As seen in the plot the WOH increases when hoisting starts, which is a result of the drill string weight being suspended in the hook. The weight is stable during hoisting at constant velocity, except for one peak at the beginning of the interval pulled. This peak is associated with static friction forces and elastic deformation, i.e. stretching, of the pipe. When starting to pull the drill string, tension forces will cause stretching of the pipe until the forces exceeds the static friction force and the pipe starts moving. When the pipe starts to move the tension force is reduced due to static friction being higher than dynamic friction, and as a result the pipe elongation will reduce. This reduction in pipe elongation is seen on the

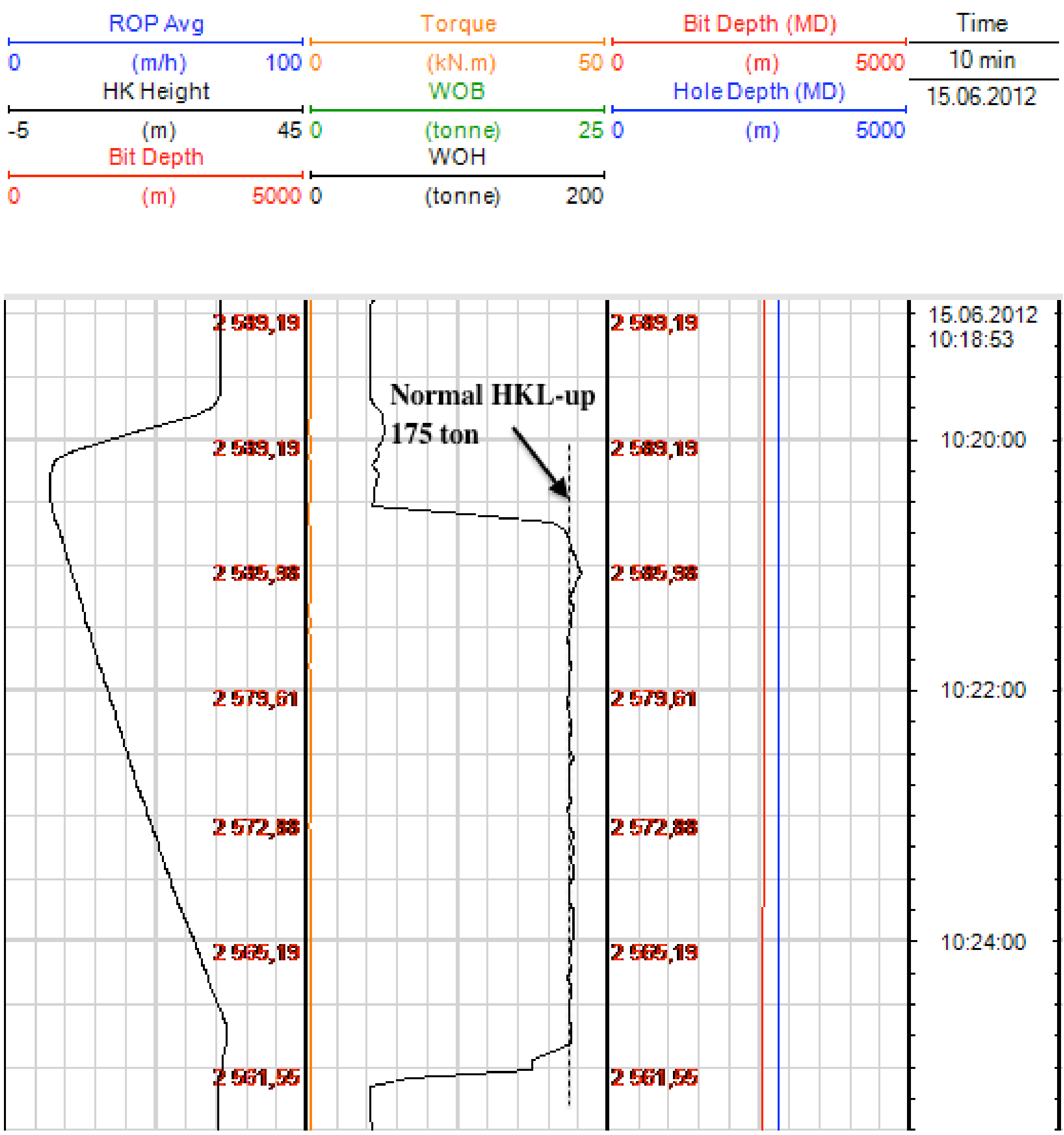


FIGURE 2.1: Normal signal for tripping of one stand.

plot as a decrease in weight on hook right after the static friction peak (Kristensen 2013).

At dynamic conditions the WOH is, as already stated, dependent on the pseudo mechanical friction factor. When a restriction is encountered the WOH is increasing, which is caused by an increase in the pseudo mechanical friction factor. This increase is called an overpull, while decreases caused by restrictions (when running into hole) is called took weight. These expressions will be used throughout this thesis.

2.3 Driller's Depth

When working with post-event analyses of restrictions downhole, correct depth measurements could be important. If you want to relate depths during drilling with depths when experiencing overpull while tripping out it is crucial to know the errors involved caused by pipe stretching.

During drilling operations the bit depth is given by the length of the drill string lowered into the hole. The length of the pipes and the BHA components are measured on the rig before running into hole and each stand of drill pipes or BHA components are registered in the tally for depth control. This method of measuring bit depth is called driller's depth and it is used in all drilling operations. The reference point for the depth measurement is the drill floor, which stays the same for fixed drilling units. On a floating unit the depth has to be corrected with changing sea levels. Figure 2.2 shows the major components of the depth measurement system, where you can see that the bit depth is equal to the pipe tally minus the stick up. (Chia et al. 2006)

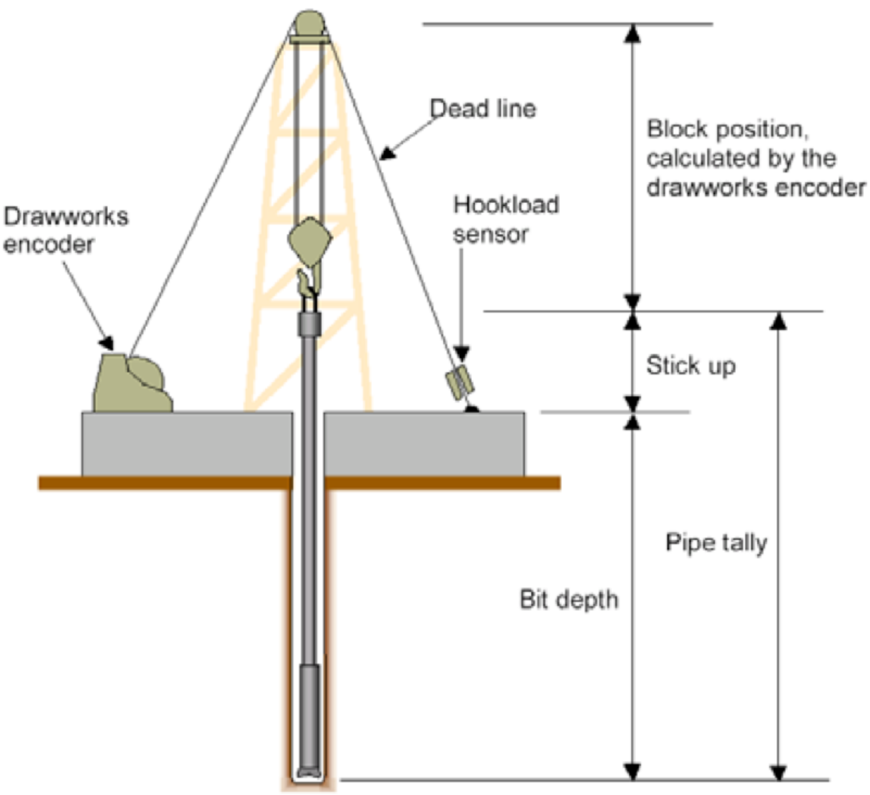


FIGURE 2.2: Sketch of major elements for the surface depth measurement (Chia et al. 2006).

In addition to the driller's depth the LWD tool is also measuring bit depth as the drill string is lowered into the hole. This depth is measured based on block movement and register only when the string is 'out of slips', which is determined by software that monitors a hook-load sensor. There are errors associated with determining the in and out of slips state, which causes the LWD depth to deviate from the driller's depth. Therefore the LWD depth has to be recurrent adjusted to match the driller's depth. (Chia et al. 2006)

Errors in Depth Measurements

There are several sources of errors associated with bit depth measurements, Chia et al. (2006) have presented the errors listed in Table 2.1.

Table 2.1: Sources of error associated with bit depth measurements (Chia et al. 2006).

Source	Description
Weight	Elongation of pipe due to the weight of the string.
Temperature	Elongation of pipe due to thermal expansion of the metal.
Axial pressure effects	Axial forces, due to a pressure drop across the drilling assembly at the bit, will cause a change in pipe length.
Ballooning effects	An expansion in radial direction because of differential pressure across the drill pipe walls, which causes a negligible shortening in length.
Friction effects	Shortening or elongation of pipe caused by drag against the side of the wellbore walls. The travelling direction decides what mechanism that is involved.
Buckling	A drill pipe that goes into compression will buckle, because it is designed to be in tension. This will affect the depth.
Weight on bit	The drill string shortens as the driller applies weight onto the bit. An effect of less stretching when relieving weight.
Drill pipe twists	As the drill pipe can store several revolutions, applying torque can affect the length.

In this post-event analysis only the friction effects and the weight on bit error are considered important for the study. This with the assumption that the other factors are present in case of both drilling and tripping or are negligible for the purpose. The operations of importance are listed in Table 2.2 together with the mechanisms involved in addition to elongation caused by pipe tension.

Table 2.2: Shortening and elongation of the drill string with respect to type of operation with static off bottom as reference.

Type of Operation	**Mechanisms Involved**
Static off bottom	-Weight of drillstring: Elongation -Static friction: Shortening In total: Neutral, used as reference
Static off bottom rotating	-Weight of drillstring: Elongation -Rotation: Elongation In total: Elongation
Drilling	-WOB: Shortening -Rotation: Elongation In total: Shortening
Tripping out	-Friction forces: Elongation In total: Elongation
Tripping in	-Friction forces: Shortening In total: Shortening
Back reaming	-Rotation: Eliminates friction In total: Shortening

Weight is applied onto the bit while drilling, which will put a part of the BHA into compression. Consequently, the tension in the drill pipe is reduced causing reduced elongation compared to when the drill string is off bottom. When pulling out of hole the stretching on the drill string will be at its maximum due to friction forces creating higher tension in the drill string. Rotation on the other hand eliminates wall friction in the direction of the wellbore, which in turn increases the stretching effect on the drill string. In the case of back reaming friction forces are eliminated by rotation making the pipe elongation equal to the static off bottom elongation. Friction is always working in the opposite direction of the movement, causing a shortening of the pipe when tripping in.

As a result there will be depth offset when comparing depths registered while drilling versus while tripping. That means that a limestone stringer registered at 2870 mMD while drilling could be encountered deeper when pulling out.

Pipe stretch can be calculated based on amount of pulling force it is subjected to (wil 2006):

$$Stretch[m] = \frac{L_{pipe}[m] \cdot P[ton] \cdot C_{pipe} \cdot 0.0254}{10^5} \tag{2.1}$$

Where L is the length of the pipe, P is the pull on the pipe and C_{pipe} is the stretch constant for the pipe. The stretch constant can be found in property tables for drill pipes.

3 | Downhole Restrictions

There are several types of restrictions with different causes. This section will discuss the physics of seven selected types of restrictions.

3.1 Cuttings Plowing

Cuttings plowing cause restrictions in inclined and horizontal wells. It occurs when cuttings bed in straight wellbores or in washouts are shoveled by the drillstring and thus restricting the pipe movement. It is normally seen in wellbores with an inclination from 30°-90°, and in such wellbores the cuttings tend to settle.

3.1.1 Cuttings Transport

The essential cause of cuttings plowing is insufficient hole cleaning, and cuttings transport is therefore an important subject. In the industry the essential factors of hole cleaning in extended reach wells are high flowrate, gauge hole, slow ROP, continuos rotation and ideal mud properties.

In vertical wells the cuttings will move with the velocity of the mud flow minus the slip velocity, which is created by gravity pulling the cuttings downwards (Fig. 3.1). The slip velocity is dependent on the rheology of the drilling fluid, which makes this an important property for cuttings transport efficiency in vertical wells.

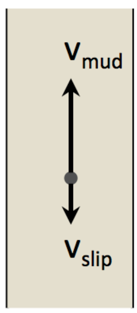


FIGURE 3.1: Transport of cuttings in a vertical well.

In horizontal and high angle wells with laminar flow there is no velocity component of the drilling fluid counteracting the gravity slip velocity component, shown in

Figure 3.2. Consequently, the cuttings will fall to the low side of the well after typically 1-2 stands, i.e. the flow cannot transport the cuttings out of the hole. The distance of which the cuttings are transported is not absolute, but rather a function of rheology, flow rate, rpm and angle. Since turbulent flow is limited to very small hole sizes and low viscosity fluids the flow in the annular space of a well will always be laminar (K&M-Technology 2011). A cuttings bed may build up until det hole packs off unless the string i rotating, this means that using a downhole motor could cause severe hole cleaning issues. Figure 3.3 shows a cut of a horizontal wellbore where the drill string is on the low-side together with a cuttings bed. The pink area is the part of the wellbore where the fluid moves, i.e. the high velocity zone, and the green part is the low velocity zone. In the left figure there is no rotation and thereby no mechanism to move the cuttings into the high velocity zone, which means that no cuttings are transported. Rotation of the drill string will create a viscous coupling around the string, i.e. the fluid in this coupling has an angular velocity component with the rotation of the drill string. This fluid velocity component will transport cuttings into the high velocity part of the annulus as shown to the right in Figure 3.3 (K&M-Technology 2011). From here the cuttings will be transported another 1-2 stand until it settles again, this transport path is illustrated in Figure 3.4.

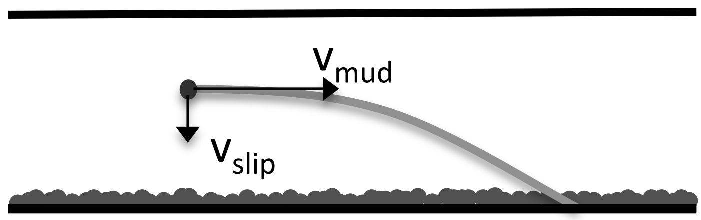


FIGURE 3.2: Transport of cuttings in a horizontal well.

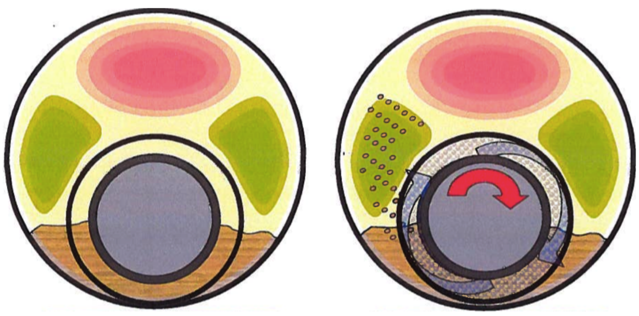


FIGURE 3.3: Cuttings beds forming at the low-side of the well and the effect of rotation to the right (K&M-Technology 2011).

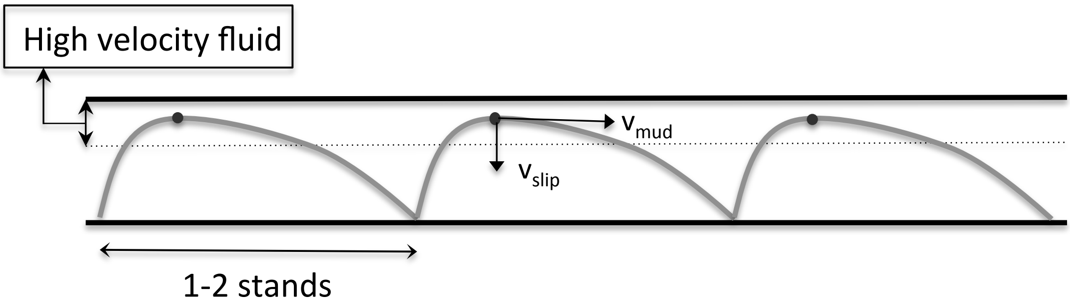


Figure 3.4: Cuttings transportation path with rotation or hydraulic lifting in a horizontal wellbore. Free after Skalle (2011).

In a medium inclined well, between ±30°-60°, the cuttings will travel a bit further than in a horizontal well. When the well is inclined the slip velocity is partly working against the flow direction and thereby less towards the low-side of the wellbore. The main issue in a medium inclined well is the risk of cuttings beds avalanching, which may cause pack offs, overpull and even stuck pipe. This could happen if the bed becomes too thick due to high ROP or during tripping operations when beds are disturbed by the moving drill string (K&M-Technology 2011). Experimental studies done by Tomren et al. (1986) showed that a cuttings bed started to form at angles of more than 35°, and that gravity will force the bed to slide down against the moving fluid. They also found that when the well reaches the critical angle of 50° the bed stops avalanching, causing a high cuttings concentration in this part of the well.

Research done by K&M-Technology (2011) has shown that not only is it important to rotate the drill string in order to clean the hole, but the speed of the rotation is critical. They found that in high angle wells with a diameter of 12¼" or larger the speed should be at least 120 rpm, and that it is a huge difference between 100 rpm and 120 rpm. Necessary rotational speed depends on the annular space, i.e. a function of wellbore diameter and drill string diameter.

3.1.2 Cuttings Plowing Through Straight Wellbore

Cuttings plowing through straight wellbores are associated with insufficient hole cleaning where beds of cuttings are formed in medium to high angle wells. These beds could cause restrictions during tripping operation and in medium angle wells they could cause avalanches that blocks off the wellbore. Cuttings plowing is seen on the hook load as an increasing trend or as a sudden over-pull.

3.1.3 Cuttings Plowing Through Washouts

Washouts will fill with cuttings during drilling, which potentially could cause problems when tripping out. Cuttings will be transported at a critical velocity that is a function of the flow area (Skalle 2011). The flow area depends on the thickness of the cuttings bed and the borehole diameter. In over-gauged parts of the wellbore, such as washouts, the cuttings bed will become thicker in order to have the same flow area as the rest of the well. When pulling the drill string through these over-gauged parts with thicker cuttings beds over-pull may be experienced, especially when larger components of the drill string are pulled through. Figure 3.5 illustrates how the cuttings create thicker beds in washouts and how over-pull is experienced when pulling through the over-gauged part and entering the in-gauge part of the wellbore.

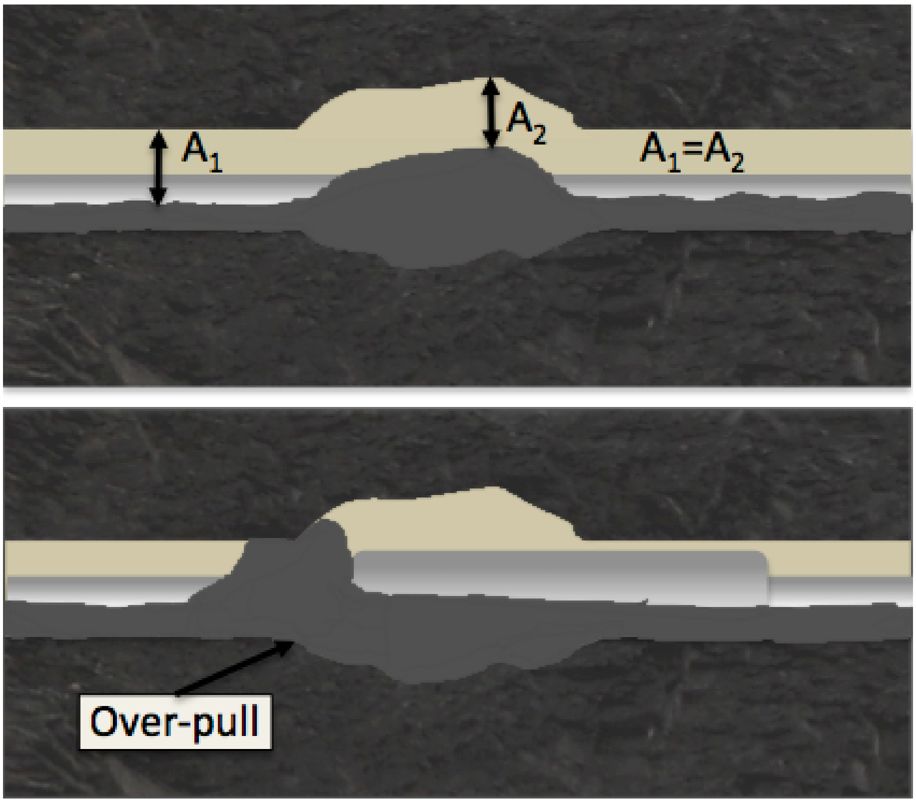


FIGURE 3.5: Cuttings accumulation in washouts and over-pull caused by cuttings plowing through the washout and piling up the cuttings. Free after Skalle (2011).

3.2 Swelling Wellbore

Swelling wellbore is a shale related instability and is caused by water entering into the shale pores causing the shale to swell. The invasion of water from the drilling fluid is changing the stress state and/or the shale strength. A reduction in shale strength creates a soft and sticky shale that are prone to erosion. Water invasion is mainly caused by hydraulic pressure gradients and chemical potential gradients (van Oort et al. 1996). Darcy's law controls the hydraulic pressure transport. However, the small pore throat size of shale makes this transport extremely slow and it can therefore be excluded. Chemical potential gradients are created if the salinity of the water phase in the drilling fluid is different than the salinity of the shale pore water. If the salinity is lower in the drilling fluid water molecules will migrate into the shale due to osmotic pressure difference and the shale will swell. The salinity is measured in water activity, a_w, which is inversely proportional to salinity. Figure 3.6 shows the mechanisms of swelling wellbore.

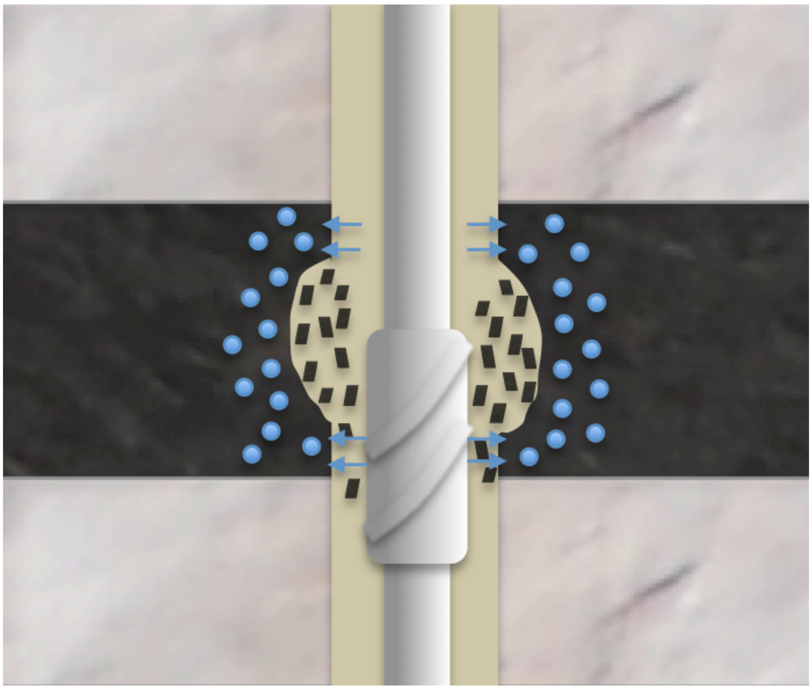


FIGURE 3.6: Water entering the shale formation causing swelling and erosion. Free after drillingformulas.com (2011b).

This problem occurs at shallow to intermediate depths where the swelling clay mineral smectite is present in the shale. Below 2500-3000 mTVD smectite is transformed to illite, which swells insignificantly (Skalle 2011). The swelling is also time-dependent; the longer the wellbore stays open the more swelling problems.

An invert emulsion fluid is commonly used to prevent swelling of shale while drilling. As already mentioned, the rock strength is reduced when water invade the shale, on the other hand the rock strength is increased if water is removed from the shale. Invert emulsion fluids has a lower water activity than the shale pore water, so that water is sucked out of the formation into the wellbore by osmosis strengthening the rock. However, removing too much water from the shale will make it inherently brittle. Experiments on shale have shown that a chemical balance, i.e. equal salinity, is not sufficient in order to prevent water from migrating into the shale. Instead a so called chemo-mechanical balance must be fulfilled to also account for mechanical effects, for the shale to remain stable. (Hemphill 2011)

The symptoms of swelling shale is that the torque and drag will increase, overpull and took weight may be experienced when tripping, the pump pressure will increase, mud properties become poor and soft hydrated cuttings are observed over the shale shaker (drillingformulas.com 2011b). The pump pressure increase may even escalate into a pack off, i.e. sudden increase in pump pressure when the flow rate is constant. The soft and hydrated cuttings could be seen as clay balls that potentially could block the shaker (Skalle 2011). The symptoms of swelling shale seen on the mud properties is as follows:

- High cation exchange capacity (CEC)
- Increased low gravity solids (LGS)
- Increased filterloss, methylene blue test (MBT), plastic viscosity (PV) and yield point (YP)

Remedies that can be done for such a restriction is to change the mud properties to have the same salinity as the shale pore water. Using oil based mud removes the swelling problem due to its inhibitive properties, but in many cases it cannot be used due to environmental concerns.

3.3 Creeping Wellbore

Creeping wellbore is a time-dependent phenomenon. The constant in-situ stress load causes it and it can occur in both saturated and dry rocks. The time scale for creep leading to rock failure could be minutes or years. The speed of the process is not only dependent on the stress regime, but also on the temperature. Generally the process is faster for higher temperatures. Creep has three different stages transient, steady state and accelerating and these are shown in the strain versus time plot in Figure 3.7. In the accelerating stage the rock is failing with a spreading of unstable fractures and borehole collapse. (Fjær et al. 2008)

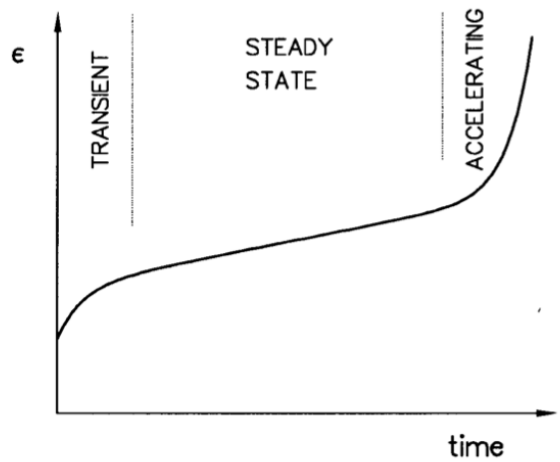


FIGURE 3.7: Strain versus time in a creeping rock (Fjær et al. 2008).

The main issue with creeping wellbore is a decrease in hole diameter due to mobile or plastic formations causing "tight hole". These formations are slowly moving into the wellbore and if the wellbore stays open for a sufficient time period the drill string may not be able to pass through anymore. The formations that especially deforms under stress is halite and claystone and these are the main contributors to creeping wellbore problems (Skalle 2011).

With regards to hook load signal in this case it is expected to show up as a sudden overpull/took weight. The drill string should be free in one direction, unless the formation has started to squeeze around the drill string. When running into the hole it should be seen as a sudden took weight and the drill string will not be able to pass that point without drilling through it again. Since one of the formations that most commonly cause such problems is halite, one of the symptoms for creeping wellbore could be an increasing salinity of the mud.

3.4 Cavings

Cavings from unstable formations could cause restrictions in the wellbore due to its size. The transport ability decreases with increasing size of the particles due to reduced shear area available to move the particle, and therefore cavings tend to stay in the well (Skalle 2011). Cavings may pack off around the drill string while drilling causing sudden SPP increases, and during tripping operations shoveling of large size cavings could cause over-pull.

There are different types of unstable formations that could lead to cavings. In fractured rocks the mud will over time penetrate into the rock changing the stress regime and the rock becomes weakened. If the mud-weight is insufficient, i.e. lower than the minimum horizontal stress, stress induced cavings will form (Osisanya 2011). The shape of the cavings can reveal its cause and thereby the correct countermeasures can be implemented. Table 3.1 gives and overview of the different geometries including their causes and countermeasures, while Figure 3.8 shows examples of them.

TABLE 3.1: Different geometry of cavings and their causes and countermeasures(Skalle 2011).

Geometry	**Cause**	**Countermeasures**
Splintery	Underbalanced drilling	-Improve fluid loss -Reduce hydraulic/mechanical attack
Angular	Abnormal stress regime	-Optimize trajectories -Increase mud weight -Monitor ECD
Blocky	Pre-existing fractures/failures	-Improve fluid loss -Reduce hydraulic/mechanical attack

FIGURE 3.8: Different shape of the cuttings. To the left a splintery, the second is an angular and to the right is a blocky caving (Skalle 2011).

3.5 Ledges

Ledges are formed in the transition between hard formations and soft or weak naturally fractured formations. They can be formed in layers of limestone and shale where the shale has experienced washouts as shown in Figure 3.9. They can also be formed in alternating weak and hard formations where the weak formations are prone to erosion from stabilizers in the BHA and tool joints (drillingformulas.com 2011a). When drilling into a harder formation with a dip angles ranging from 5-90° (Jr. et al. 1986) the bit may ream down the soft formation, which causes bit deflection. An example of this is shown in Figure 3.10, where the effect is even stronger due to the inclination of the well. A ledge is formed due to this deflection and is seen on the hook load signal as took weight when running into hole. Generally ledges are seen as sudden changes in the hook load signal with a steep slope.

Ledges can also be formed in the transition between the casing shoe and the drilled cement. Such type of ledges is easily identified because they appear when the BHA, especially the large diameter components, are pulled through the casing shoe. This type of ledge is not visible when running into hole.

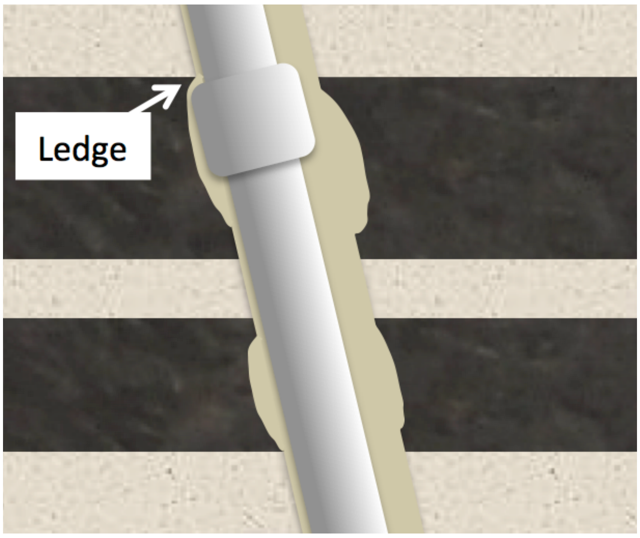


FIGURE 3.9: Ledges forming because of layering of soft and hard formations.

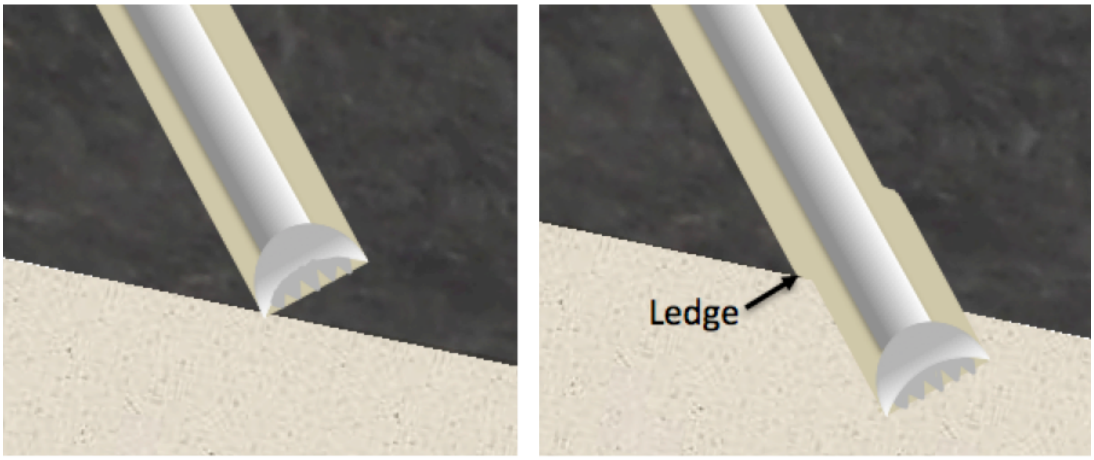


FIGURE 3.10: Ledge forming due to bit deflection when drilling into a harder formation with a dip angle.

3.6 Local Dogleg

Dogleg is normally referred to as a particularly bended part of the wellbore. This part will apply higher bending forces on the drill string and the string will be in contact with the borehole wall. In a particular location along the dogleg there will be a spot that experiences excessive wear from the drill string interaction with the borehole wall, which will form a keyseat (Figure 3.11). The keyseat could cause stuck pipe when larger diameter parts of the BHA are pulled through

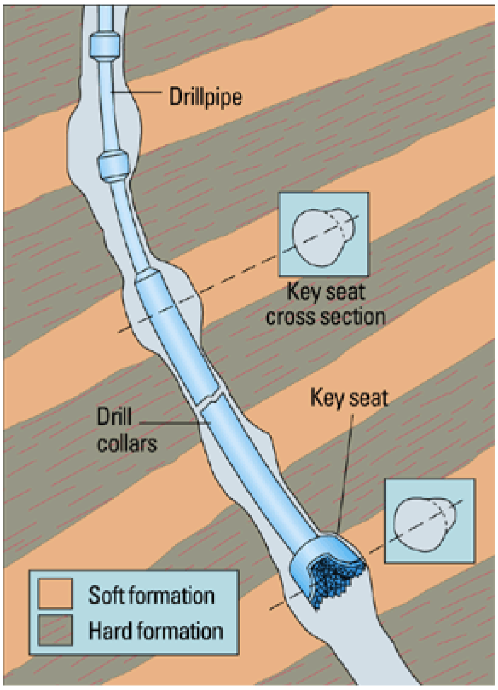


FIGURE 3.11: Keyseats formed due to local dogleg (Choudhary 2011).

this worn spot. The restriction is somewhat similar to ledges when it comes to restriction problems. Stiffness of the BHA is of importance, if the BHA is changed after a dogleg the string may not be able to enter the hole again if the new BHA is stiffer. Also, an increased drag may be experienced when pulling the BHA through this part of the well because the BHA is stiffer than the rest of the drill string (Schlumberger 2013).

The keyseat will appear at one point in the well, when trying to get pass it several overpulls at the same depth might be experienced. The overpull is expected to be sudden with a steep slope just as the ledge signal. The strongest symptom for it is off course a high dogleg, $>3°/30$ m. In addition to this the torque and drag will increase for the interval drilled below the high local dogleg, because of increased bending forces on the pipe.

3.7 Differential Pressure Pipe Sticking

Differential pressure pipe sticking, normally denoted as differential sticking, is a time dependent phenomena that happens during static conditions and it causes problems in the transition to dynamic conditions. It is caused by a part of the drill string being embedded in the mud cake due to poor mud properties causing thick mud cake and higher pressure in the wellbore than in the formation. Figure 3.12 shows the mechanisms of differential pressure pipe sticking. The force, F_p, required to pull the drill string free from the borehole wall is a function of the differential pressure, Δp, and the area of contact between the drill string and the mudcake, A_c.

$$F_p = f \Delta p A_c \tag{3.1}$$

The differential pressure can expressed as

$$\Delta p = p_m - p_{ff} \tag{3.2}$$

where p_m is the hydrostatic pressure from the mud and p_{ff} is the formation pressure. (PetroWiki 2012)

Differential pressure pipe sticking is more likely to occur in a directional well than in a vertical because the drill string is in contact with the wellbore walls.

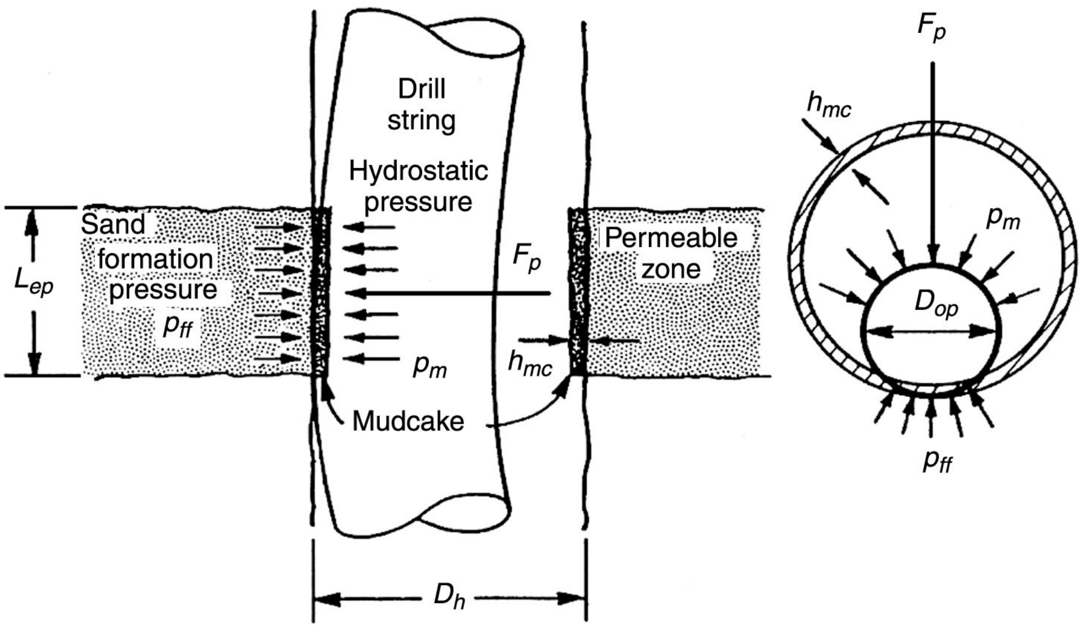


FIGURE 3.12: Mechanisms of differential pressure pipe sticking (PetroWiki 2012).

4 | State of the Art of Revealing Deviation in HKL Signals

The goal of this thesis is to be able to distinguish different types of restrictions by looking at the hook load signal. There are little studies covering this area. However, work done by Cordoso et al. (1995) has identified hook load type curves for borehole closure and ledges, which can be helpful in this study. Cordoso et al. (1995) compared hook load signal with type curves in their diagnostic hook load data analysis. The different type curves are presented below.

4.1 Tripping Type Curve

The tripping type curve is the type curve for normal hook load signal when tripping one stand, i.e. when no restrictions or other abnormalities are present. In Figure 4.1 the hook load curve can be divided into three parts; acceleration, constant velocity and deceleration respectively. The acceleration part is where the hoisting of the drill string starts and the hook load is rapidly increasing until it reaches a maximum, seen as the first peak on the curve. This peak represents the static friction that needs to be exceeded in order to move the pipe. The center part will oscillate around an average value, which is a function of the true borehole friction factor at dynamic conditions. The variations in the signal of the center part will depend on conditions such as heave on rig, i.e. signals from a fixed rig will be more stable than on a floater. f_b^s is the true borehole friction factor, which is zero at static conditions and it is considered normal if the value is in between 0.20 and 0.40.

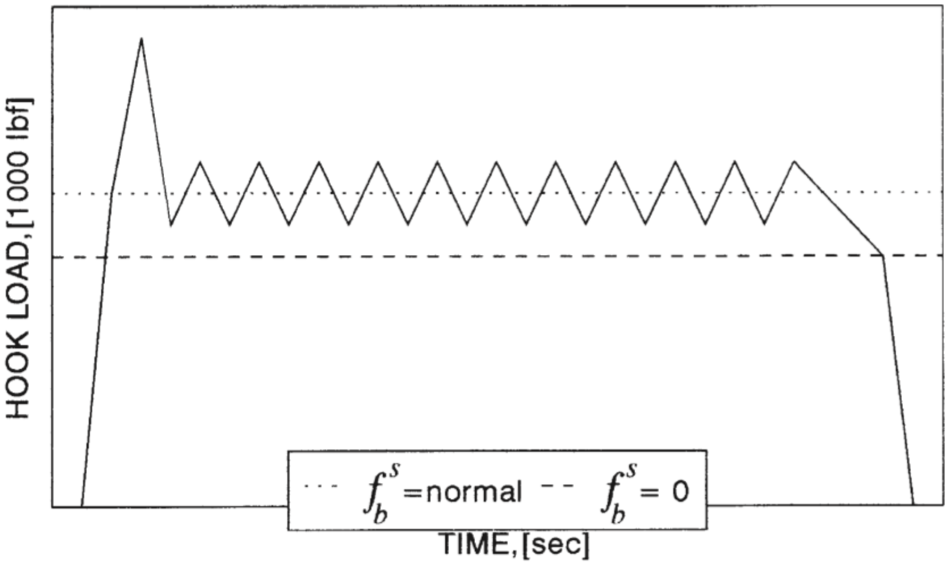


FIGURE 4.1: Type curve for tripping with no abnormalities (Cordoso et al. 1995).

4.2 Ledge Type Curve

Figure 4.2 shows the ledge type curve with two disturbances in the signal. The disturbances is simulating larger diameter parts of the drill string hitting ledges when tripping. The first peak in the ledge signal is governed by pipe stretching, and is followed by a negative peak that is a result of excessive acceleration due to compression of the pipe when the ledge let go of the pipe. The drill string is pulled at constant velocity for the entire stand. In this type curve it is the tool

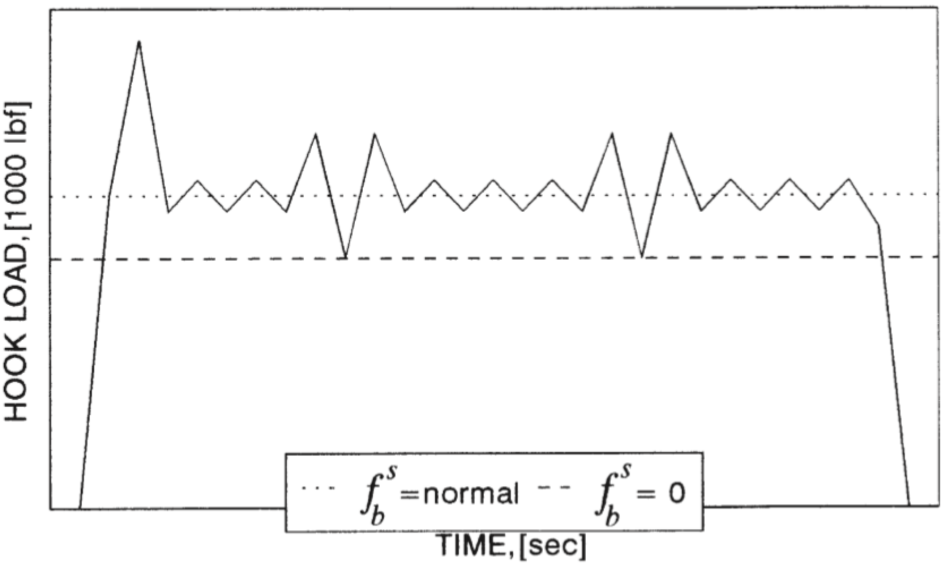


FIGURE 4.2: Type curve for ledges (Cordoso et al. 1995).

joints that are hitting against the ledges, it can be seen by the spacing between them that is representing one single pipe.

4.3 Borehole Closure Type Curve

Figure 4.3 shows a typical borehole closure signal indicating difficulties in all instances in moving the pipe. The pipe is moving continuously upwards and the hook load signal shows stretching of pipe followed by rapid movements with high acceleration and deceleration and then stretching again. This continues throughout the section indicating borehole closure.

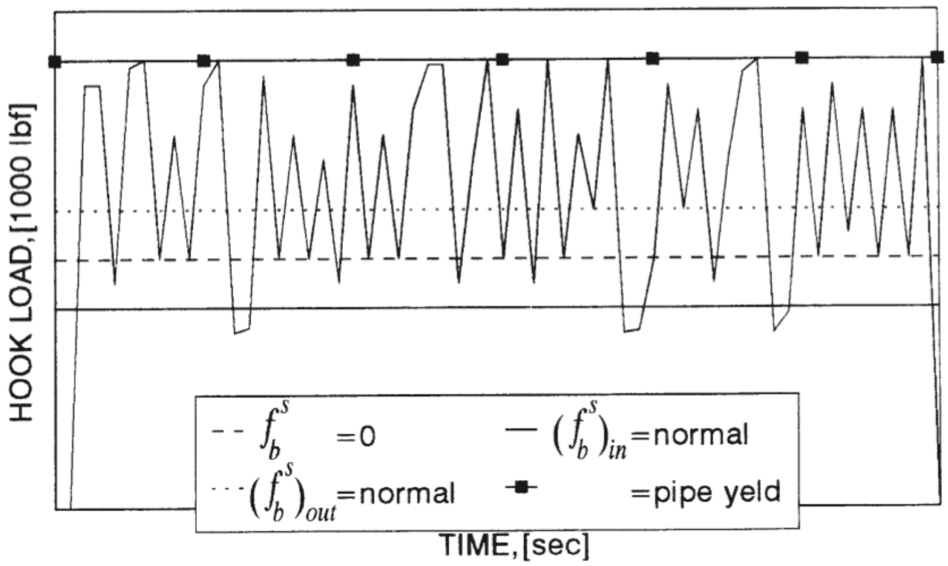


FIGURE 4.3: Type curve for borehole closure (Cordoso et al. 1995).

4.4 Differential Sticking Type Curve

Differential sticking is a type of downhole restriction happening at static conditions. This means that it happens during connection or other static events. Figure 4.4 shows a typical differential sticking hook load signal, where the axial force has to exceed the differential sticking force to free the pipe. The signal starts with an abnormal high hook load followed by a normal signal for the rest of the stand pulled.

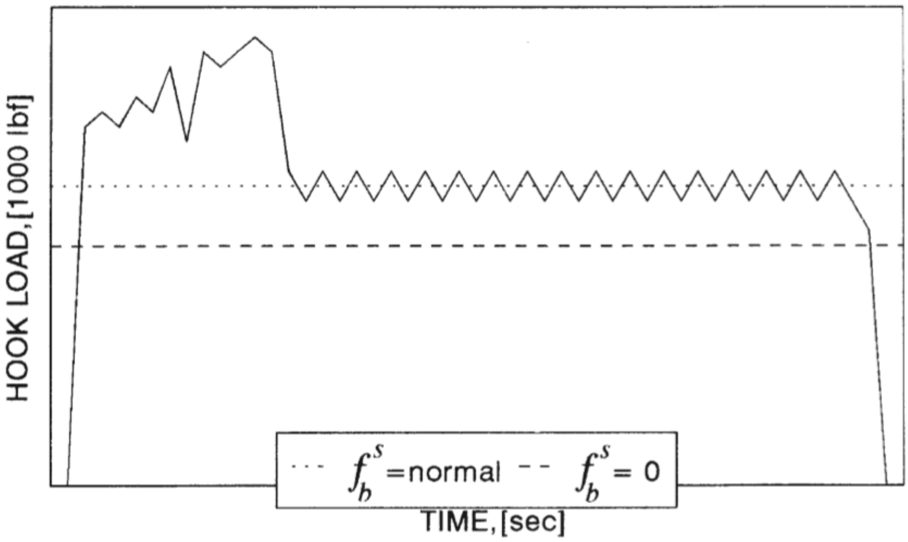


FIGURE 4.4: Type curve for differential sticking (Cordoso et al. 1995).

5 Post-event Analysis

In order to find special hook load signatures related to causes of restrictions it is crucial to know what caused the restriction with a high level of confidence. The post-event analysis and its results are presented in this chapter.

5.1 Field Data

The first step in the hook load signal analysis was to collect real time drilling data and daily reports from different drilling operations. Data from six wells at three different fields were collected and processed. The daily reports include operation activity descriptions, directional data, fluid remarks, geological remarks and BHA data. The real time drilling data were accessed from a database and the data were displayed graphically with the option of converting them into text files. They include limited amounts of downhole data, only the data that is transmitted to the surface during drilling.

The next step was to go through all the daily drilling reports in the search for hook load restrictions, which was done by reading all the operation activity descriptions in the reports. When a restriction was found other relevant information from the report was gathered into a table for further investigation. Other relevant information was hole inclination, dogleg, casing shoe depth, stringers, type of formation, BHA length, mud properties and information from the activity description. A visual inspection of the hook load signal from the real time drilling data was then conducted and it was included in the excel sheet. After gathering all this information for all restrictions found, an investigation of causes could be carried out. This investigation is presented in Section 5.2 together with the mentioned tables and hook load signals. In the following subsections the different field data used in the analysis are presented, focusing on the importance of including them in the study.

5.1.1 Directional Data

The directional data is of major importance for revealing causes of downhole restrictions. Especially when determining wether the restriction is caused by cuttings loads or not. Cuttings will not settle at an inclination of 35° or less, while at an inclination of 35° and up to about 55° the cuttings will settle and avalanche causing problems (ref. Section 3.1.1). The dogleg of the well could also cause problems as depicted in section 3.7. If the dogleg is high in a part of the well where problems were encountered the restriction could be a key seat. The dogleg is normally considered high if it is 3°/30 m or more

5.1.2 Geological Data

Geological data is important for determining what type of restriction is causing problems. Some restrictions only occur in one type of formation while other could occur in several types. For instance swelling wellbore only occurs in shale formations. An important geological phenomena is limestone stringers which often causes restrictions in form of ledges due to its hardness. They could also cause bit deflection if the formation has a dip angle, or ledges could be formed due to washouts in the surrounding formations.

5.1.3 BHA and Bit Data

The BHA of the drill string contains many large diameter components with the bit and the stabilizers as the largest. All of these components could potentially cause problems when passing restrictions. Knowing the length of the BHA is therefore important in order to know what area of the well the restriction most likely is within. Also it could be helpful to know the length from the bit to the different stabilizers to connect overpulls with ledges that is present higher up than the bit depth. This part of the daily report also includes wear data on bit and stabilizers after a run.

5.1.4 Drilling Fluid Data

This part of the daily report includes information about the fluid properties. It also includes a section with fluid remarks where important abnormalities are reported. It contains results from fluid tests such as solids content, viscometer tests and filtration tests.

5.1.5 Missing data

For quality assurance it would be desirable to have access to more data than what was used in this analysis. Useful data in addition to the available data would be a roadmap and a trip risk log. The roadmap includes simulated torque and drag data together with actual values, which enables a comparison of those two. This comparison may strengthen cases of restrictions where it is likely that cuttings beds are involved. A trip risk log is made for the driller to use when tripping out. It contains a formation evaluation (FE) log with information about critical intervals in the well that may have washouts, stringers, doglegs or other irregularities (Blaasmo et al. 2007).

5.2 Results From The Analysis Process

The process of analyzing all the data lead to the finding of a total of 22 cases of restrictions that could be related to one of five groups. These are summarized in Table 5.1 and the number of incidents are distributed in terms of causes. All of the cases occurred in the $17^1/_2$" section. 19 of the incidents occurred when pulling out of hole (POOH), while 3 happened when running into hole (RIH). The findings are mainly based on information available in the daily drilling report as presented above. However, in some cases where it was hard to conclude, the hook load signal has been used for final conclusion.

Incidents of hook load restrictions are recognized on the hook load signal as overpull or took weight. A signature plot for normal hook load while tripping out was presented in Figure 2.1 and definitions of overpull and took weight in Section 2.2. An example real-time drilling data plot is shown in Figure 5.1 where both overpulls and took weight occurs. The plot includes 3 columns of signal data and one

Table 5.1: Restriction incidents distributed in what was likely to be causing them.

Cause of Restriction	**Number of Incidents**
Unstable formation	2
Ledge	9
Cuttings accumulation	7
Differential sticking	1
Local dogleg	3
Total	22

with time data. In the first column the Average rate of penetration (ROP Avg) is plotted together with the hook height (HK Height). Since the plot shows tripping operation the ROP Avg is zero. In the next column Torque, weight on bit (WOB) and weight on hook (WOH) is plotted. Torque is equal to zero in this plot because there are no rotation. In the third column the bit depth and the hole depth is plotted, the numbers written in red represents the bit depth. The red line is parted from the blue line, which means that the bit is off bottom.

In the Figures 5.2-5.5 hook load signals from the 22 cases summarized in Table 5.1, except for differential sticking, are presented. There was only one case of differential sticking, to which the signal is presented in Section 5.2.4, and is therefore not presented here. Each figure represents one of the causes of restriction presented in Table 5.1 and includes several sections selected from a real-time drilling data plot such as in Figure 5.1. In this plot the selected section is marked by a black box, which is the same section as the first in Figure 5.2 chosen just for illustrative purpose. Each section represents one of the incidents for that specific cause of restriction and it shows the hook height (HK Height), weight on hook (WOH) and bit depth. Weight on hook is mostly referred to as hook load signal and together with hook height they are the most important parts of the real-time plots and are essential in the hook load signal analysis. The hook load signal is useless without the hook height signal, because it will then be impossible to know if the increase in hook load was due to change in pulling speed or caused by restrictions. Some of the cut out parts also includes weight on bit in cases when running into hole and the bit 'took weight'. Some parts also include torque signal, which is in cases where the string was rotating either because of reaming operations or because of an attempt to rotate through the restriction. The cases that were picked out for the extensive post-event analysis in the Sections 5.2.1-5.2.5 are marked with a red frame in each of the figures.

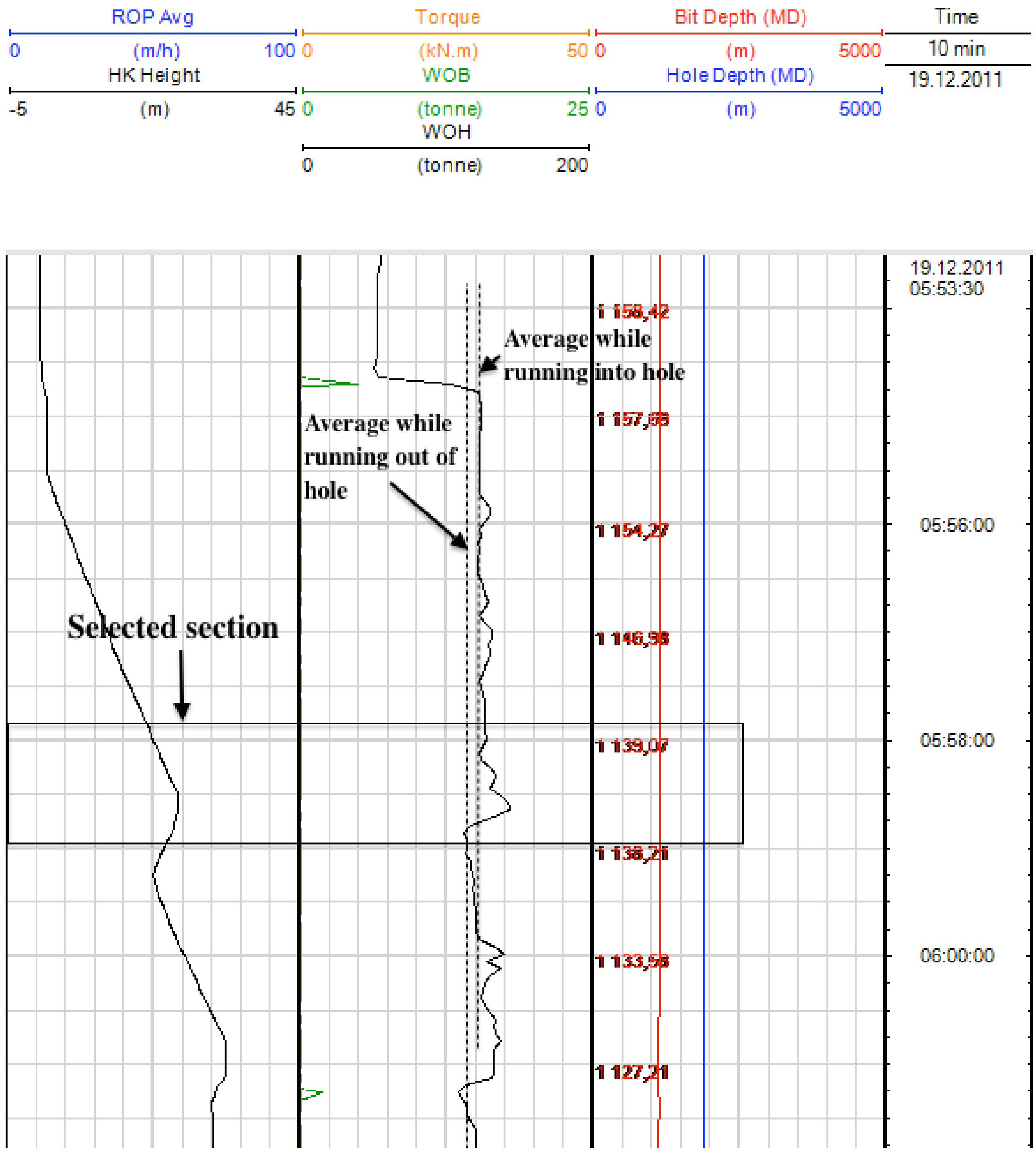


FIGURE 5.1: Overpulls experienced while pulling one stand of drill pipe. It can be seen as an increase in weight on hook (WOH) while pulling at constant speed (HK Height). It is also one took weight towards the end of the plot (at about 1127 mMD) when running back into hole again, it can be seen by WOB increasing from zero (green line) and WOH lower than average. The black box shows the cut-out section presented in Figure 5.2.

Figure 5.2 shows parts of the real-time drilling data plot for the two cases of unstable formation causing restriction. In the first part the hook load signal shows a building tendency, while the second part shows a more sudden and sharp peak. It can be seen that the hook is moving a larger interval upwards during the first case of overpull than what it does for the second case.

In Figure 5.3 the real-time signal for the 9 cases of ledges causing restrictions are

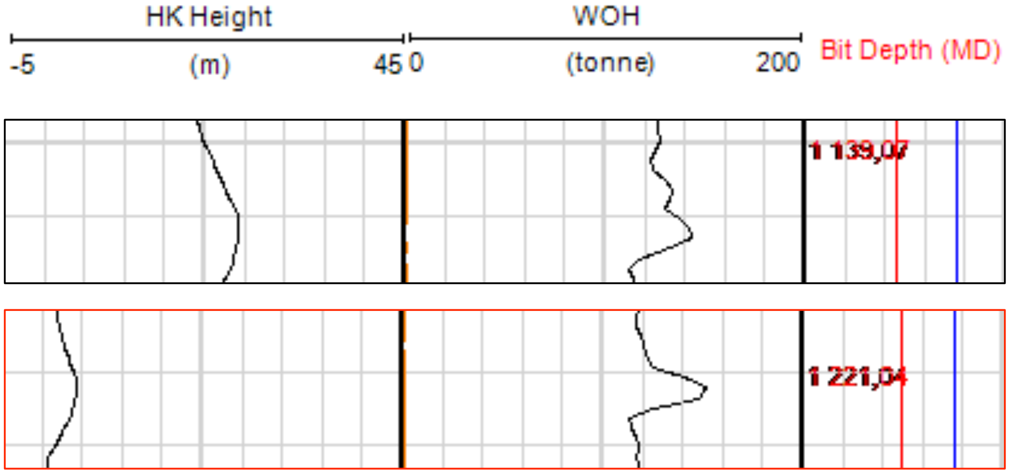


FIGURE 5.2: Unstable formation: Selected parts of the hook load signal (WOH) and hook position (HK Height) for the 2 cases of restriction caused by unstable formation. They are categorized as unstable formation based on information about cavings generation from the daily drilling report.

presented. They all have in common that the overpull signal is sudden and has a steep slope.

The real-time signals for the 7 cases of restriction caused by cuttings accumulation are presented in Figure 5.4. Most of the overpull signals have a building tendency, but some also shows a sudden increase. The last of the signal sections occurred when running casing into hole and the overpulls/took weight are therefore much higher here due to the high yield strength of casing.

Figure 5.5 shows the real-time signals for the three cases of restriction caused by high local dogleg. These hook load signals are similar to the signals for ledges causing restrictions, associated with sudden overpulls. However, the cut out part in the middle has an overpull that is more building up, i.e. less steep slope.

The signals in the figures 5.2-5.5 proves that dividing the hook load signals into 5 distinctive signature groups could be challenging. It seems like there are two main differences; sudden and building signal. However, even though one is more present in one cause of restriction group it could also include the other type. One restriction from each of the cause groups were picked out for an extensive post-event and hook load signal analysis. The chosen cases were those that had hook loads signals that was assumed to be typical for that cause based on type curves presented by Cordoso et al. (1995) in Chapter 4 and knowledge about the restriction types presented in Chapter 3. Also the cases were picked based on available information to strengthen the cause together with signal readability. 4 out of 5 of the chosen cases were drilled from a fixed drilling unit, thus with no wave disturbances, which makes the signal easier to analyze. For the last cause of restriction, local dogleg, no cases from a fixed drilling unit was available and that is why this case is from a well drilled from a floating drilling unit.

The post-event analysis was conducted for the purpose of strengthening the hypothesis of what caused the restriction. That will also increase the quality of the hook load signal analysis. However, it is important to note that the signal analysis is not independent of the post-event analysis. In some cases the signal is one of the main proofs for what the restriction is caused by based on type curves presented in the previous chapter.

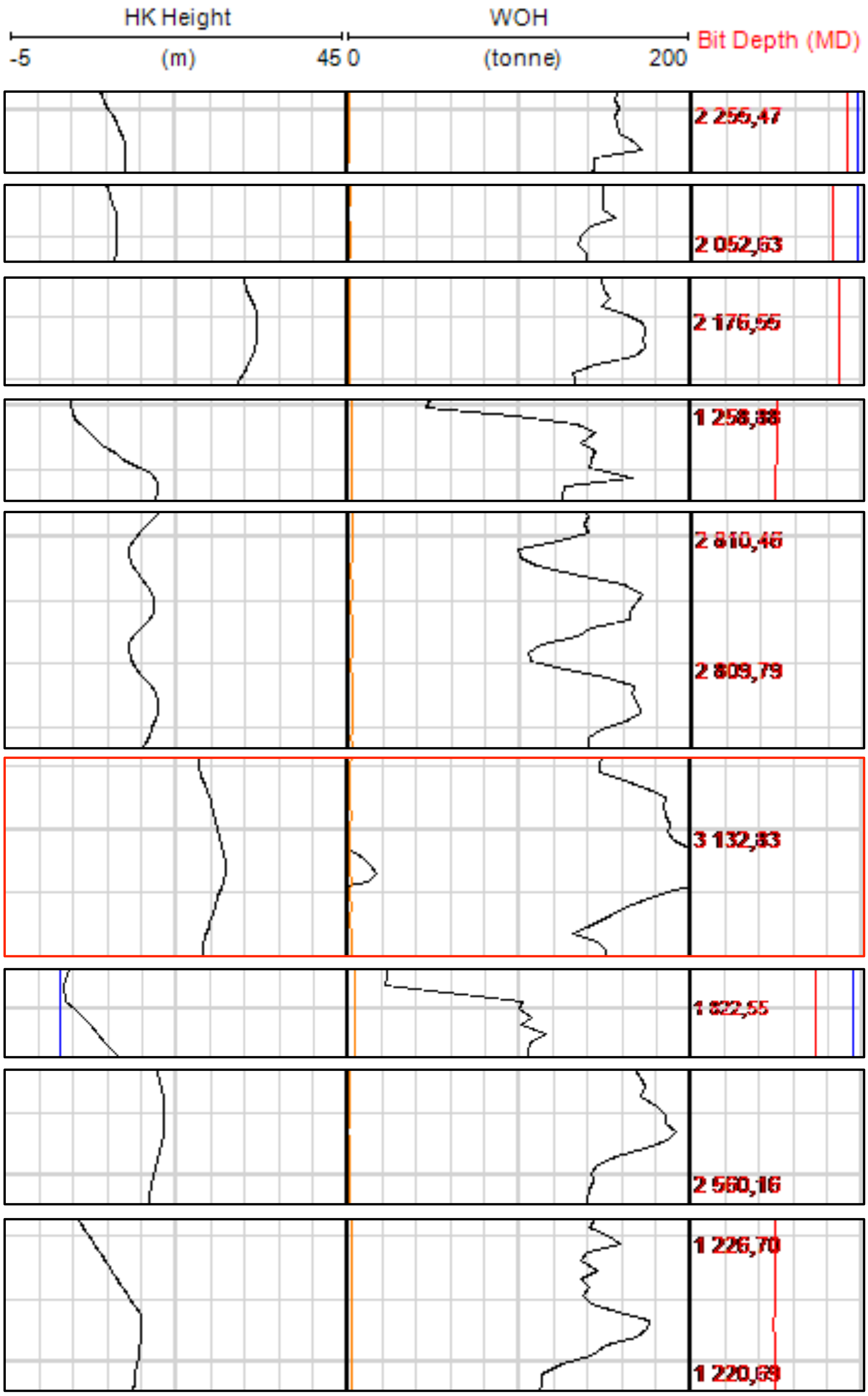


FIGURE 5.3: Ledges: Selected sections of the hook load (WOH) and the hook height (HK Height) signals for the 9 cases of restriction caused by ledges. One box represent one of the cases. They are mainly categorized due to stringers present or other phenomena that could cause ledges, e.g. casing shoe.

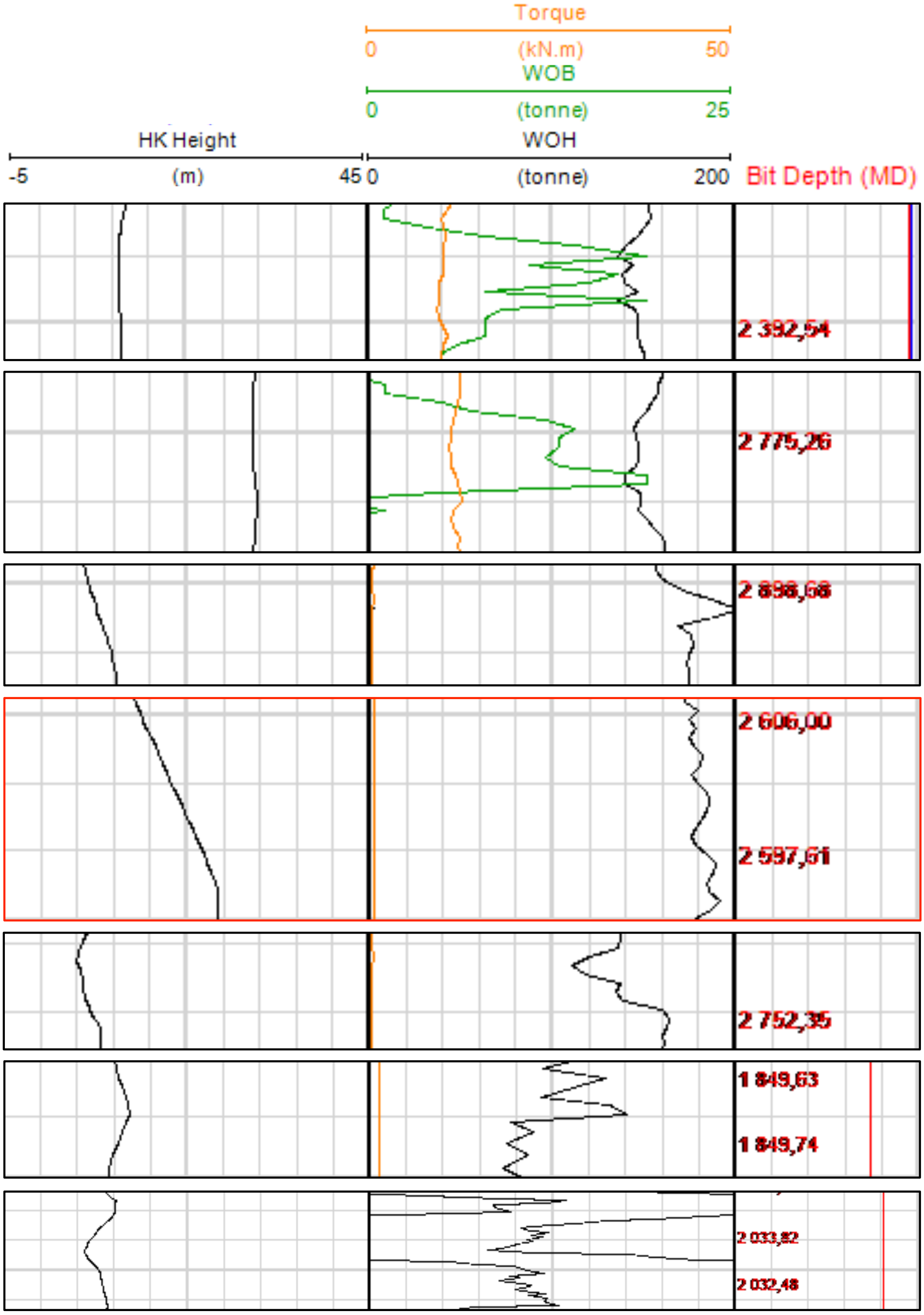


FIGURE 5.4: Cuttings accumulation: Selected sections of the hook load (WOH) and hook height (HK Height) signal for the 7 cases of restriction caused by cuttings accumulation. The categorization is mainly based on information about hole inclination, drilling rate of penetration before pulling and to some extent the hook load signal (wether it is erratic).

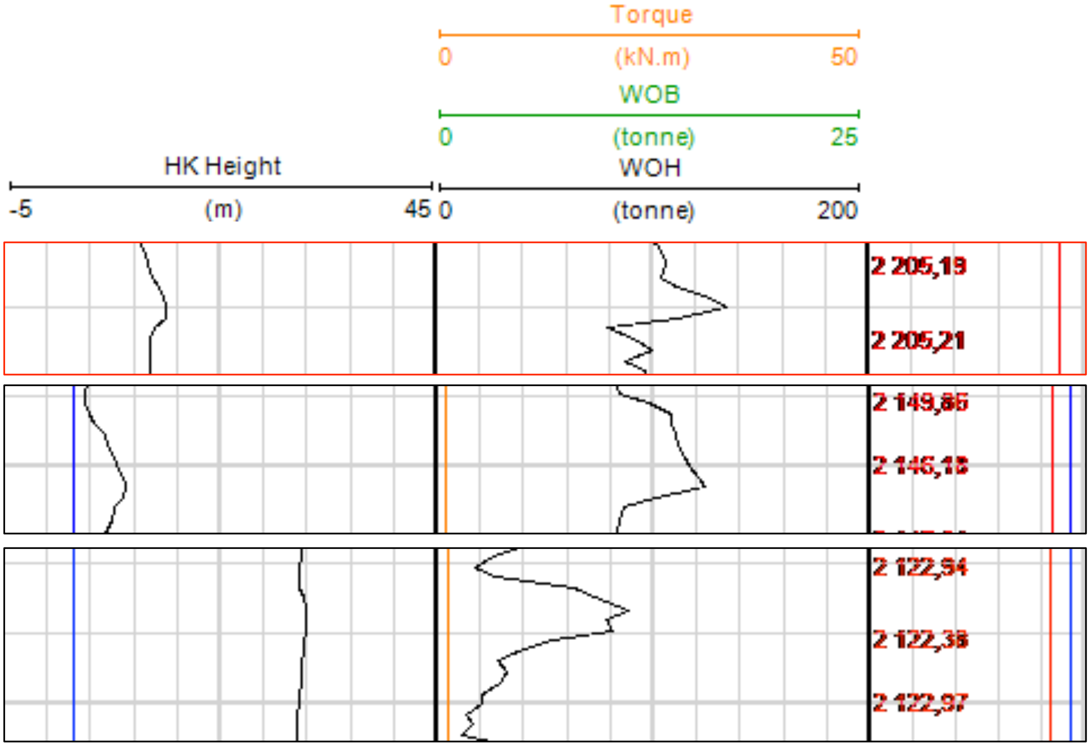


FIGURE 5.5: Local dogleg: Selected parts of the hook load (WOH) and the hook height (HK Height) signal for the 3 cases of restriction caused by high local dogleg. They are categorized based on the high local dogleg for all the three cases.

5.2.1 Well A-5 - Unstable Formation

In well A-5, 15 overpulls occurred that are likely to be caused by an unstable formation. An unstable formation is normally caused by shales suffering swelling or embrittlement, or by natural fractured formations caving out. Information about the wellbore conditions are listed in Table 5.2.

Table 5.2: Wellbore information for the interval of unstable formation in well A-5.

Probable Cause	Unstable formation
Operation	Tripping out
Depth	1290-1021 mMD
TD well	1881 mMD
Casing shoe	1024 mMD
Inclination	25-16°
Average Dogleg	2.03-1.07°/30m
BHA length	228 m
Max pore pressure gradient	1.03 g/cm^3
Mud pressure gradient	1.35-1.44 g/cm^3
Formation	Claystone and sandstone with traces of limestone and dolomite

Event Description

Experienced overpull while tripping out at 1290 mMD (Figure A.1), continued tripping out experiencing several tight spots up to 1117 mMD. Ran into hole and circulated bottom up several times at 1350 mMD. Abundant amounts of cuttings that consisted of silty claystone were seen on shakers while circulating. There were some traces of flat and thin shaped mechanical cavings with a size range of 1-4 cm. After circulating 7 bottoms up the amount of mechanical cavings were increased to 4%, which indicated that more cuttings were produced by the rotation due to drill string interaction with the borehole walls. Backreamed out until bit was inside casing at 1021 mMD. The overpulls experienced are listed in Table 5.3, together with the depths of the large diameter components of the BHA.

Remarks While Drilling Before the Event

Fluid tests indicated that formation water had been dragged out of the formation into the mud by osmosis, the water phase salinity (WPS) of the active system was maintained by using sacked Calcium Chloride. While drilling this interval a climbing rheology with increasing LGS, YP and PV was experienced. Drilled with instant rate of penetration (ROP) of 20 m/hr due to weather and cuttings

Table 5.3: List of overpulls experienced in well A-5 together with the corresponding depths for each large diameter BHA component.

		Depths [mMD]			
Overpull Number	**Overpull [ton]**	**Bit Depth**	**Bit end Depth**	**In Line Stab (ILS)**	**Roller Reamer**
1	15	1290	1289	1271	1258
2	25	1221	1220	1202	1189
3	25	1213	1212	1194	1181
4	20	1207	1206	1188	1175
5	5	1204	1203	1185	1172
6	15	1197	1196	1178	1165
7	15	1191	1190	1172	1159
8	25	1178	1177	1159	1146
9	25	1177	1176	1159	1145
10	25	1176	1175	1157	1144
11	25	1125	1124	1106	1093
12	25	1135	1134	1116	1103
13	25	1123	1122	1104	1091
14	25	1121	1120	1102	1089
15	25	1117	1116.	1098	1085

offloading to boat at the beginning of the section. Drilled with low ROP due to hard formation before pulling out. Three limestone stringer were identified while drilling the interval that was causing the restrictions, as listed in Table 5.4. Flow checked before POOH (lost 170 litres in 15 min), but did not circulate before pulling out. Flow rate varied between 4500-4000 lpm when drilling.

Table 5.4: Depths of limestone stringers in well A-5.

Limestone Stringers	
From [mMD]	**To [mMD]**
1161	1162
1178	1179
1255	1256

Hook Load Signal Analysis

Figure 5.6 shows the weight signal (WOH) when tripping through unstable formation. The plot shows the depth interval from 1224 mMD to 1213 mMD and includes overpull number 2 and 3 from Table 5.3. The real-time signal plots for the rest of the overpulls in Table 5.3 are included in Appendix A.1. The signal shows several overpulls. First two at about the same depths 1221 mMD (OP #2) and when continuing pulling at constant velocity the signal is unstable. Towards the end of the plot two overpulls are visible at the same depth of 1213 mMD (OP

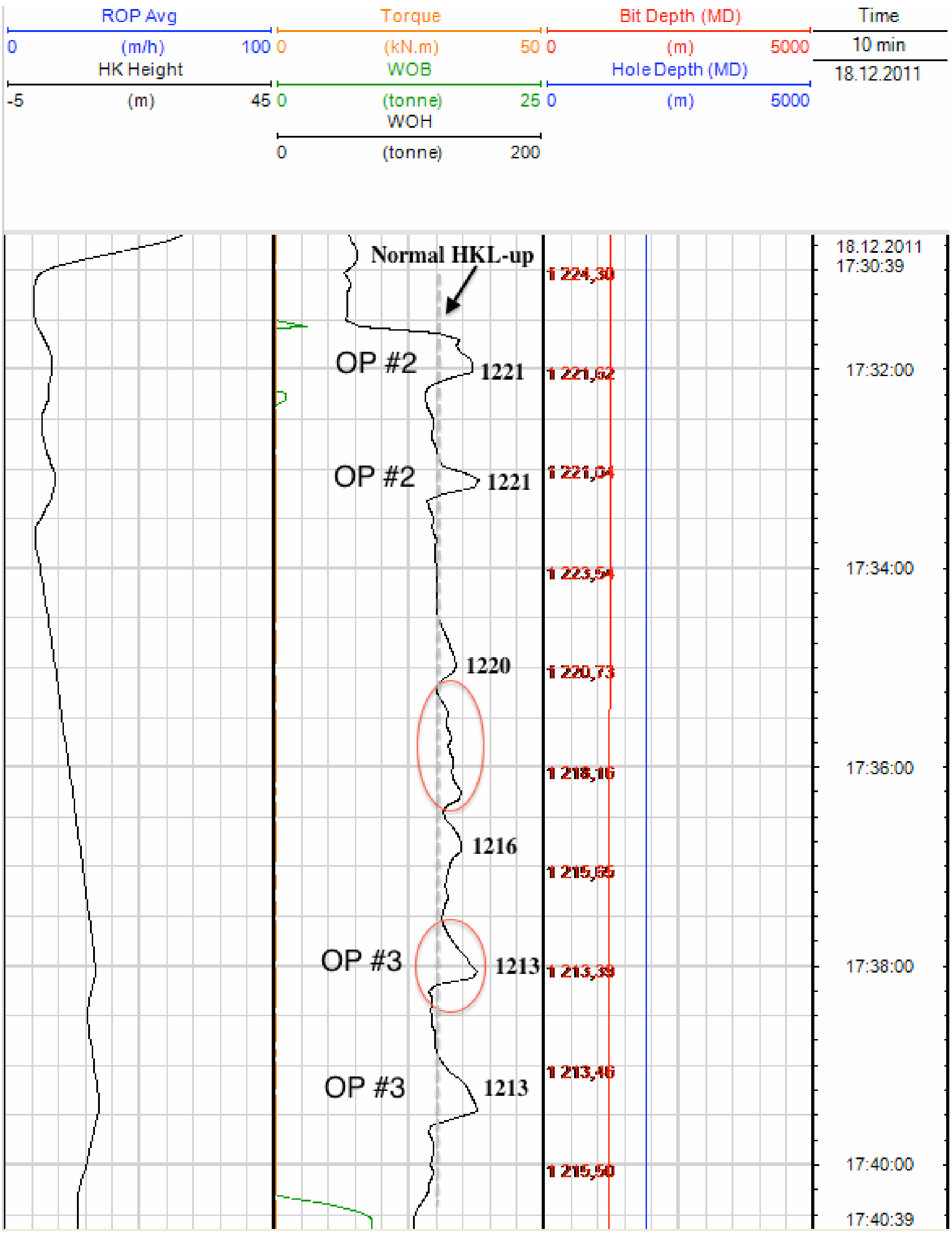


FIGURE 5.6: Hook load signal for unstable wellbore. OP denoting overpull while the numbering is related to Table 5.3. The grey dashed line indicates the normal hook load when pulling and the depths of occcurence are written next to the overpulls. The two types of signatures found are circled in red.

#3). The two overpulls at the beginning and at the one at the end has in common that they are both sudden with a steep slope and appears at the same depth twice. The middle part of the plot consists of predominantly unstable signal with small self-rectifying overpulls. The overpull at around 1218 mMD, marked by the first red circle, is building up with an unstable signal over a couple of meters before it self-rectifies. The other two overpulls in the middle part, at 1220 mMD and 1216 mMD, looks more like the four main overpulls, with a sudden, though stable, increase in weight. A physical interpretation of the two signatures could be that the sudden restriction is fixed while the one that is unstable and is building an overpull slower is moveable. Thus, the weight increase in the first case is governed by an increase in pipe tension and thereby pipe stretching. In the case with the moveable restriction the restriction will move upwards while pulling. That means that the mass causing restriction is being shoveled upwards along with the drill string by the large diameter components of the bottom hole assembly. The friction increases and thereby also the weight until it self-rectifies. The self-rectifying feature could be caused by cuttings/cavings being stored in washouts or somehow is released pass the stabilizers and falls down the wellbore.

Discussion on Cause of Restriction

The inclination of 16-25° is too low for the cuttings to settle along the wellbore. Also, the ROP was limited for most of the time during the previous drilling both due to cuttings offloading issues and due to hard formations. The latter was the case for the last 12 meters, which took 13 hours to drill, before pulling out. It is therefore likely that the cuttings concentration in the annulus is low and should not cause trouble. There are many factors pointing at an unstable formation causing the restriction, especially the cavings coming over the shakers.

All three of the stringers drilled can be directly related to three of the overpulls. The first overpull at a bit depth of 1290 mMD (Figure A.1) can be related to the stringer at 1255-1256 mMD, because the Roller Reamer is positioned at 1258.4 mMD. That gives a deviation of 2.4 m, which is acceptable. The signal is also sudden with a steep slope. The third overpull at the depth 1213 mMD can be related to the stringer at 1178-1179 mMD, where the roller reamer is positioned at 1181.4 mMD again giving a difference of only 2.4 m. This overpull is present in Figure 5.6 showing that the signal is sudden and is occurring twice at the same depth. Overpull number 4 at 1197 mMD can be related to the stringer ending at 1162 mMD. That is because the Roller Reamer is positioned at 1165.4 mMD, which gives a deviation of 3.4 m. The deviation is caused by pipe stretching, errors in measuring stringer depths and errors in measuring overpull depth, which is further discussed in the Well A-12 T2 Post-event Analysis in Section 5.2.2.

While drilling this problem interval of the section fluid tests showed that formation water had entered into the mud, which is what the drilling fluid was designed for.

However, dragging too much pore fluid out of the formation will at some point make it brittle or unstable. Most of the section were drilled with a mud weight of 1.44 g/cm^2, which creates an overbalance of 48.2 bars at 1200 mTVD. Cavings caused by underbalance should therefore be unlikely unless the swabbing effect was very large during tripping. In order to investigate the swabbing effect while tripping, pressure data from the measure while drilling (MWD) tool is needed, which was not available in this study. A climbing rheology while drilling could be a sign of swelling shale and therefore indicate that the WPS is not sufficient for keeping the shale stable. However, there were no signs of swelling shale while tripping and circulating.

Analyzing the signal it seems there are two types of restrictions possible to distinguish between; fixed, and moveable. The fixed restriction can be related to washouts, while the moveable restriction can be related to cavings. Both can be related to an unstable formation. Cavings cannot be stored along the wellbore wall at this inclination (16-25°), but if they are generated while pulling out they might be stored on top of stabilizers and other large diameter components of the BHA. They will then be pushed up along with the drill string and thereby cause restrictions.

5.2.2 Well A-12 T2 - Ledges

Several overpulls occurred in well A-12 T2 that are being related to ledges, which are resulting from layers of hard limestone. Wellbore conditions are listed in Table 5.5.

TABLE 5.5: Wellbore information for the selected interval in well A-12 T2 where ledges caused problems.

Probable Cause	Hard stringers causing ledges
Operation	Tripping out
Depth	3191-3050 mMD
TD well	3244 mMD
Casing shoe	1021 mMD
Inclination	60°
Average Dogleg	0.3-0.67°/30m
BHA length	212 m
Max pore pressure gradient	1.02 g/cm^2
Mud pressure gradient	1.40 g/cm^2
Formation	Sandstone with claystone interbeds and limestone stringers

Event Description Related to Ledges

Had to pull out of hole due to extremely low drilling progress the last hour. Prior to pulling out of hole the well was circulated 3 times bottoms up with 4212 lpm while reciprocating at 150-180 rpm. Several overpulls were experienced and two of them are shown in Figure 5.3. Experienced 15 tons overpull at 3191 m (Figure A.6), 3157 m (Figure A.7 and Figure A.8) and 3144 m (Figure A.9). Went below tight spots and managed to work string through after a few attempts. Were unable to pass tight spot at 3132 m (Figure A.10 and Figure A.11) and had to lubricate through with a flow rate of 800 lpm. Continued POOH and observed 15 ton overpull at 3124 m (Figure A.12 and Figure A.13), attempted to work/ream through with 4180 lpm and 120 rpm without success. Had to ream back to TD at 3244 m where a total of 2 bottoms up were circulated while reciprocating pipe. Pulled out of hole with 20 rpm rotation from 3126-3098 m observing no significant tight spots. Pulled further up to 3070 m while rotating string at 20-50 rpm and experienced several overpulls from 3084-3070 m (Figure A.14) with a maximum of 30 tons. Continued pulling with a rotation of 50 rpm, got stuck at 3050 m (Figure A.15) with an overpull of maximum 35 tons and string stalled out with 40 KNm. Jarred string free down on first stroke and was able to establish free string rotation.

Decided to back ream out of open hole until bit was inside casing. Several tight spots were observed, but the hole conditions improved higher up in the wellbore. Large amounts of cuttings were seen over the shakers and an increasing drag and equivalent circulating density were observed when reaching a depth of 2273 mMD. The cuttings were mainly newly generated cuttings from back reaming and rotation of pipe.

When laying out the BHA components, stabilizers and the roller reamer were gauged showing significant wear. The two stabilizers placed closest to the bit had most dominant wear on the low side of them, while the wear on the NM stabilizer and the Roller Reamer dominated in the middle. Table 5.6 presents the four large diameter components with their length of the BHA including gauge after bit run. The bit came out 1/16" undergauged with minor wear on inner and outer cutting structure and worn cutters.

Table 5.6: List of large diameter components of the BHA including length and wear data after pulled.

String Component	OD [in]	Length [m]	Total string length [m]	Under gauged [in]	Dominant wear
Stab Sleeve	17.5	0.42	0.95	0.219	Low side
In Line Stab (ILS)	15.5	1.18	15.8	1.25	Low side
String Stab, NM	17.5	2.12	28.26	1.06	Middle
Roller Reamer	17.5	2.48	33.91	2.25	Middle

Remarks While Drilling Before the Event

Drilled several hard limestone stringers from 2836 mMD down to TD at 3244 mMD, they are listed in Table 5.7. When drilling the limestone stringers the ROP varied between 1 and 4 m/hr, while achieving an ROP of up to 40 m/hr for the claystone and 10-12 m/hr for the sandstone. The flow rate was kept in between 3700 lpm and 4500 lpm with, while the rotation was varied between 60-180 rpm. At the end of the section a very low ROP was achieved while drilling hard cemented sandstone. The parameters were varied in an attempt of achieving an acceptable ROP. The highest ROP of 4 m/hr, was achieved with high rotation and high WOB. It was decided to pull out of hole and set TD at 3244 mMD due to no drilling progress the last hour. It was assumed that the bit was worn out and lost its cutting ability, which proved to be wrong when the bit came to the surface as stated in the previous section.

TABLE 5.7: Depths of limestone stringers.

Limestone Stringers			
From [mMD]	To [mMD]	From [mMD]	To [mMD]
2754	2755	3041	3042
2773	2774	3069	3070
2836	2837	3072	3073
2863	2864	3086	3087
2875	2876	3112	3113
2901	2902	3126	3128
2909	2910	3140	3141
2920	2922	3144	3146
2943	2945	3171	3173
2980	2982	3178	3179
2994	2995	3196	3198
3019	3021	3214	3215
3037	3038	3227	3228
3039	3040		

Stringers Related to Overpulls

Based on the fact that there were many stringers present in the problem zone these were early suspected to be the cause of the restriction. However, it is important to gain as much evidence as possible for ledges to obtain a high level of confidence. A study of relating overpull depths with stringer depth was therefore conducted and presented next. Since there are three BHA components with same outer diameter (OD) as the bit, 17 1/2", and one with an OD of 15 1/2" it is just as likely that these components are causing overpull through restrictions as if the bit is causing them. Table 5.8 presents bit depths when experiencing overpull together with depths for each BHA component at that instance of overpull. When comparing

TABLE 5.8: List of overpulls experienced together with the corresponding depths for each large diameter BHA component.

		Depths [m]				
Overpull Number	Overpull [ton]	Bit	Stab Sleeve	In Line Stab (ILS)	String Stab, NM	Roller Reamer
1	15	3191	3190	3175	3163	3157
2	15	3157	3156	3141	3129	3123
3	15	3144	3143	3128	3116	3110
4	44	3132	3131	3116	3104	3098
5	15	3124	3123	3108	3096	3090
6	20	3097	3096	3081	3069	3063
7	35	3050	3049	3034	3022	3016

these overpull depths with the depths of the stringers, the end depth of the stringers should be used, because that is where ledges that cause trouble when tripping out are formed. Another factor to take into account is the additional elongation of the drill string when tripping out compared to when drilling, which is covered in chapter 2.3. The stringer depths were registered while drilling, and for this reason the pipe was more compressed here than when the overpulls were registered while pulling out. The elongation for each overpull was calculated using Equation (2.1), assuming that the additional elongation of the pipe is only caused by the difference in hook load while drilling and while tripping at the same depth. The pipe stretch constant were found in Tech Facts Engineering Handbook assuming a 5½" 21.9# drillpipe were used. The pull on the pipe to be used in (2.1) then yields:

$$P[ton] = HKL_{tripping} - HKL_{drilling} \tag{5.1}$$

The hook loads were read manually from the real time drilling data available. The $HKL_{tripping}$ was read while the block was moving up at constant velocity with a stable hook load right before it started increasing. The $HKL_{drilling}$ was read when drilling that exact depth earlier in the operation. The results from these calculations are presented in Table 5.9. The next step was to find which of the five

TABLE 5.9: Pipe elongation caused by different tension in pipe above the BHA while drilling versus tripping. The pipe length was set to 3000 m.

Overpull Number	$HKL_{drilling}$ **[ton]**	$HKL_{tripping-out}$ **[ton]**	ΔHKL **[ton]**	**Elongation [m]**
1	150	192	42	1.6
2	148	193	45	1.8
3	155	192	37	1.5
4	152	192	40	1.6
5	150	165	15	0.6
6	155	190	35	1.4
7	145	169	24	1.0

depths for each overpull that was closest to any of the stringers listed in Table 5.7. Obviously the stringer has to be above the depth of overpull since the pipe is moving upwards. The difference in depth between them was calculated and then the elongation was subtracted from it resulting in a final deviation. The results for each overpull are listed in Table 5.10.

Table 5.10: Overpulls related to the closest stringer and their depth deviation taking pipe elongation into account.

Overpull Number	Depth [mMD]	Stringer Depth[mMD]	ΔDepth [m]	Elongation [m]	Deviation [m]
1	3175.4	3173	2.4	1.6	0.8
2	3128.7	3128	0.7	1.8	-1.1
3	3143.0	3141	2.0	1.5	0.5
4	3116.4	3113	3.4	1.6	1.8
5	3090.1	3087	3.1	0.6	2.5
6	3081.4	3073	8.4	1.4	7.0
7	3021.7	3021	0.7	1.0	-0.3

Hook Load Signal Analysis

The hook load signal for overpull number 4 and 5 from Table 5.8 is shown in Figure 5.7. The overpulls are marked by yellow lines, and the red boxes to the right are containing bit depth at that instance. The first two overpulls are experienced at the same depths, 3145.4 mMD, and then there are three more overpulls higher up, all located at about the depth of 3133 mMD. All of the overpulls are sudden with a steep slope and the weight increase is stable. When running into hole again no took weight is seen and the weight is decreasing linearly. The hook load signals for the rest of the overpulls listed in Table 5.8 are included in Appendix A.2.

Discussion on Cause of Restriction

The main proof for the restriction being caused by ledges is that there are many limestone stringers in this part of the wellbore section. Figure 3.9 shows how ledges are formed due to layers of hard rock in soft formations. Back-reaming showed that the hole conditions improved higher up in the well, probably because there was no limestone stringers there. When circulating and back reaming through the problem zone no remarks on cuttings on shakers were reported, while large amounts of cuttings were observed when reaching a depth of 2273 mMD. Considering cuttings transport mechanism in medium inclined wells, covered in chapter 3.1.1, and the time it takes for the cuttings to reach surface these could come from the problem zone. However, it is not likely that cuttings beds caused the problems. The last hour of drilling before reaching TD suffered extremely low ROP, which combined with a flow rate of about 4000 lpm and a rotation of about 150 rpm should not leave more than an acceptable cuttings concentration along the wellbore wall. Also, most of the cuttings coming over the shakers during this event were newly generated from pipe rotation, which strengthens that theory. The average dogleg is low and should not cause any trouble.

A strong proof of ledges causing the restrictions exists. Table 5.10 shows that 6 out of 7 overpulls can be directly related to a stringer. All of them are deviating from the exact position of the stringer, but 6 of them are in within the limit of what should be accepted. The depths of the overpulls are taken from the daily report and is the depth the driller registered. It is of high relevance when the depth was registered during the event. If the depth was registered when the overpull was at its maximum, let us say 30 ton, the pipe would be in an additional stretch of 1.2 m compared to before the hook load started to increase. This will therefore be an important source of information. Another source of deviation in the data is the depths of the stringers. All of the stringers have depths given in integers, which is indicating that these depths are not exact. Also, the measurement itself of when the stringer ends is assumed not to be precise, but rather include errors. Overpull number 5 has the highest deviation, of 2.5 m, of those 6 related to stringers. Considering the possible sources of error mentioned above it seems reasonable to say that it is caused by the stringer. On the other hand, overpull 6 has a deviation of 7 m between the location of the stringer and the depth of overpull and it is not reasonable to think that the errors mentioned above could be that high.

Notice that the stringers may have caused more trouble than the overpulls. There was no progress in drilling the last hour, which could be caused by stabilizers hanging on ledges. It is possible to look at the WOB measured downhole to confirm this, but that data was not available in this study. Considering the fact that the bit came out with minor wear and that the stabilizers had suffered significant wear on the low side and in the middle. Limestone stringers were present both at 3214 mMD and 3227 mMD and when drilling at 3244 mMD the beginning of the Roller Reamer was positioned at approximately 3213 mMD and could have been hanging on a ledge resulting in no ROP.

The hook load signal for the overpulls are of the type that has been described for ledges in previous work done; a sudden and stable increase in hook load with a steep slope. Thus, the hypothesis of ledges causing these overpulls becomes stronger.

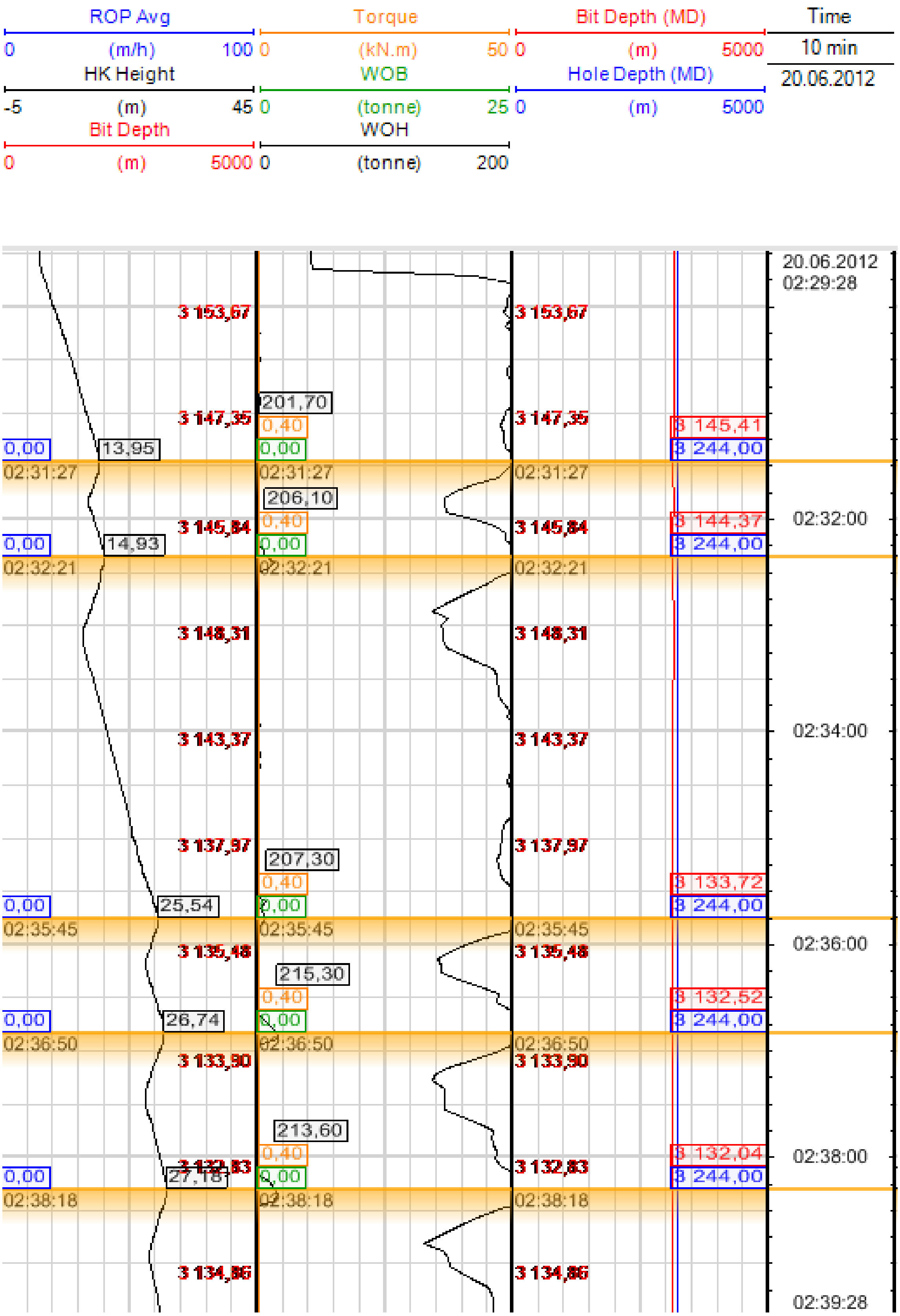


FIGURE 5.7: Hook load signal for ledges causing overpull.

5.2.3 Well A-12 T2 - Cuttings Accumulation

In well A-12 T2 problems occurred that are related to cuttings accumulation. Information about the well is listed in Table 5.11.

TABLE 5.11: Wellbore information for well A-12 T2 in the interval of cuttings accumulation.

Probable Cause	Cuttings accumulation
Operation	Tripping out
Depth	2600 mMD
TD well	2818 mMD
Casing shoe	1021 mMD
Inclination	49°
Average Dogleg	$2.93°/30m$
BHA length	212 m
Max pore pressure gradient	1.02 g/cm^3
Mud pressure gradient	1.40 g/cm^3
Formation	Sandstone with minor claystone interbeds

Event Description

Took 15 ton overpull at 2600 mMD (Figure 5.8), 50 meter above kick off point for the sidetrack. Ran in below restriction and pulled through without further problems.

Remarks While Drilling Before the Event

Drilled with a flow rate of 3850-4500 lpm, a rotation of 80-170 rpm and an ROP of 2-20 m/hr. Experienced lateral vibrations when drilling with a rotation of 150+ rpm, which reduced when reducing to 130 rpm.

Hook Load Signal Analysis

The hook load signal (WOH), shown in Figure 5.8, shows an increasing trend until it finally results in a final overpull at approximately 2598 mMD. A trend line is drawn in the plot to emphasize the increasing trend. The signal is fluctuating with increasing amplitude before the final overpull. The plot shows a stable signal when running into hole again with no took weight. When pulling out of hole again the signal is more stable except for one small peak, circled in Figure 5.8, which more or less self-rectifies. After the peak the signal is slightly above normal until 2590 mMD where it stabilizes at normal weight, 175 ton. Normal weight, 175 ton, is also seen in Figure 5.9, which is the signal for tripping the following stand and it is included for comparison.

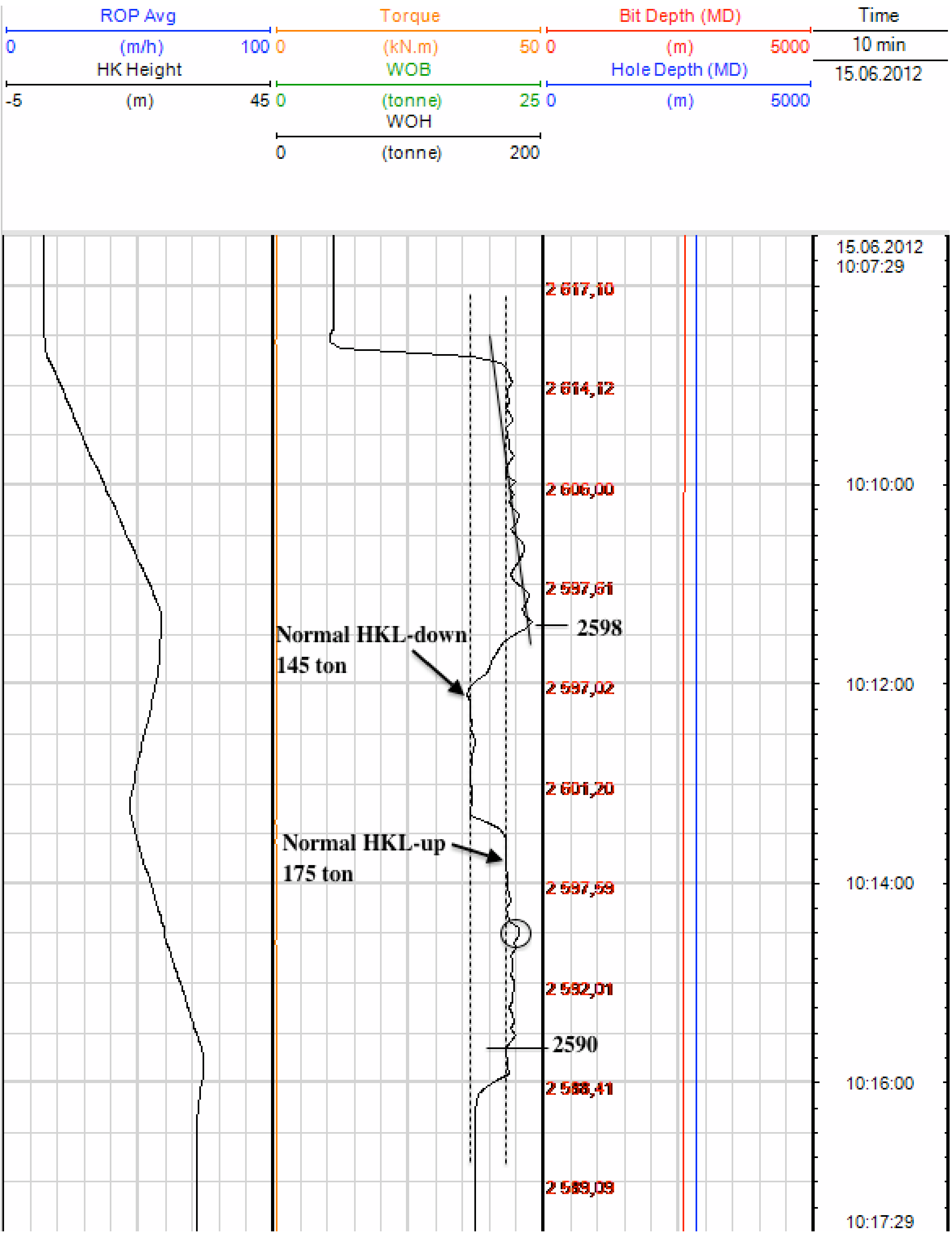


FIGURE 5.8: Hook load signal for cuttings accumulation.

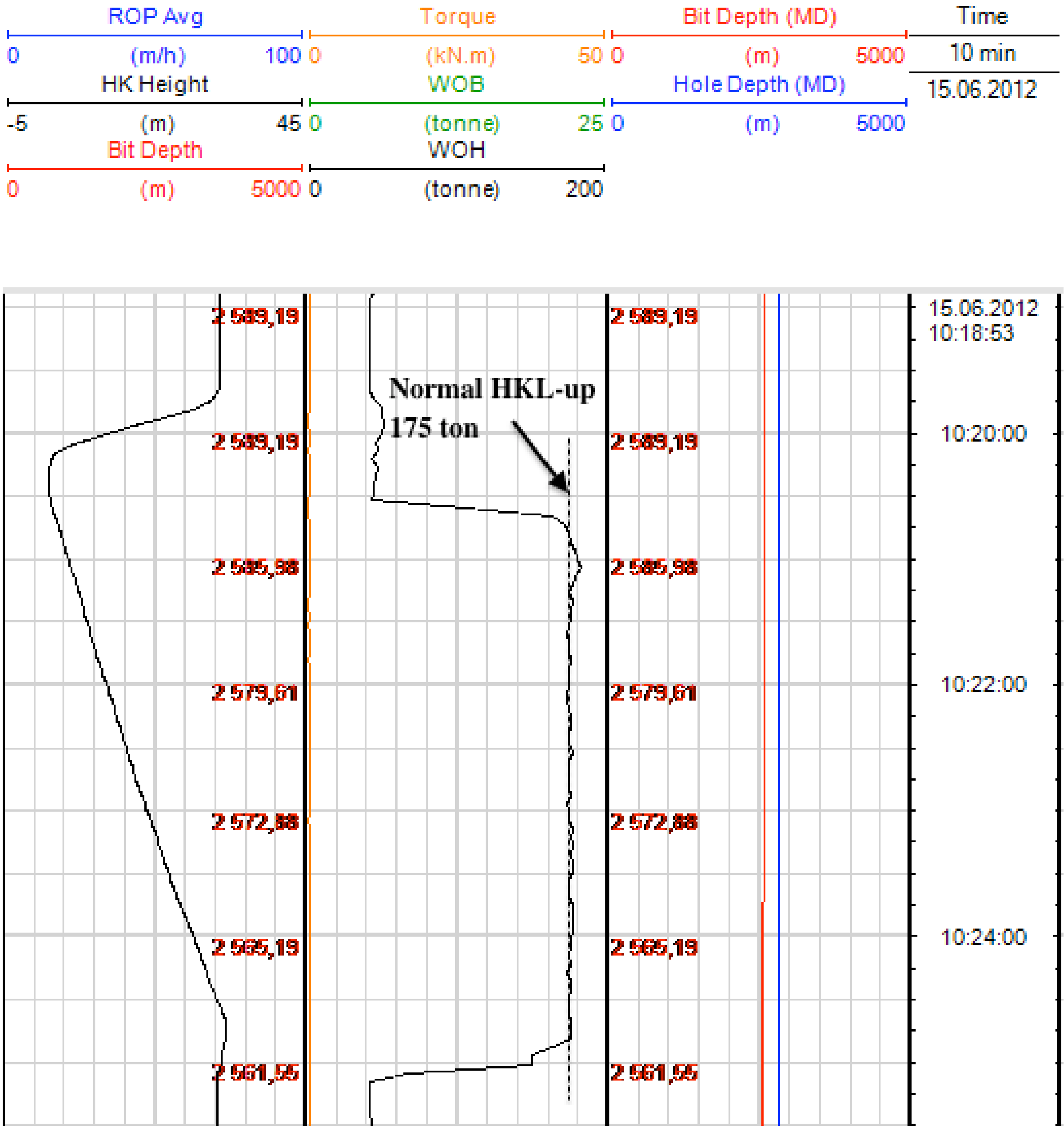


FIGURE 5.9: Normal hook load signal one stand after the stand that experienced overpull.

Discussion on Cause of Restriction

The hook load signal is obviously the most important proof of the restriction being caused by cuttings accumulation. In the case of ledges and key seats the hook load signal would show a very rapid increase, normally without fluctuations, due to string hanging onto something at a specific depth. However, in this case the overpull is building up over several meters and the WOH is fluctuating. The fluctuations is probably a result of something being pushed along with the BHA when pulling, thus a moveable restriction. Fluctuations could also be caused by an uneven wellbore, but the increasing trend indicates that something is building up, e.g. cuttings.

The inclination of 49° proves that cuttings can accumulate along the wellbore. It is very close to the critical angle of 50°, where cuttings stops sliding and accumulates (ref. Section 3.1.1). There are no overpulls or increasing drag when pulling the stand above or below the restriction, which indicates that the restriction is present only along this specific pipe stand. Cuttings beds also have the property of almost completely disappear when moving the string down again due to the fact that they are moveable. While drilling this section the parameters were most of the time within the limits of what K&M-Technology (2011) recommends for sufficient hole cleaning (120 rpm, ref. Section 3.1.1). Based on all these facts it is likely that cuttings have avalanched creating a cuttings bed that caused the restriction.

5.2.4 Well A-12 - Differential Pipe Sticking

Problems that occurred in well A-12 are being related to differential sticking, which is caused by high pressure differences between the wellbore and the formation pore pressure. Information about wellbore conditions are listed in Table 5.12.

TABLE 5.12: Wellbore information for well A-12 in the interval of differential sticking.

Probable Cause	Differential pipe sticking
Operation	Tripping out
Depth	3100 mMD
TD well	3102 mMD
Casing shoe	1021 mMD
Inclination	56.7°
Average Dogleg	$0.67°/30m$
BHA length	212 m
Max pore pressure gradient	1.02 g/cm^3
Mud pressure gradient	1.40 g/cm^3
Formation	Sandstone with claystone interbeds

Event Description

Pulled 90 ton overpull right after a 15 minutes flowcheck and the pipe came loose. The hook load signal is presented in Figure 5.10. For the next two stands pulled the weight fluctuated between 180, which is normal HKL up weight, and 215 ton and overpulls were experienced in the beginning of each stand (Figure 5.10 and Figure 5.11). When starting to pull the last stand the up weight rapidly increased to about 230 ton followed by a sudden drop to 165 ton (Figure 5.11), which was 15 tons lower than normal up weight. After that no more overpulls were seen and the hook load stabilized at about 165 ton when pulling. When the string came out of hole it was found that the string had parted in the jar and 90 m of the BHA was left in the hole.

Remarks While Drilling Before the Event

The last hours of drilling before the event were associated with low ROP. First because one mud pump was down, then because of a hard stringer. Before drilling the last 0.4 m of formation, 45 minutes were spent reaming the area from 3080 to 3101 mMD. The area was reamed with a flow rate of 4022 lpm and rotation of 135 rpm. No stringers are reported in the area of overpull except for the one at the last two meters of the section.

Hook Load Signal Analysis

Figure 5.10 shows the overpull on the first stand. The overpull happens imidiately when starting to pull upwards at 3099 mMD after a 15 minutes period of still standing. After the overpull the signal is somewhat stable, only with small fluctuations. Figure 5.11 shows pulling of the second stand with an overpull in

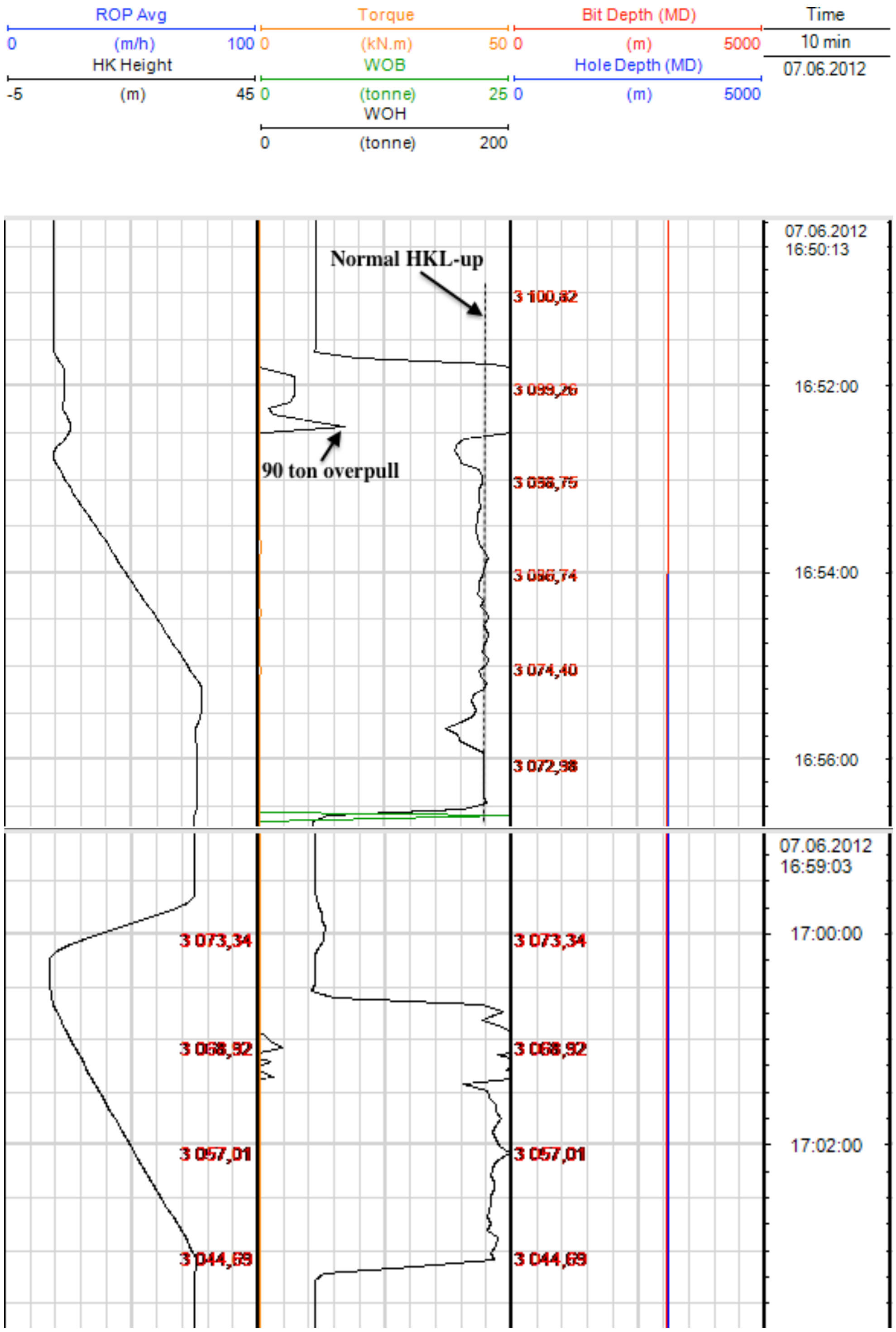


FIGURE 5.10: Hook load signal for differential sticking at 16:51:45 and 17:00:45.

the beginning of the hoisting at 3068 mMD. The weight is stabilizing afterwards except for one small overpull in the middle of the stand. When pulling the third stand the weight acts a bit different, seen in top of Figure 5.11. The overpull at the beginning of the hoisting is present at 3041 mMD, but it is also one at the end of the stand at 3024 mMD. The bottom of Figure 5.11 shows pulling of the last stand, where the hook load rapidly increasesto 40 ton over the normal at 3016

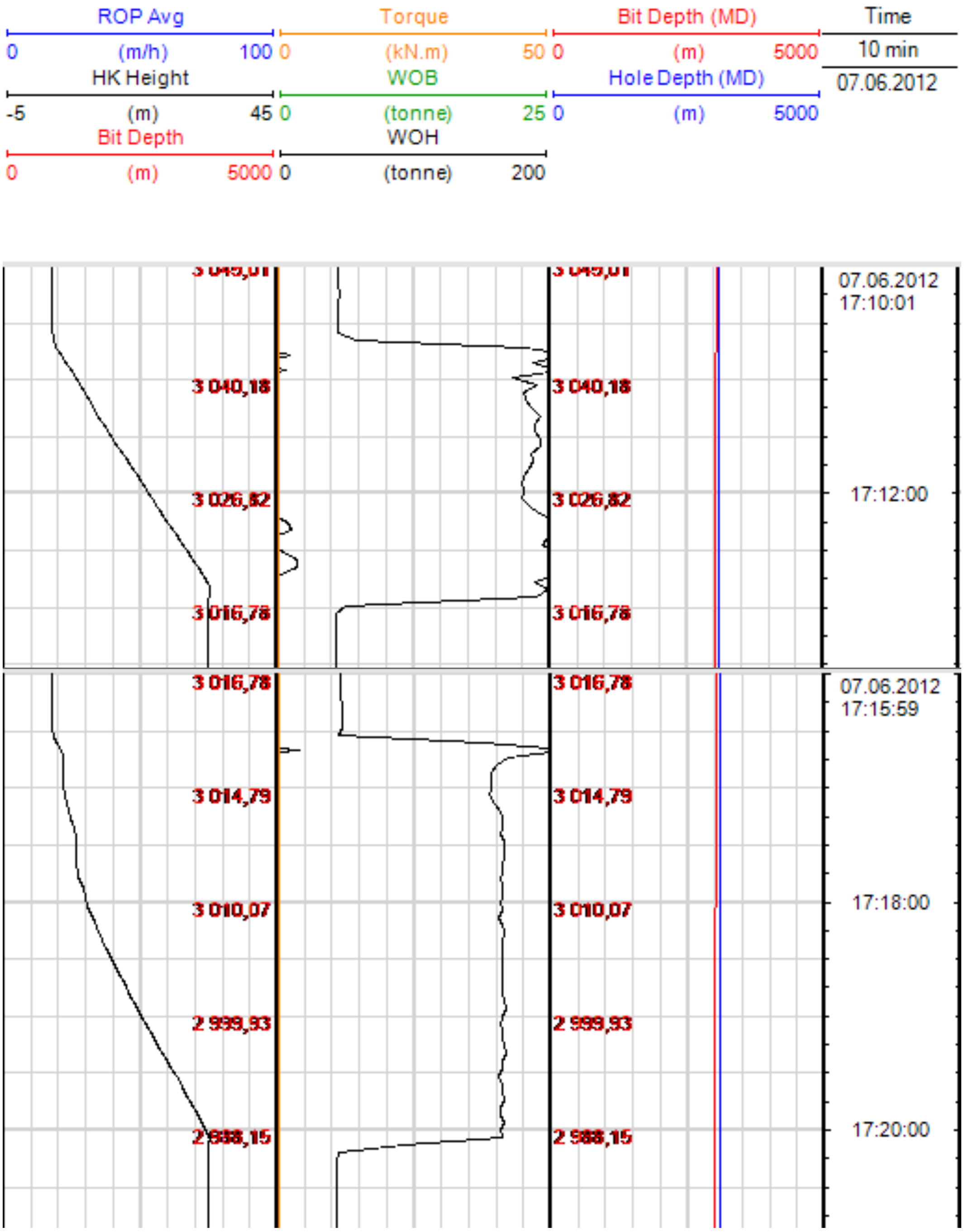


FIGURE 5.11: Hook load signal for differential sticking at 17:10:50 and 17:16:40. The last one is the stand where the string parted.

mMD and is followed by a rapid drop and then the weight stabilizes. The signal throughout the rest of the stand is more stable than what is seen in the previous three stands that were pulled.

Discussion on Cause of Restriction

The weight signal together with the 15 minutes static period before the overpull is the strongest proof of differential sticking. Differential sticking is a static time dependent phenomena and is visible in the transition from static to dynamic conditions, as stated in Section 4.4. It is likely to believe that the 90 ton overpull damaged the jar when pulling the first stand since the string parted in the jar. Each of the following three stands experienced overpull when starting to pull, which can be related to differential sticking. However, the overpulls during dynamic conditions while hoisting must be caused by something else than differential sticking. It might has something to do with the damaged jar since the signal becomes very stable after loosing 90 m of the BHA from the jar and down.

The conditions necessary for differential sticking to occur are present. The formation in this problem zone is sandstone which is permeable. The well is in a relatively high overbalance of 0.38 g/cm^2, which at this depth gives a differential pressure between the wellbore and the formation of 115.6 bar. The inclination of 56.7° causes the string to be in contact with the wellbore walls and thereby facilitates differential pipe sticking. Results from a filtration test of the drilling fluid could be useful to strengthen this theory, but unfortunately it was not available for this study.

By comparing the type curve for differential sticking, in Figure 4.4, to the signal in Figure 5.10 similarities are found. It can also be compared to the signal for ledges, i.e. fixed restrictions. However, here tension and stretching is transferred to the pipe until it exceeds the force that is holding the pipe up against the wall and the string releases. Thus, tension in pipe is released while moving string out of hole.

5.2.5 Well D-3 - Local Dogleg

The problems in well D-3 is being related to a local dogleg, a high local change in inclination causing sharp bends. Information about the wellbore conditions is listed in Table 5.13.

Table 5.13: Wellbore information for the interval of high local dogleg in well D-3.

Probable Cause	Local Dogleg
Operation	Tripping out
Depth	2208-2185 mMD
TD well	2626 mMD
Casing shoe	1242 mMD
Inclination	65.6°
Average Dogleg	$4.1°/30m$
BHA length	196 m
Max pore pressure gradient	1.40 g/cm^3
Mud pressure gradient	1.47 g/cm^3
Formation	Shetland group; Chalk facies of chalky limestones, marls, calcerous shales and mudstones.

Event Description

Tight spots from 2208 mMD to 2185 mMD. Took 37 ton overpull due to heave on rig, were not able to pass through. The hook load signal for the overpull interval is presented in Appendix A.3 and the interval from 2213 mMD to 2204 mMD is shown in Figure 5.12. Ran into hole with 3 stands and reamed the interval from 2240 mMD to 2258 mMD. Pulled through interval without further problems.

Remarks While Drilling Before the Event

One stringer was reported at 2133-2137 mMD. The last large diameter component of the BHA was placed 26.4 m behind the bit. Doglegs for the interval are presented in Table 5.14. Drilled from 2123 mMD down to TD with a ROP of 10-30 m/hr, a rotation of 120-180 rpm and a flow rate of 3400-4800 lpm. Reamed area from 2123 mMD to 2179 mMD because of high dogleg and washed down to 2201 mMD.

Hook Load Signal Analysis

The hook load signal for the event is shown in Figure 5.12. For comparison the signal before the restriction occurred is presented in Figure 5.13. The signal for the

Table 5.14: Dogleg severities in the area around and inside the problem zone.

Depth [mMD]	**Dogleg Severity [°/30m]**
2232	2.5
2205	4.1
2179	4.5
2150	3.7

restriction is quite unstable, which probably have something to do with operating from a floating unit. Comparing it with the signal before the restriction, it shows a more unstable signal. A typical frequency of sea waves is one every 10-15 s, which means 4-6 waves/minute[1]. In Figure 5.13 an interval of 1 minute is marked with an arrow and within this interval 5 peaks are found, which are numbered in the figure. As their frequency coincides well with the wave frequency it is concluded that the rig heave is the cause. There are four overpulls at the same depth of 2204 mMD followed by two overpulls at 2202 mMD. Looking at the signal type it has the properties of a fixed restriction signal, e.g. ledge signal. The first two and the last overpulls have a relatively straight increase in weight, while the two middle overpulls are more unstable. Again it is important to remember that the well is drilled from a floating rig, which means that while tripping the string will move up and down with the rig because of waves. The heave compensator is not active during normal tripping operations. The two signal peaks on the third overpull could be explained by the rig moving upward and then down again while hoisting up at constant velocity. The hook load signals for the rest of the overpulls experienced in the interval 2208-2185 mMD are included in Appendix A.3.

In Section 3.6 concerning local dogleg it was mentioned that the drag will increase when the BHA is pulled through the interval of local dogleg due to its higher stiffness. In this case, with a BHA length of 196 m, an increase in drag, i.e. hook load, should be visible at around 2404 mMD. An illustration of the BHA being pulled through the local dogleg area is found in Figure 5.14. The first illustration shows when the BHA is entering into the local dogleg interval and the bit depth is 2404 mMD. In the second illustration the last 26 m of the BHA, containing large diameter components, are entering the local dogleg area. Figure 5.15 shows a real-time hook load signal starting at 2484 mMD up to the area where the tight spots started at 2209 mMD. The purple dashed line indicates the hook load at the

[1]Personal communication with P. Skalle. 2013. Trondheim: NTNU.

depth where pulling of the BHA through the tight area starts, at approximately 2404 mMD. The red dashed line indicates the hook load at 2250 mMD, 41 m before the tight area with the local dogleg starts. The hook load will normally decrease when tripping out of hole due to less pipes, i.e. weight, being suspended from the hook. In this case it is clear that the hook load is increasing in the interval shown. Just before the tight area starts the hook load has increased with almost 20 ton.

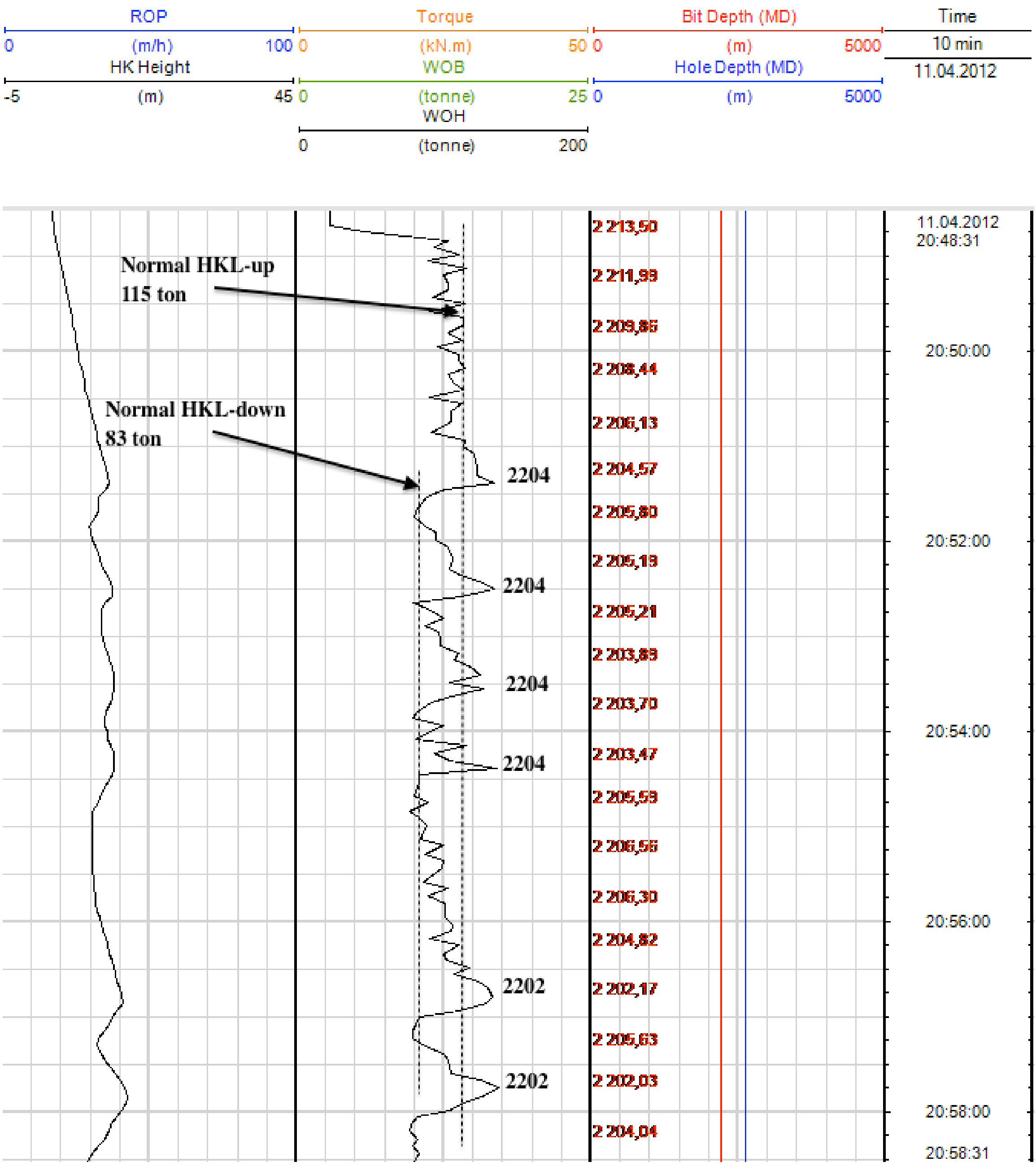


FIGURE 5.12: Hook load signal for dogleg.

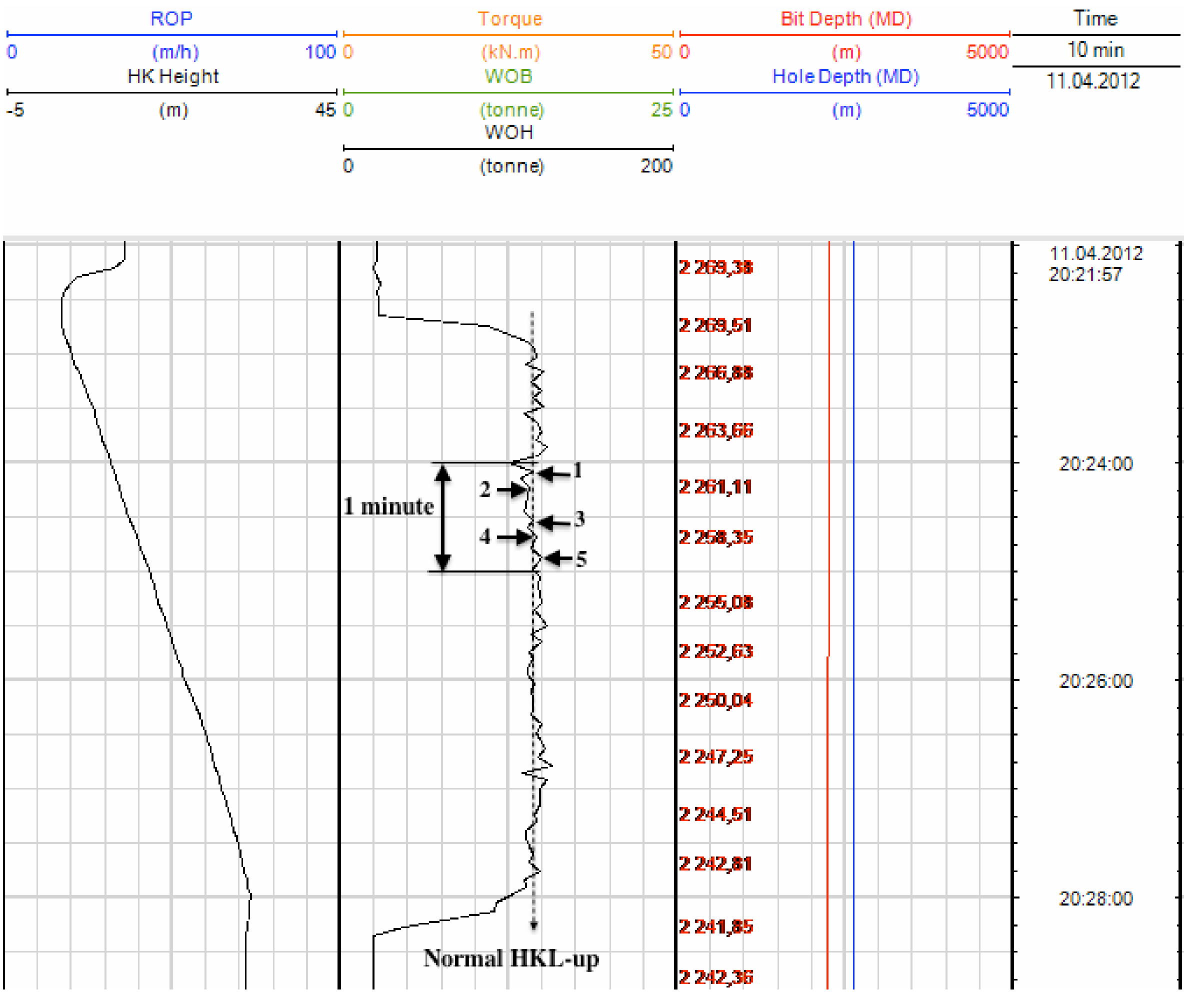


FIGURE 5.13: Normal unrestricted hook load signal for the same well right before the restriction was encountered. The number marks indicates peaks caused by heave on the rig.

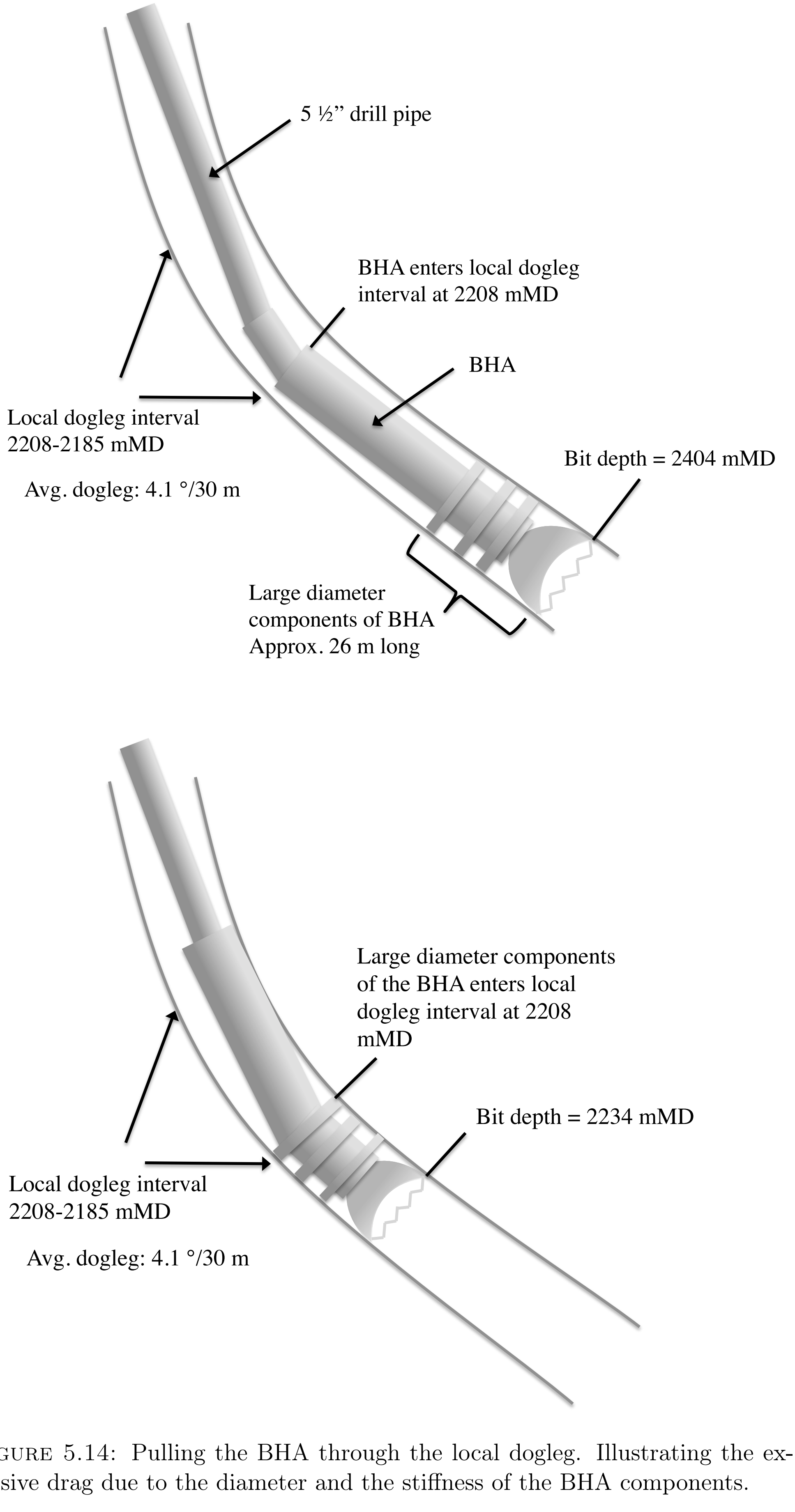


FIGURE 5.14: Pulling the BHA through the local dogleg. Illustrating the excessive drag due to the diameter and the stiffness of the BHA components.

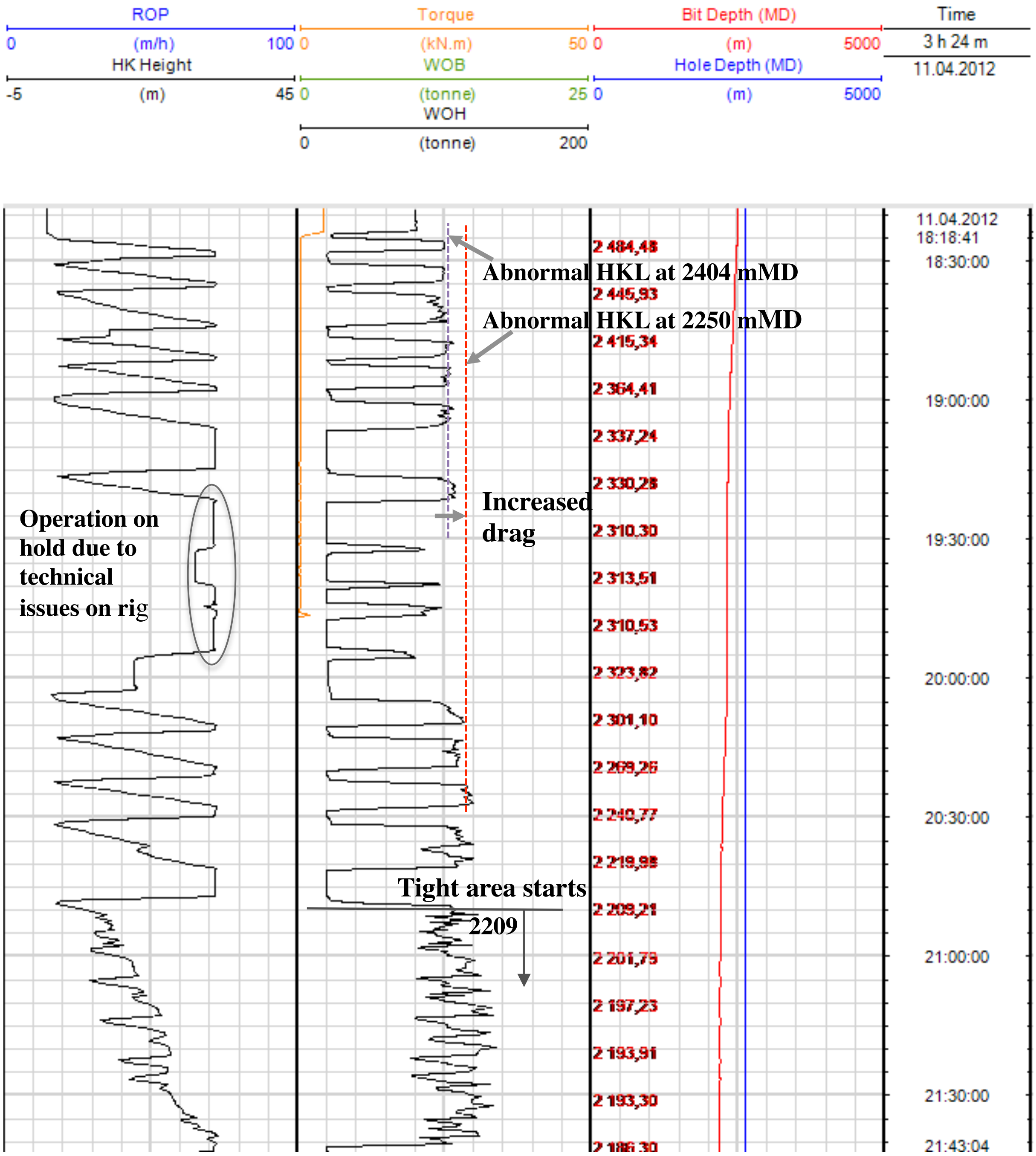


FIGURE 5.15: Real-time hook load signal for tripping the interval before the area of high local dogleg, 2484-2208 mMD. An increased drag is seen in the area where pulling of BHA through the local dogleg starts at about 2404 mMD, indicated by the purple dashed line. The blue dashed line indicates the unrestricted normal hook load up at that depth, while the red dashed line shows the hook load right before the tight area starts.

Discussion on Cause of Restriction

The main proof of high dogleg being the cause is that the dogleg read from the file actually is high in this exact interval with a range from 4.1 °/30 m to 4.5 °/30 m. The dogleg is decreasing both above and below the problem zone, which indicates dogleg being the cause of the restriction. In Section 3.6 it states that problems with high doglegs are often related to key seats, which behaves similar to ledges. That means that they appear in the same locations in the well and the signal is sudden with a steep slope, i.e. a fixed restriction. The signal analysis in the section above proves both of these facts, which makes it even more likely to be caused by local dogleg. The increasing drag when the BHA entered into the zone of local dogleg is also strengthening the conclusion. The drag increased even more when the bit was 30-40 m below the tight spots. The large diameter components of the BHA has a higher stiffness than the rest of the BHA. Knowing that these are within 26 m above the bit, the increase in drag above the tight spots could be related to a stiffer BHA being pulled through it.

6 | Evaluation of Results

The results presented in the previous chapter led to several findings. These are summarized and discussed in more detail here.

6.1 Physical Interpretation of Signatures

In Section 5.2 two main types of signatures were identified. The two types could be related to fixed and moveable restrictions. Thus, a restriction that is fixed to one point in the well and one that can be moved up or down in the well. From here on the complex analysis is simplified by merging the five categories presented in Section 5.2 into the two main types of signatures. The following physical interpretations of the signatures are done according to the hook load theory and descriptive figures presented in Chapter 2. The goal of this interpretation is to relate the signatures to physical phenomena, making the conclusion more reliable.

6.1.1 Fixed Restriction Signature

The signature for a restriction caused by ledges, i.e. fixed restriction, is shown in Figure 6.1 together with the block position. The signature plot is divided into six parts marked with numbers and are interpreted as follows:

1. *Acceleration of drill string.* This part of the signal is where the hoisting up motion starts, i.e. the acceleration phase.
2. *Constant hoisting velocity.* At this part of the signal the drill string is hoisted at constant velocity without any restriction downhole, thereby the weight is constant.

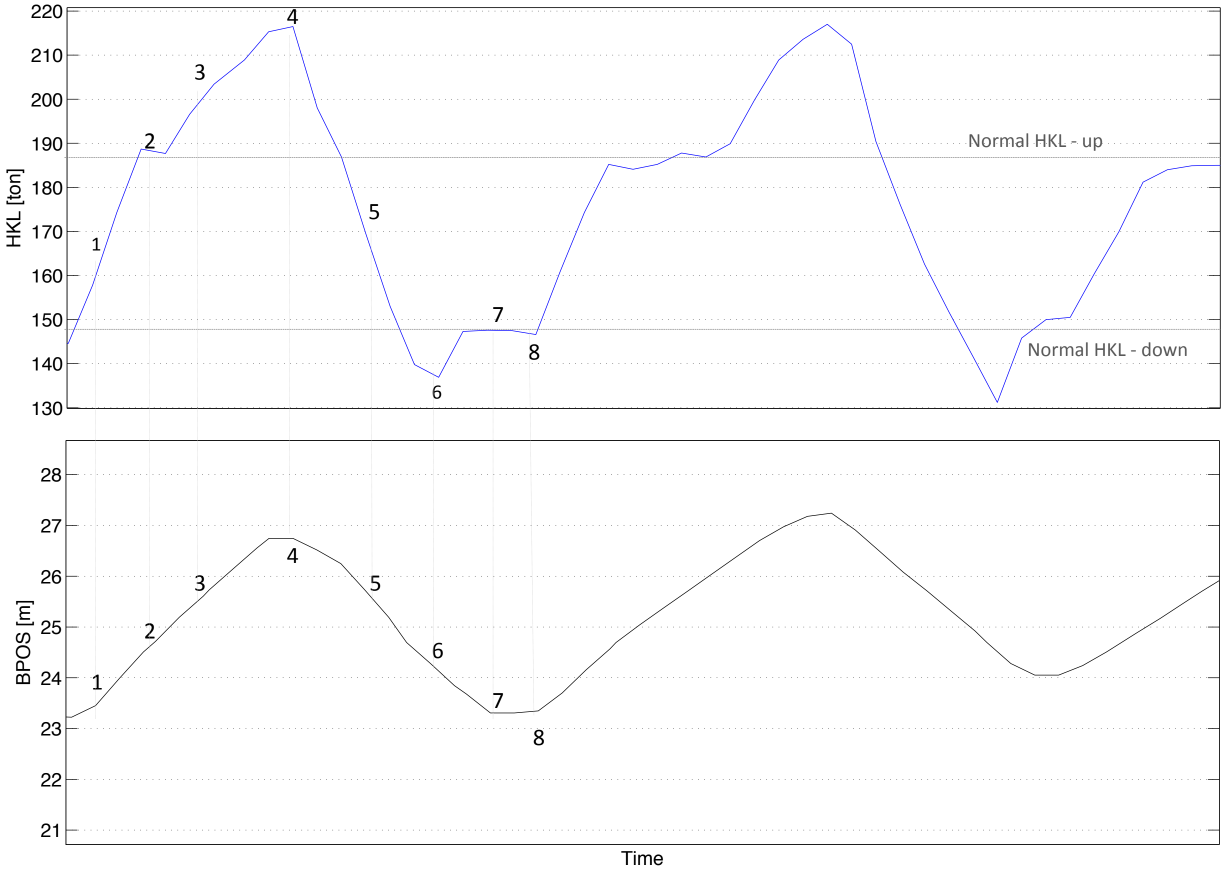


FIGURE 6.1: Hook load (HKL) signature for a fixed restriction, here ledge, together with the block position (BPOS). Lines for normal unrestricted HKL while pulling up and down are indicated and related numbers of the different parts of the signal are shown. The signal is taken from Figure 5.7 and the time coincides vertically for both plots.

3. *Pipe stretching.* This part of the signal is governed by pipe stretching. The ledge is restricting the movement of the drill string and the change in block position from this point on is equal to the pipe elongation, causing a linear trend.

4. *Transition between POOH and RIH.* This peak represents the maximum overpull and maximum stress exerted on drill string. This is the point where the driller decides to stop the stretching and lowers the string back into the hole again.

5. *Release of pipe tension.* At this part of the signal the drill string tension is released by running into hole again. The length of the drill string is reduced until the next point below is reached.

6. *Negative peak due to reduction in pipe elongation and static friction effects.* This peak is a result of the reduction in pipe elongation together with the static friction effects. The peak represents the point where the static friction threshold is exceeded and the complete drill string starts accelerating downwards. The peak is followed by an increase in weight due to the transition from static to dynamic conditions. It should be noted that the drill string is moving into hole with constant velocity when reaching 7, i.e. the string moves freely downwards.

7. *Transition between RIH and POOH.* This is the part where the drill string movement goes from running into to hole to pulling out of hole.

The hook load signal in phase number 3, which is governed by pipe stretching, can be expressed by Equation 6.1:

$$\Delta HKL = \frac{\Delta BPOS \cdot 10^5}{MD_{OP} \cdot C_{pipe} \cdot 0.0254} \tag{6.1}$$

The formula is derived from Equation 2.1 and is a measure of how the hook load will change with changing block position when the pipe is fixed at a restriction at a depth equal to MD_{OP}. C_{pipe} is a constant for that particular drill string, and thereby the expression can be rewritten as:

$$\Delta HKL = \Delta BPOS \cdot C \tag{6.2}$$

where C is a constant and yields

$$C = \frac{10^5}{MD_{OP} \cdot C_{pipe} \cdot 0.0254}. \tag{6.3}$$

This proves that the hook load is proportional to the block position during stretching, thus the hook load signal should be linear. In part number 4 of the plot the hook load and the block position should have the same relationship as presented above, because it is also governed by stretching effects. Calculating the stretch for the overpull numbered in Figure 6.1 gives a stretch of 1.2 m assuming a 5½" 21.9# drill pipe. Stretch for same drill pipe type when subjected to additional load are presented in Table 6.1 for different lengths of drill pipe. Looking at the block position in Figure 6.1 from stretching starts until it stops the block has moved

Table 6.1: Typical stretch of 5 ½ " 21.90# drill pipe for different length of drill pipe; 1000 m, 2000 m, 3000 m and 4000 m.

Length	1000 m	2000 m	3000 m	4000 m
ΔHKL [ton]	ΔL [m]			
5	0.06	0.1	0.2	0.3
10	0.1	0.3	0.4	0.5
15	0.2	0.4	0.6	0.8
20	0.3	0.5	0.8	1.0
25	0.3	0.6	1.0	1.3
30	0.4	0.8	1.1	1.5
35	0.4	0.9	1.3	1.8
40	0.5	1.0	1.5	2.0
45	0.6	1.1	1.7	2.3

about 1.8 m. There is a deviation of 0.6 m from calculated value to actually value read from the plot. That is probably errors related to the stretch constant because it is unknown what pipe was used.

6.1.2 Moveable Restriction Signature

The moveable restriction signature is presented in Figure 6.2, which is from the case of cuttings accumulation that was presented in Section 5.2.3. The signal is much more unstable and is hard to predict or express through formulas as was done with the fixed restriction signature. As seen in the first part of the signal there is an increasing trend together with an unstable signal. Looking at the block position it shows that the increase happens over an interval of about 11 m. Considering this length together with the weight increase of 15 tons it is clear that the whole drill string is moving upwards during the interval. Especially when the fixed signal in Section 6.1 showed a weight increase of about 30 tons when moving the string only 2 meters. The signal is interpreted as cuttings that are shoveled upwards, probably by the larger diameter components of the BHA. The increasing trend is governed by an increasing pseudo friction factor. The peaks of the unstable signal is interpreted as the drill string stops moving for a short while due to cuttings accumulation until the additional tension exceeds the threshold for moving those cuttings. The following negative peak is governed by excessive acceleration and compression. Each new peak has a higher value than the previous one, indicating that more and more cuttings are shoveled resulting in an increasing

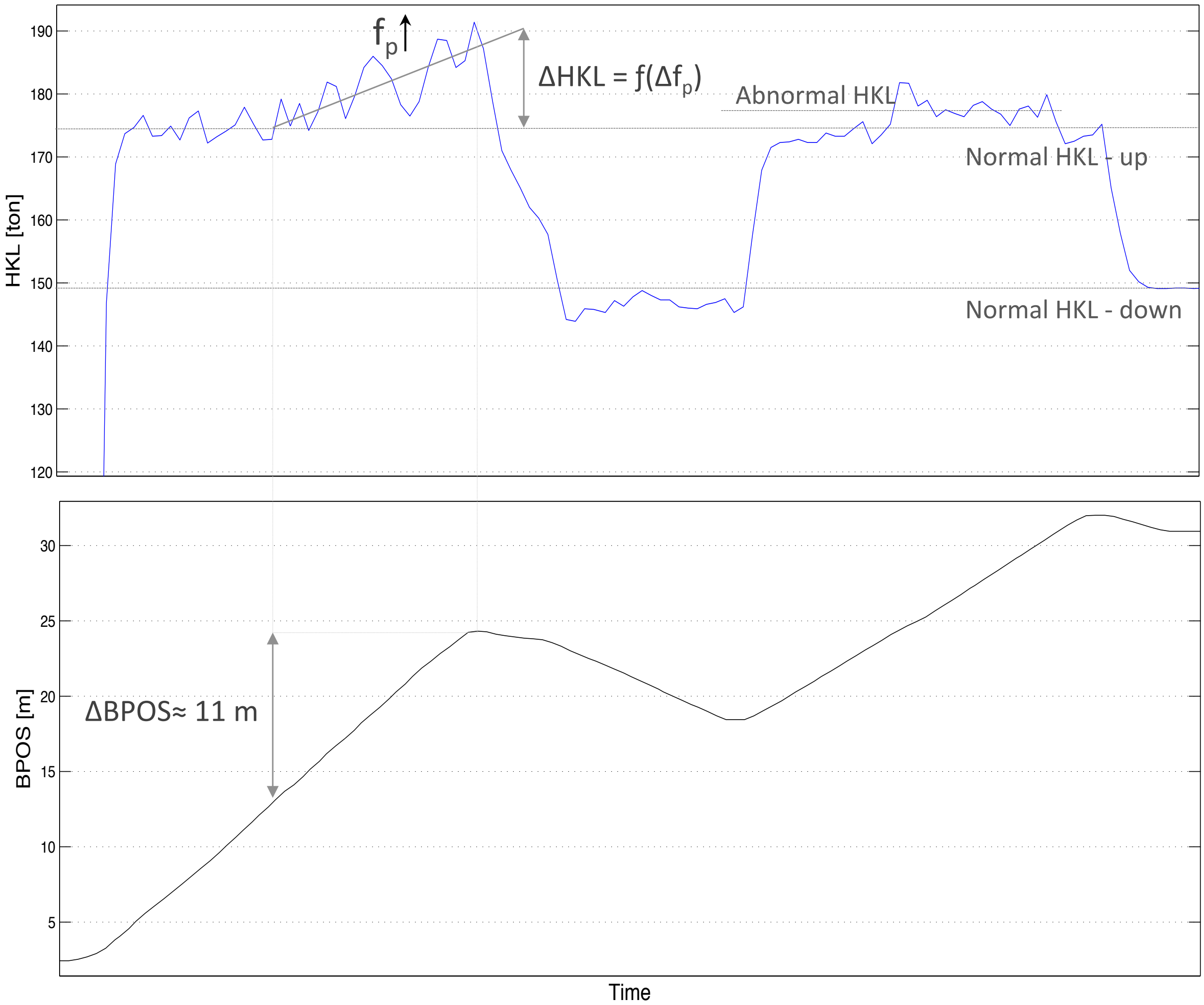


FIGURE 6.2: Hook load (HKL) signal for a moveable restriction, here cuttings, together with the block position (BPOS). Lines for normal unrestricted hook load up and down, and one for the abnormal hook load are indicated.

pseudo friction factor. Thus, the increase in hook load (ΔHKL) is a function of the pseudo friction factor, f_p.

When running into hole again the weight decreases just as for the fixed signal only the negative peak at the bottom is much less visible than what it was for the fixed signal. This negative peak has already been interpreted as an effect of pipe compression and static friction threshold. In the case of the fixed signal the pipe was assumed to be free when moving downwards, while in this case the pipe is not completely free when moving downwards due to the cuttings bed. When the static friction was overcome the weight did not go straight up to the normal HKL down line, but rather stayed unstable at lower weight values. Thus, if the restriction allows fully unrestricted movement downwards that negative peak will probably stand out clearly. In this case it did not.

In the beginning of the plot, before the increase in HKL, the weight follows the normal HKL up line, though with some instabilities. Overall it is not increasing, which indicates that the cuttings are not shoveled along with the string, but rather stays in place after each peak. The same tendency is seen on the last part of the plot, only here the first big peak leads to an increase that causes the signal to oscillate around an abnormal HKL line, thus an increased f_p. This indicates that cuttings are shoveled by the string, but the amount of cuttings shoveled is not increasing as was seen earlier in the plot.

6.1.3 Main findings: Fixed- vs. Moveable HKL Signature

This section sums up the main findings in the physical interpretation of the signals for fixed and moveable restrictions.

Fixed Restrictions

- Overpull signal is governed by the formula for pipe stretching, which gives a linear line. At this depth the stretch was up to 1.8 m at 28 ton.
- Negative peak, compared to normal HKL-down, after running into hole again is strong due to the drill string movement down is unrestricted.

Moveable Restrictions

- Overpull builds up less rapid over several meters because the drill string is moving downhole. The buildup is governed by shoveling of increasing amounts of cuttings/cavings.
- The signal is unstable because of all the loose material, causing sort of a stick-slip behavior. The drill string stops moving when restricted by the material until the tension is high enough to either shovel the material in front and/or slide over it. This is followed by a decrease in hook load because of excessive acceleration caused by compression of drill string.
- Two types: Abnormal hook load level due to shoveling of cuttings/cavings and hook load build-up due to shoveling of increased amounts of cuttings/-cavings.

6.2 Distinguishing Between Causes of Restriction

The 5 restrictions from the post-event analysis can be divided into the two type groups as shown in Table 6.2. As the table shows it should be possible to distinguish between several groups of restriction by analyzing the hook load signal with regards to fixed or moveable signatures only. Taking into account that differential sticking has its own signature it should be possible to distinguish between the following 4 groups of causes:

TABLE 6.2: Causes of restrictions and their belonging type of restriction.

	Restriction Type	
Cause of Restriction	Fixed	Moveable
Unstable Formation	X	X
Ledges	X	
Cuttings Accumulation		X
Differential Sticking	X	
Local Dogleg	X	

1. Ledges, Local dogleg
2. Cuttings accumulation
3. Unstable formation
4. Differential sticking

Ledges and local doglegs are hard to distinguish between by only looking at the signal. That is because keyseats and ledges are causing the same fixed restriction signature. However, local doglegs may cause an increased drag, which will be visible already when drilling. Thus, the increase in friction is not seen on the signal as a result of the overpull, but is already present. Something worth noting, which was discussed in Section 5.2.5, is that the drag might increase when pulling stiffer parts of the drill string, i.e. BHA, through it. To find this increase in drag an analysis of the hook load signal before and after the BHA enters the problem zone is neccessary.

Cuttings accumulation has, as already noted, its own signature and it should be possible to distinguish it from the other three groups by analyzing the signal.

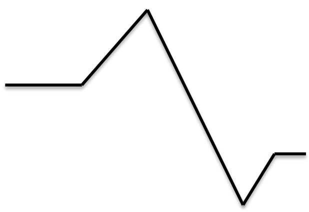
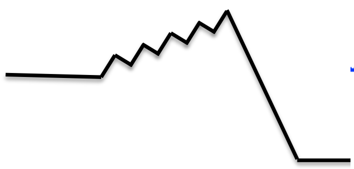
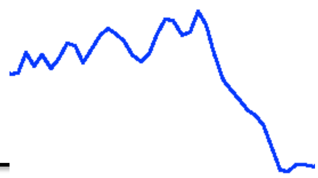
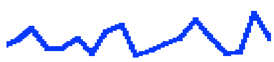
Unstable formation can be related both to fixed and moveable restriction, which was noted in Section 5.2.1. Creation of cavings could lead to the forming of ledges due to borehole expansion. Thus, both moveable and fixed restrictions could be present.

Differential sticking already has a type curve, created by Cordoso et al. (1995), that seems to concur with the observations in this study. Knowing this together with the fact that it happens when pulling starts, one should be able to distinguish this signal from the other with a relatively high level of confidence.

6.2.1 Diagnostic Tool

When a restriction downhole occur the first approach is to look at the hook load signal and try to identify whether it is fixed or moveable. Table 6.3 presents the type curves found together with the field curves that were used in the analysis. These type curves can be used when identifying the type of restriction. Even

TABLE 6.3: Restriction types and their type curves and field curves.

Restriction Type	**Type Curve**	**Field Curve**
Fixed		
Moveable Building		
Moveable Stationary		

though the signal is assumed to have a high level of confidence the nature can be unpredictable. Several restrictions could be present or you might have heave on the rig, both making the signal less readable. The moveable restriction might even show up as a fixed one, e.g. cuttings completely packs off around the drill string. In order to strengthen the level of confidence Table 6.4 can be used as a diagnostic tool. The purpose of the table is that the drilling team offshore can use it at the moment they encounter a restriction. Therefore, it is simple and includes only information that they can quickly access. When a restriction is encountered the table can be used to check all the symptoms present in that case and thereby find what cause of restriction that is most promoted. The signal types are included in the first two rows and are separated from the other by a horizontal line because these are the most important symptoms.

Table 6.4: Different symptoms related to the different causes of restrictions.

$+$ = promotes cause - = makes cause unlikely
$\circ$ = eliminates cause "blank" = indifferent

	Cause of Restriction				
Symptoms	Ledges	Local Dogleg	Differential Sticking	Unstable Formation	Cuttings Bed
Moveable	$\circ$	$\circ$	$\circ$	+	+
Fixed	+	+	+	+	-
Several OP at same depth	+	+	-	+	-
Took weight after OP	-	-	+	+	+
Low ROP before POOH					-
Stringers	+				
Instant OP			+		
Unstable signal	-		-	+	+
Increased drag when OP	-	-	-	+	+
Increased drag (drilling)	-	+	-	+	+
Inclination 0-30°			-		-
Inclination >30°			+		+
Inclination close to 50°					+
Dogleg $>3°/30m$		+			
Permeable formation			+		
Shale formation			$\circ$	+	
Cavings during drilling				+	-
Climbing rheology (drilling)			+	+	
High overbalance			+	+	

6.2.2 Ledge Indicator

In Section 5.2.2 a method to prove that ledges was causing the restriction was demonstrated. The method can be summarized as an indicator expressed as follows:

$$MD_{OP_i} = MD_{bit} - \Delta L_{stab_i} - \Delta L_{stretch} \tag{6.4}$$

Where MD_{OP_i} is the depth where the overpull could have happened, MD_{bit} is the bit depth when overpull was experienced, ΔL_{stab_i} is the length from the bit to the end of the large diameter component of the BHA while $\Delta L_{stretch}$ is the pipe stretch caused by the difference in load when drilling versus while tripping out. The formula generates all possible depths of occurrence for each overpull, assuming that the overpull happens when a large size diameter part of the BHA hits a ledge. The number of possible depths depend on how many large diameter components the BHA consists of. The depths are compared with stringer depths and are related to a stringer if they are within ±3 m range from the stringer depth.

6.3 Technical Discussion

Relating the results to the previous work done by Cordoso et al. (1995) shows that a different approach was used. The main focus for their study was type curves based on block moving at constant velocity where all overpulls were self-rectifying. They also only had three type curves for restrictions; ledge, differential sticking and borehole closure. In this study most of the signals that were analyzed were caused by restrictions causing such a high overpull that running back into hole again was necessary. This created a different curve for ledges than their type curve. Their differential sticking type curve proved to be similar to what was found in this analysis. This case was also the only case that had about the same conditions, the block was moving upwards constantly until the overpull self-rectified. No previous work on cuttings accumulation signatures was found and present work therefore represents new knowledge.

The results can be used for visual recognition of the hook load signal to find probable causes of restrictions on site. The diagnostic table presented can be used in addition to the hook load signal if in doubt or just for strengthening purposes.

Another practical applicability of the results is to use it for developing a data agent to detect what cause of restriction that is encountered automatically.

6.4 Self Assessment

Quality of Data

The real-time drilling data used in the study was sampled every 4 second. This is not a very high sampling rate and some peaks and instabilities may not be visible in the signal. However, it is regarded sufficient in this study. The reason for this is that when restrictions are encountered the driller will move the drill string in slower motions and thereby changes in HKL signal will happen slower, due to the high inertia of the system. Thus, it is less likely that important parts of the signal are being suppressed by the low sampling rate.

The amount of field data available in the post-event analysis varied. For some wells a lot of information were found in the daily reports and for some there was a lack of information, which lead to a weakening of some conclusions. For the extensive post-event analysis presented in Section 5.2 all of the cases except one had sufficient information available. For the case with local dogleg there was a lack of information in the daily report so that the conclusion is not as strong as it should be.

Quality and Shortcomings of Analysis

The hook load signal studied for both fixed and moveable restriction were both sampled from the same drilling rig at the same field. The drilling rig was a fixed installation causing no heave disturbances on the signal. The analysis is therefore only valid for drilling from fixed installations/rigs. However, one might be able to see through the heave disturbances, which should appear periodically, and spot out the signal characteristics necessary to diagnose the problem.

Both of the hook load signals analyzed in Section 6.1 are taken from the same well. This means that they had the same geological conditions in the well. It also means that the same operating procedures probably were followed and it may even be the same driller that was handling the situation. The operating procedure may influence the hook load signal and therefore the signature might be different in other wells. It is important to have in mind how the block is moving in relation with the hook load signal.

The post-event analysis is based on the problems that were encountered for three different fields. It is well known that one field may suffer the same types of restriction several times because of geological conditions for that specific area. Using only three fields in the analysis is therefore not representable for what causes of restrictions that are most likely to occur. Also, the diagnostic table presented in Section 6.2.1 is based on the post-event analysis and is therefore limited to the 5 causes presented.

Further Work

Future work to be done is to study hook load signals from floating drilling units where heave is disturbing the signal. The goal would be to try and recognize the same signatures in hook load signals with heave disturbances. One of the main challenges would be to distinguish between instabilities in hook load caused by heave and those caused by cuttings accumulation. Overpulls might also look more erratic and sudden with a steeper slope due to the heave and the peak value may not be representative for the difference in hook height. Also, more extensive studies on the signatures presented should be conducted. The approach should be to first strengthen the signatures found in this study using hook load signals from a wide range of fields. The wells should be drilled from fixed installations/rigs and with the same causes of restrictions. The second stage will then be to study signals from floaters. Doing this, one will be able to distinguish and recognize a wider range of signatures and the findings can be applied to operations on floating drilling units. Also, the cases should include different causes of restriction to obtain a more reliable analysis. When a new post-event analysis on a larger amount of fields are finalized the diagnostic table can be updated to include new findings.

The knowledge gained in this study can be applied when studying self-rectifying restrictions seen on the hook load. A study of self-rectifying signals is focusing on finding abnormalities before they cause problem and is of great importance when it comes to detecting cuttings accumulation. Being able to detect cuttings accumulation at an early stage could prevent extensive cleaning activities or event stuck pipe.

For automatic detection of restriction type, a data agent can be developed. This would give a quick answer to what restriction that is suspected to cause the problems. However, since the span in signatures is so wide for field curves, the development of an automatic detector will be a challenging task.

Application of the gained knowledge is to be able to quickly find cause of restriction by recognizing the hook load signature. When more mature the hook load signature will be quickly recognized automatically by a data agent regardless of what type of rig the well is drilled from.

7 | Conclusion

Based on the results, evaluation and self assessment the conclusions about hook load signatures revealing causes of restrictions are as follows:

- Recognizing signatures in real-time hook load signals is a challenging task.
- Type curves for some of the restrictions had already been developed, but with a different approach than what was used in this study.
- Based on the analysis two distinct mechanisms of restrictions creating different hook load signal were identified and physically interpreted. These are so called fixed restrictions and moveable restrictions.
- Relating the causes of restrictions to the main restriction mechanism groups makes it possible to distinguish between causes of restrictions by looking at the hook load signal only.
- Lack of available information for some fields lead to a weakening of some of the post-event analysis results.
- A more extensive study on the two signatures found must be conducted, in order to use hook load signals from a wide range of oil fields.
- Analysis of hook load signals from floating rigs must be implemented before the signatures can be validated for such conditions.
- A potential application of the knowledge gained here is to develop a data agent to quickly recognize cause of restriction. However, this will be a challenging task due to the wide span in signatures.

8 Nomenclature

8.1 Abbreviations

NPT	**N**on-**P**roductive **T**ime
HKL	**H**ook-**L**oad
RTDD	**R**eal **T**ime **D**rilling **D**ata
TVD	**T**rue **V**ertical **D**epth
SPP	**S**tand**P**ipe **P**ressure
BHA	**B**ottom **H**ole **A**ssembly
CEC	**C**ation **E**xchange **C**apacity
LGS	**L**ow **G**ravity **S**olids
MBT	**M**ethylene **B**lue **T**est
PV	**P**lastic **V**iscosity
YP	**Y**ield **P**oint
FE	**F**ormation **E**valuation
ROP	**R**ate **O**f **P**enetration
MD	**M**easured **D**epth
WPS	**W**ater **P**hase **S**alinity
POOH	**P**ull **O**ut **O**f **H**ole
RIH	**R**un **I**nto **H**ole
MWD	**M**easure **W**hile **D**rilling
WOB	**W**eight **O**n **B**it
OD	**O**uter **D**iameter
WOH	**W**eight **O**n **H**ook
BPOS	**B**lock **Pos**ition

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A | Hook Load Signals from RTDD

The additional hook loads signals for three of the post-event analysis is included here; unstable wellbore, ledges caused by stringers and local dogleg. For the two remaining causes of restriction all of the signal plots are found in the post-event analysis results in Section 5.2.

A.1 Well A-5 - Unstable Wellbore

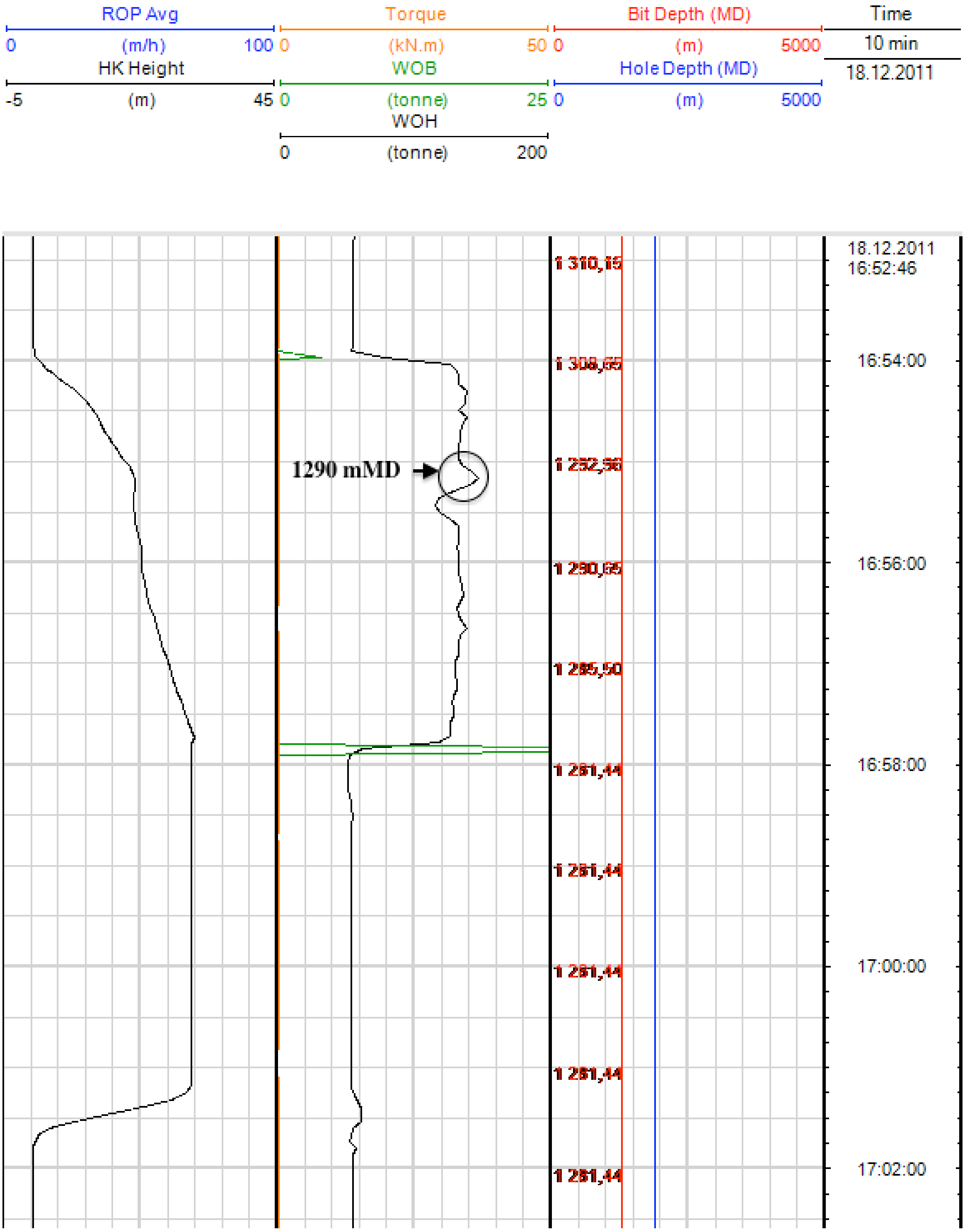

FIGURE A.1: Hook load signal for unstable wellbore.

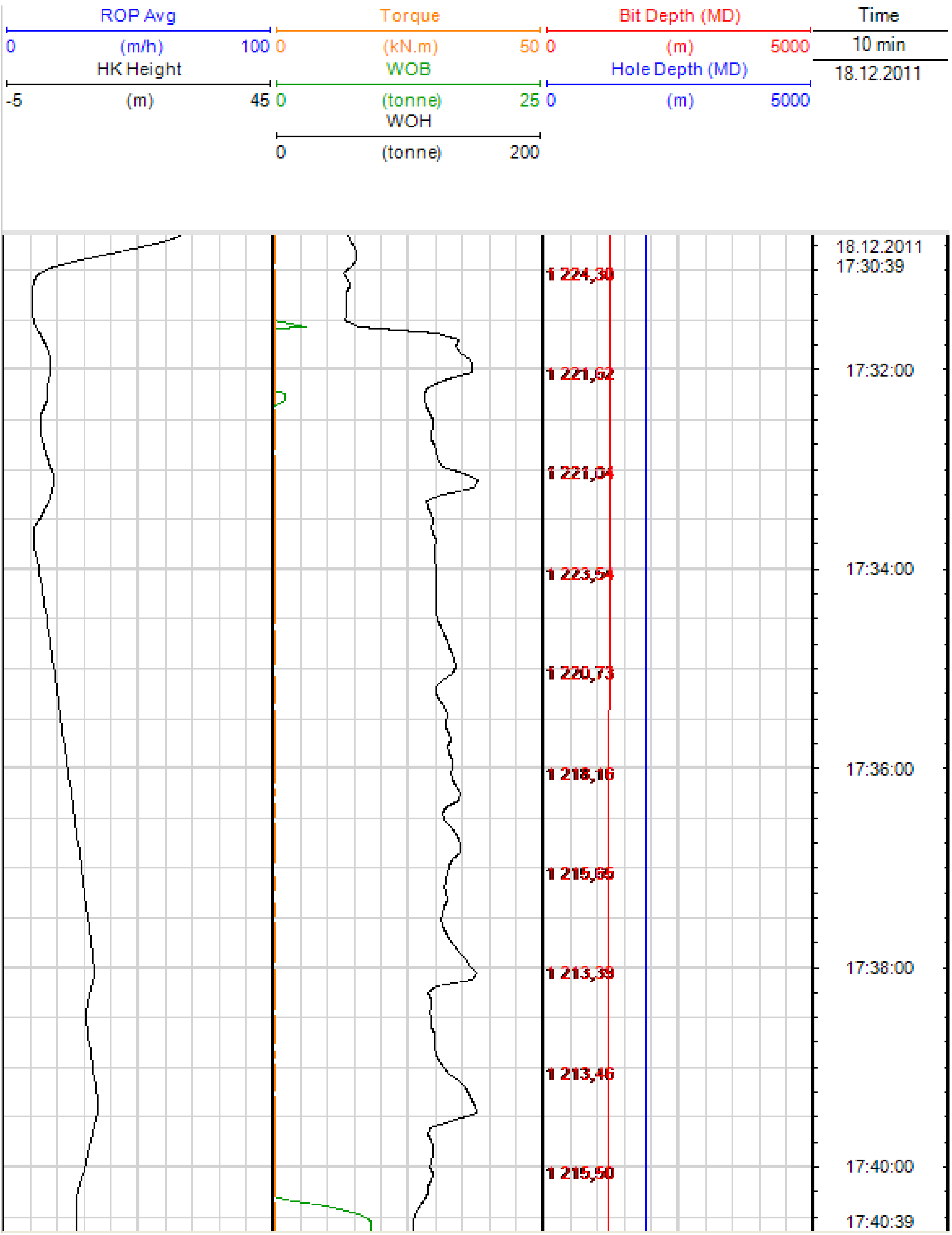

FIGURE A.2: Hook load signal for unstable wellbore.

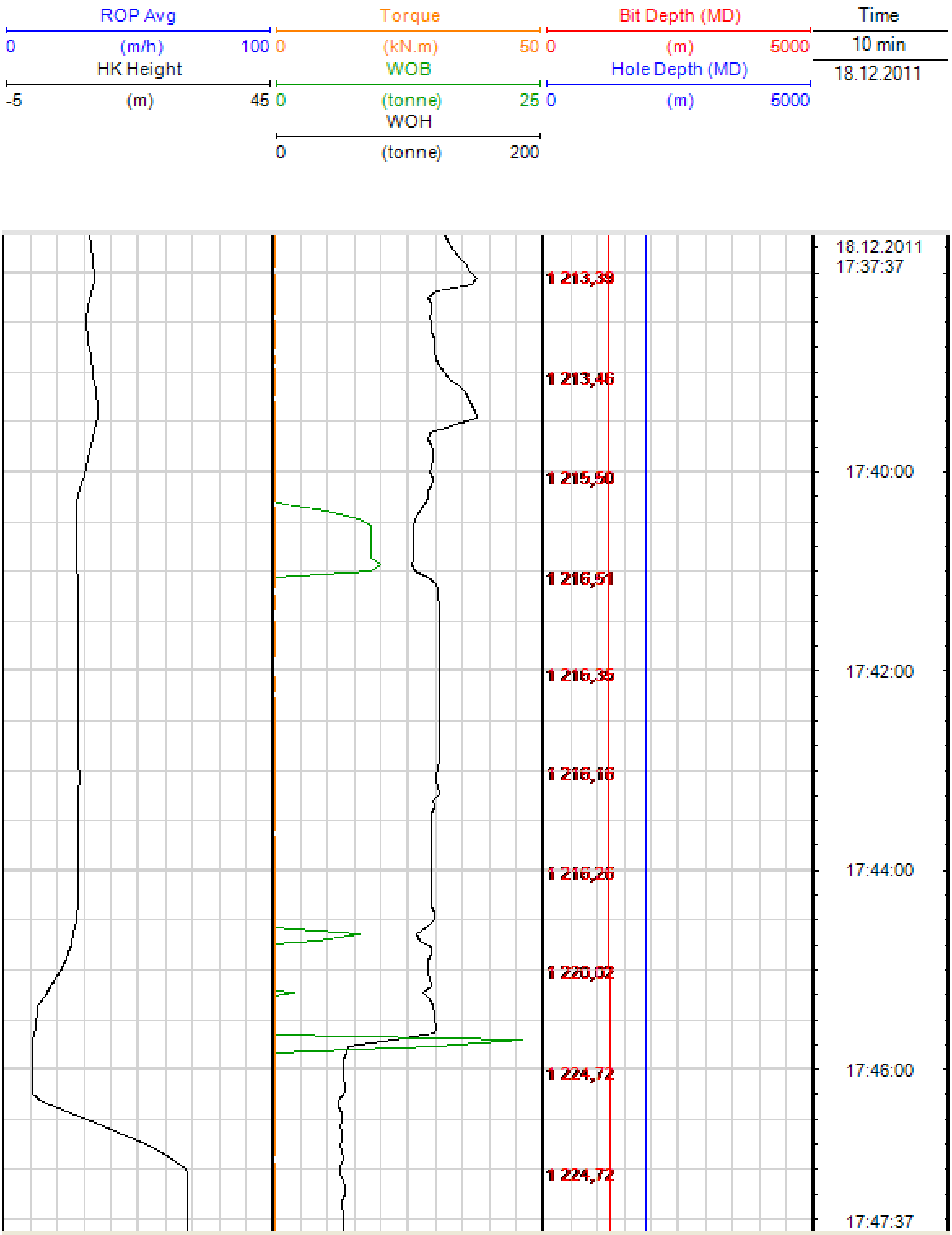

Figure A.3: Hook load signal for unstable wellbore.

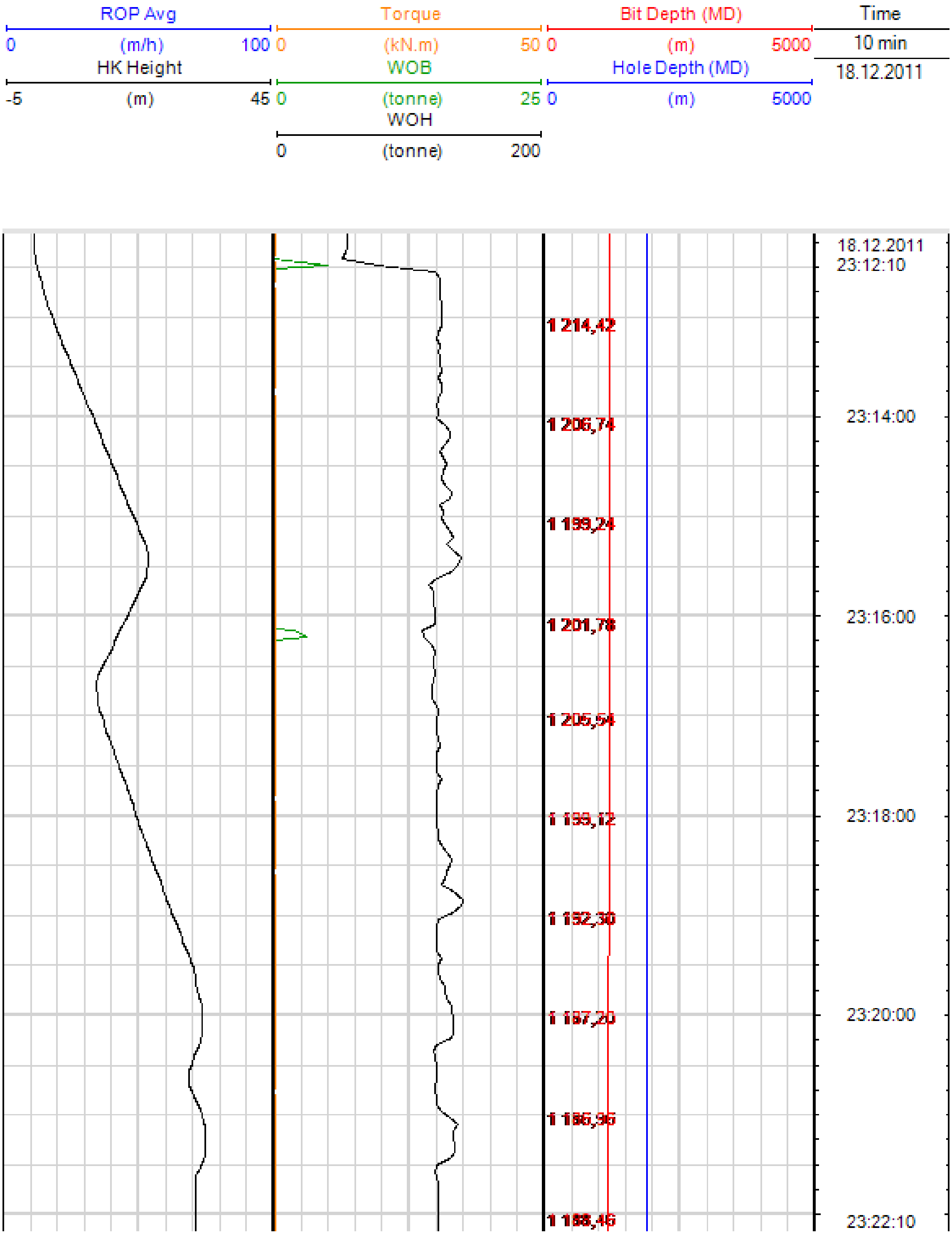

Figure A.4: Hook load signal for unstable wellbore.

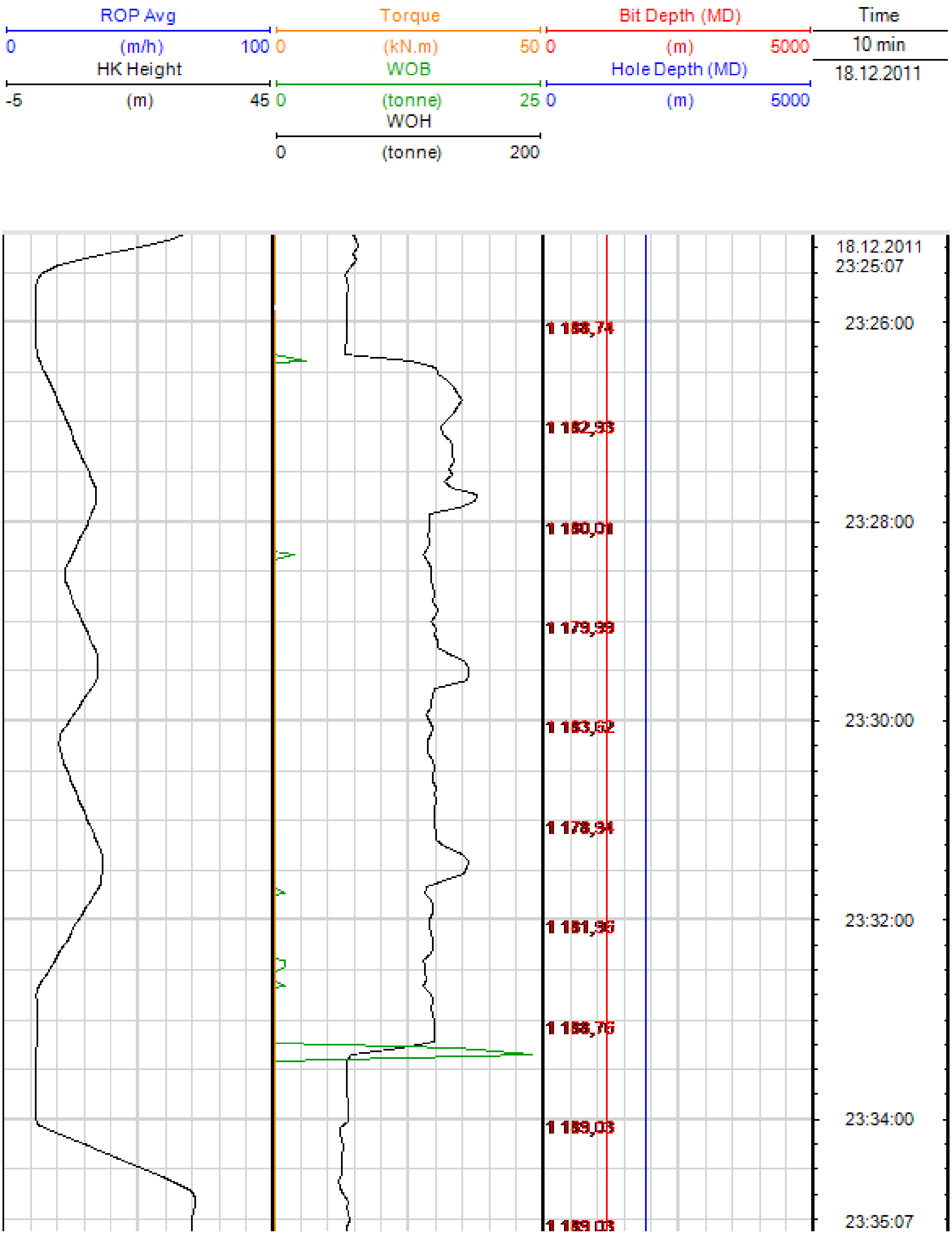

Figure A.5: Hook load signal for unstable wellbore.

A.2 Well A-12 T2 - Ledges Caused by Stringers

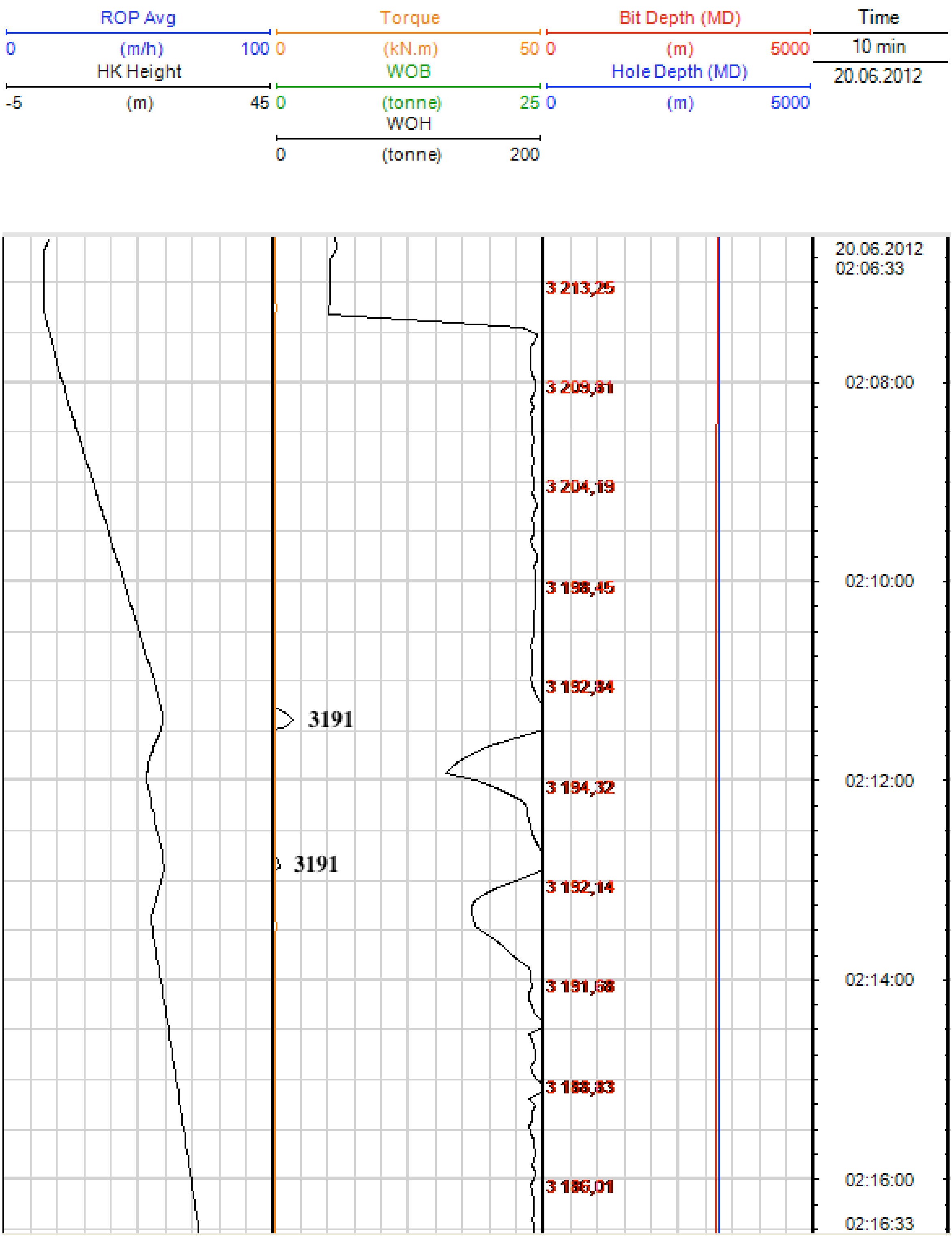

Figure A.6: Hook load signal for ledge.

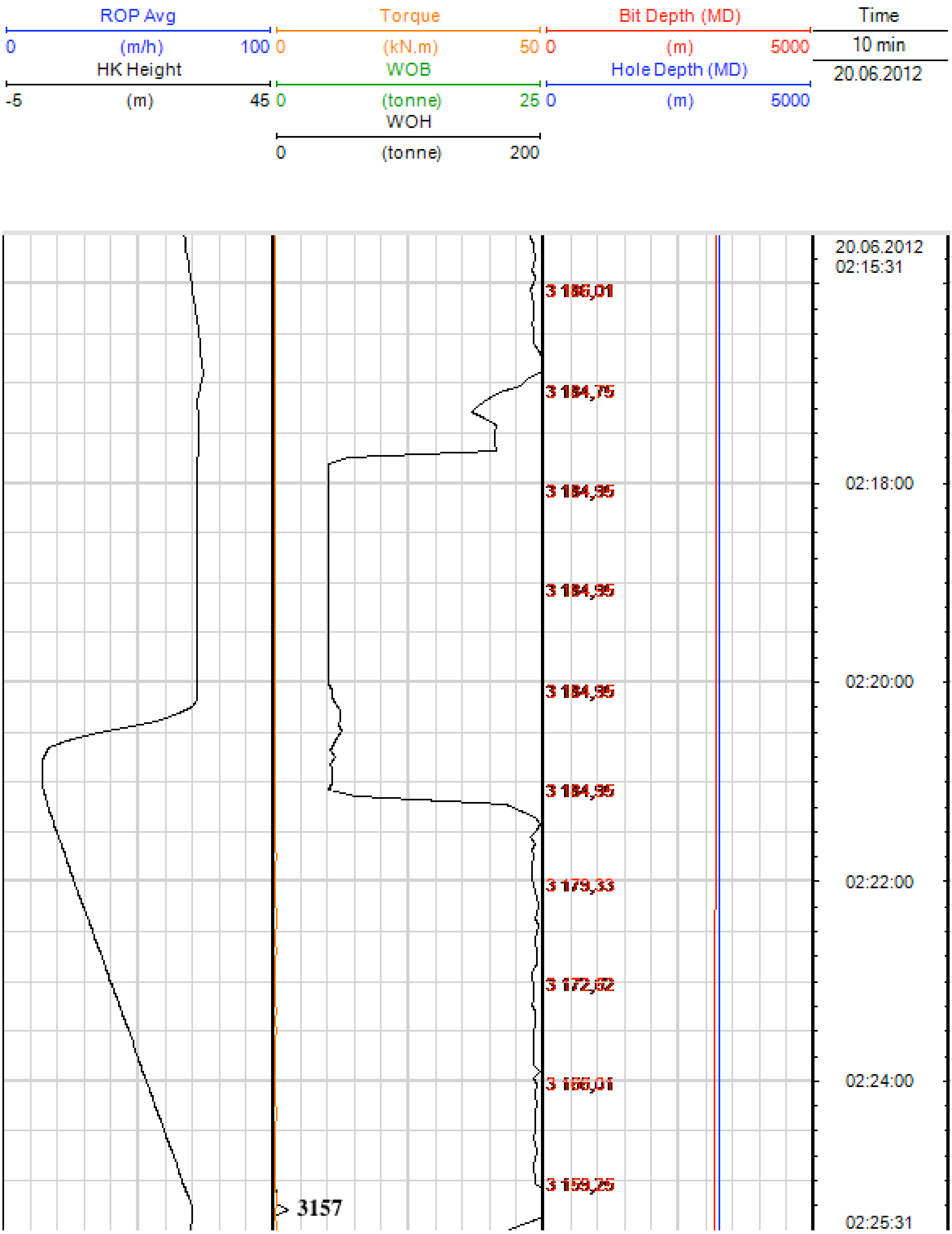

Figure A.7: Hook load signal for ledge.

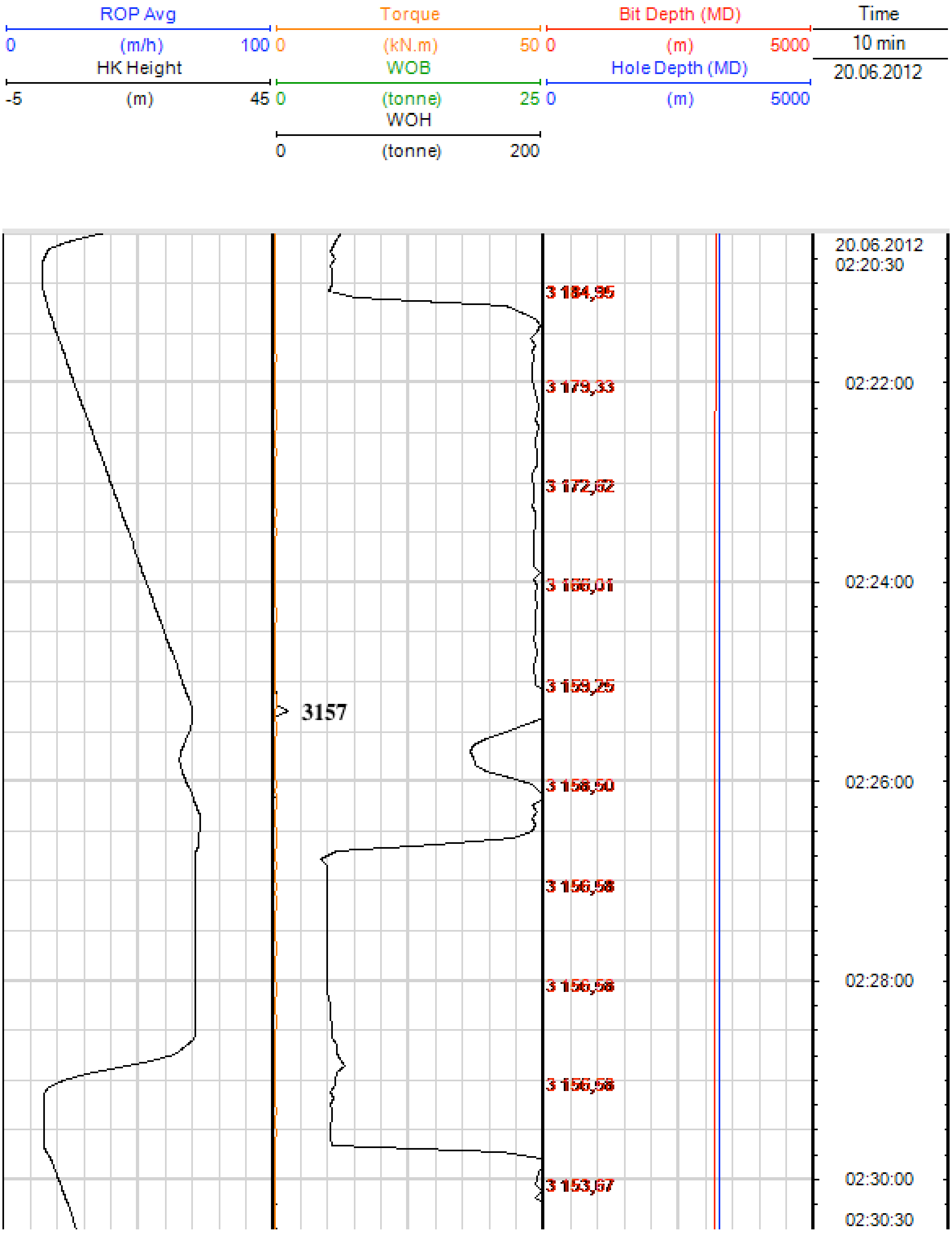

FIGURE A.8: Hook load signal for ledge.

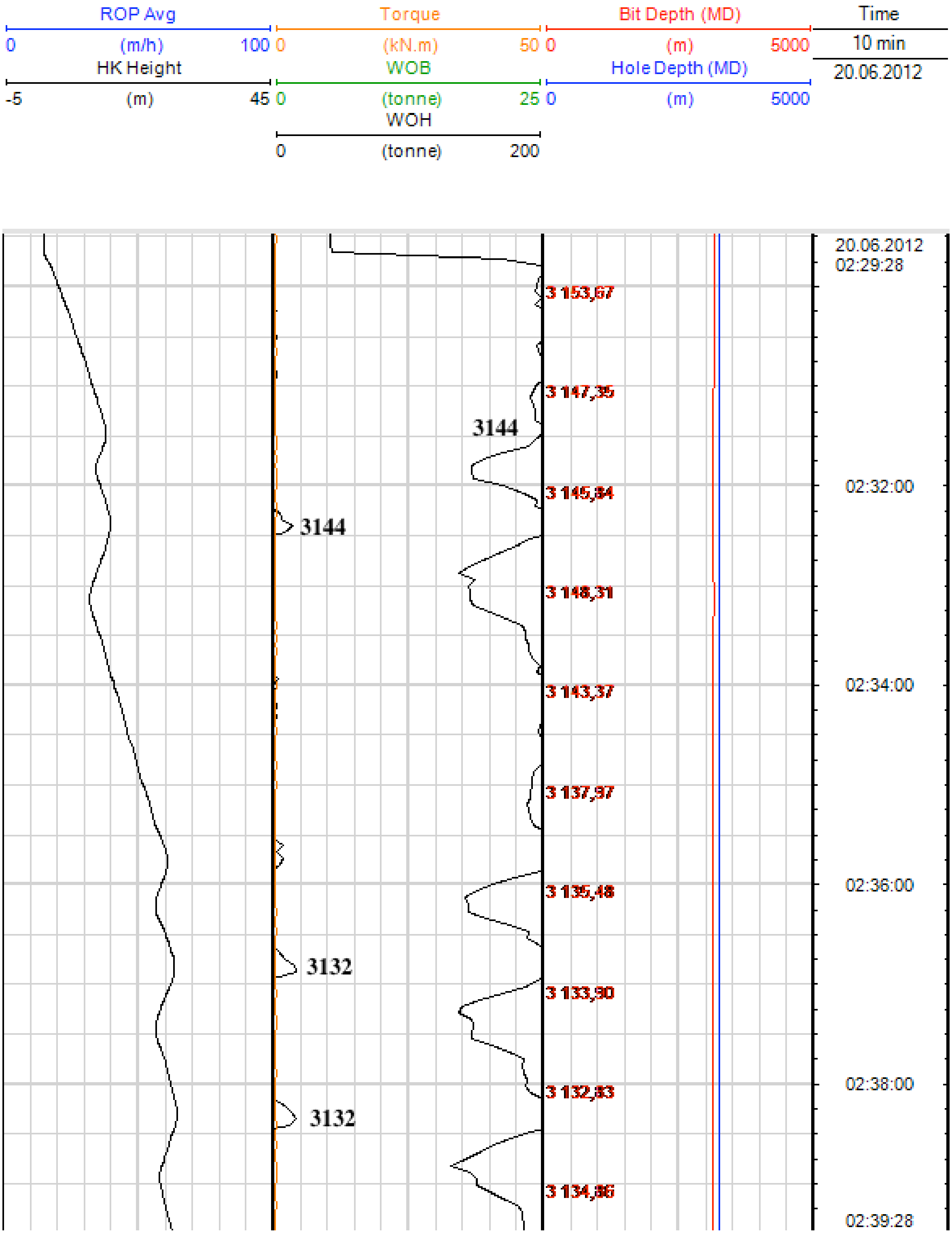

FIGURE A.9: Hook load signal for ledge.

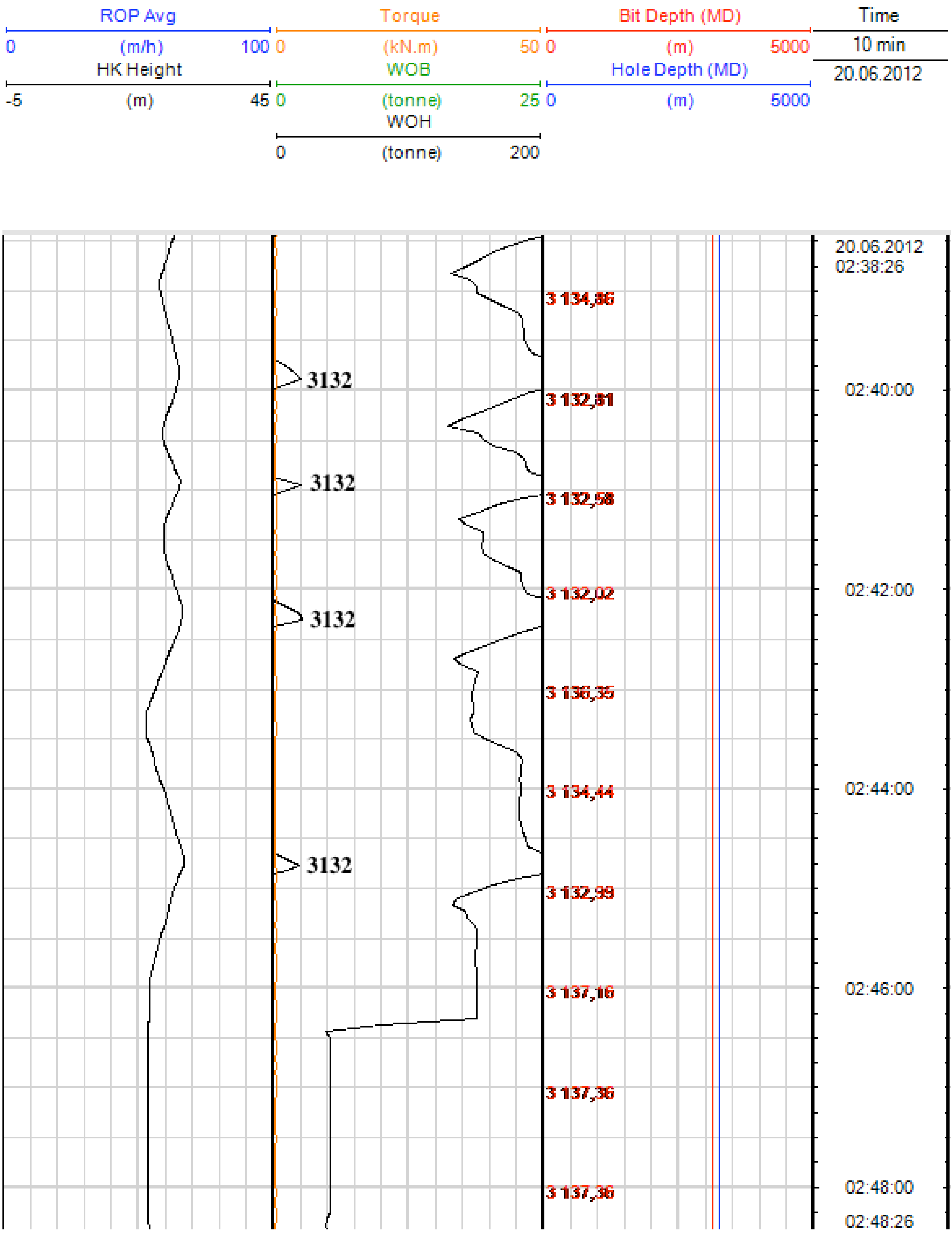

FIGURE A.10: Hook load signal for ledge.

FIGURE A.11: Hook load signal for ledge. Tripping out with rotation.

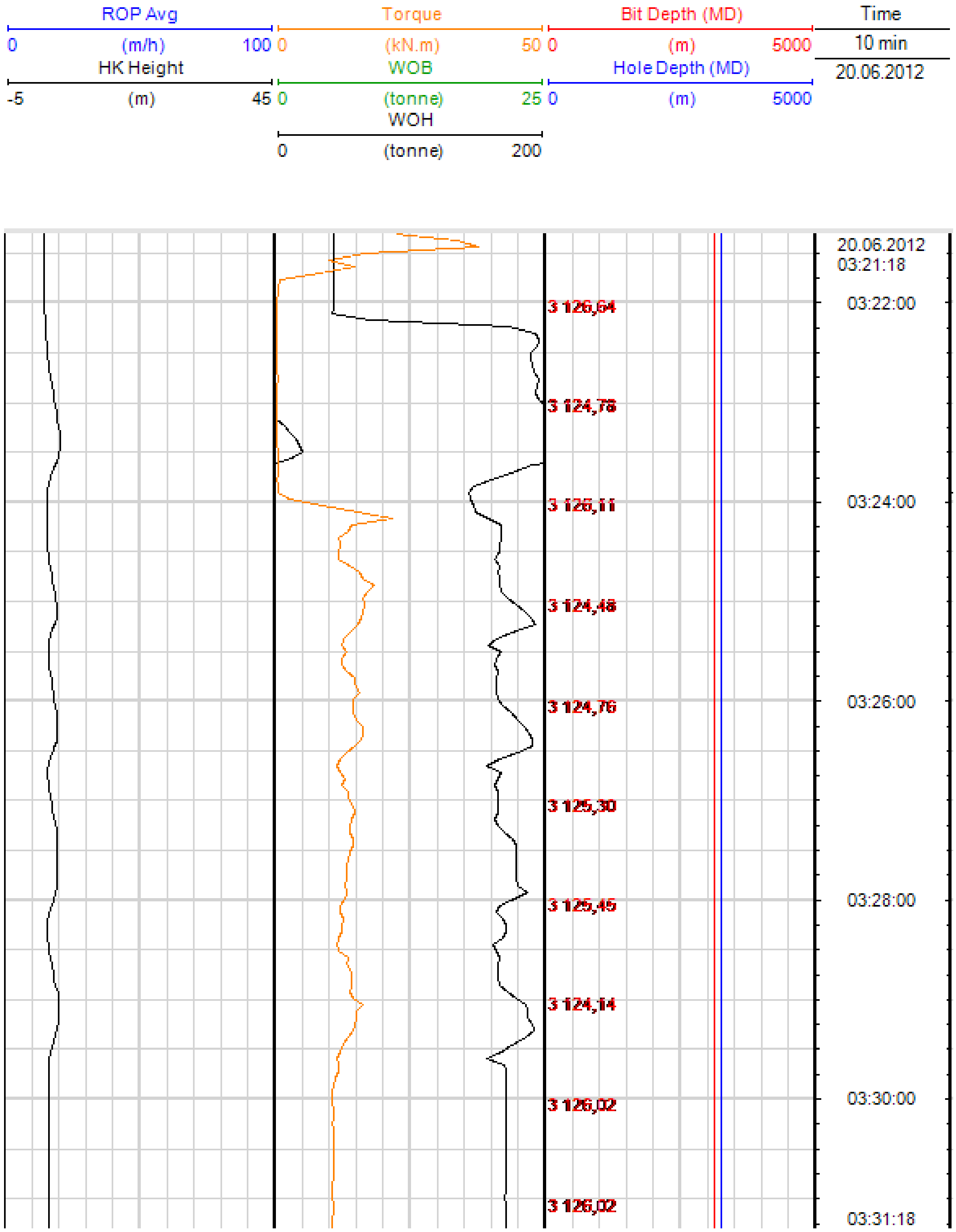

Figure A.12: Hook load signal for ledge. Tripping out with rotation.

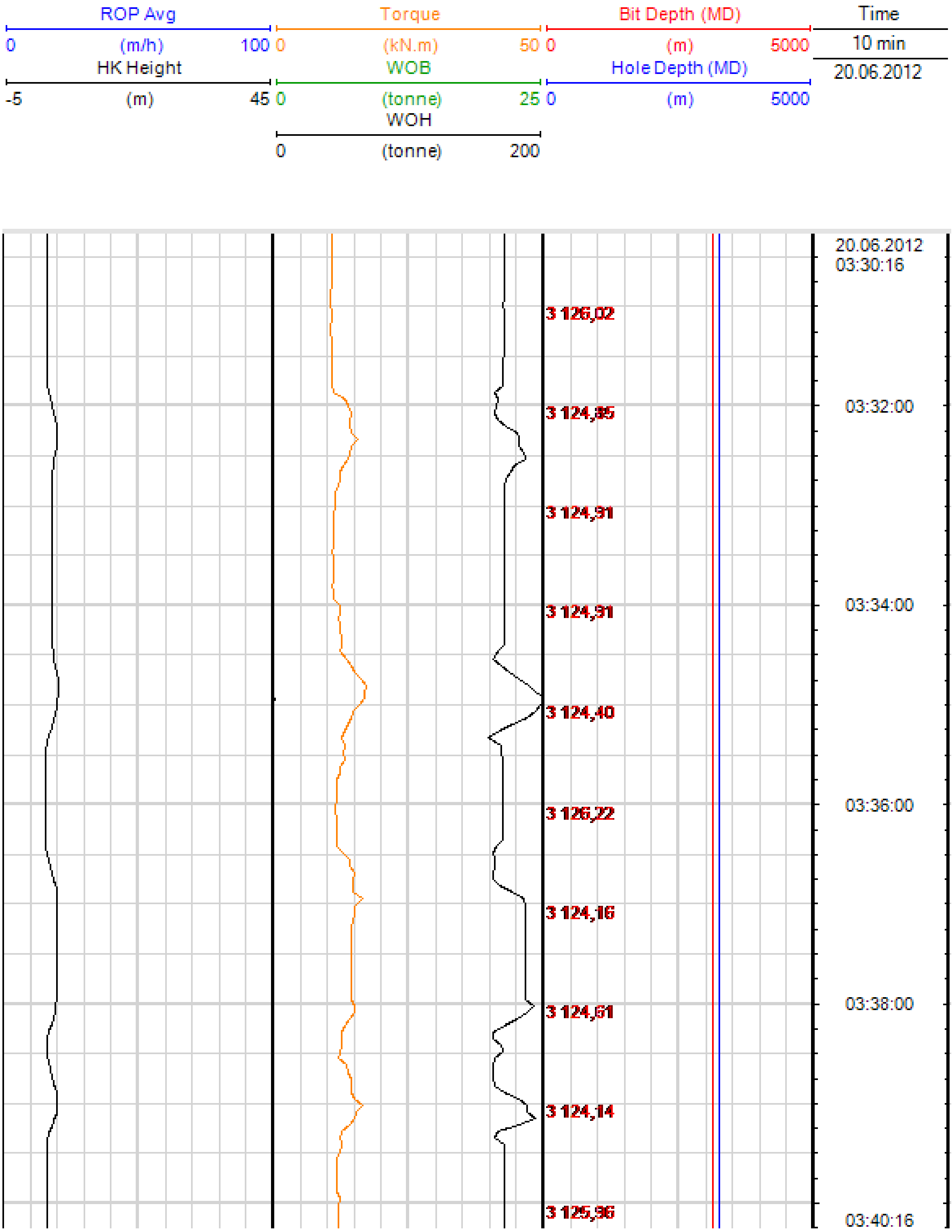

FIGURE A.13: Hook load signal for ledge. Tripping out with rotation.

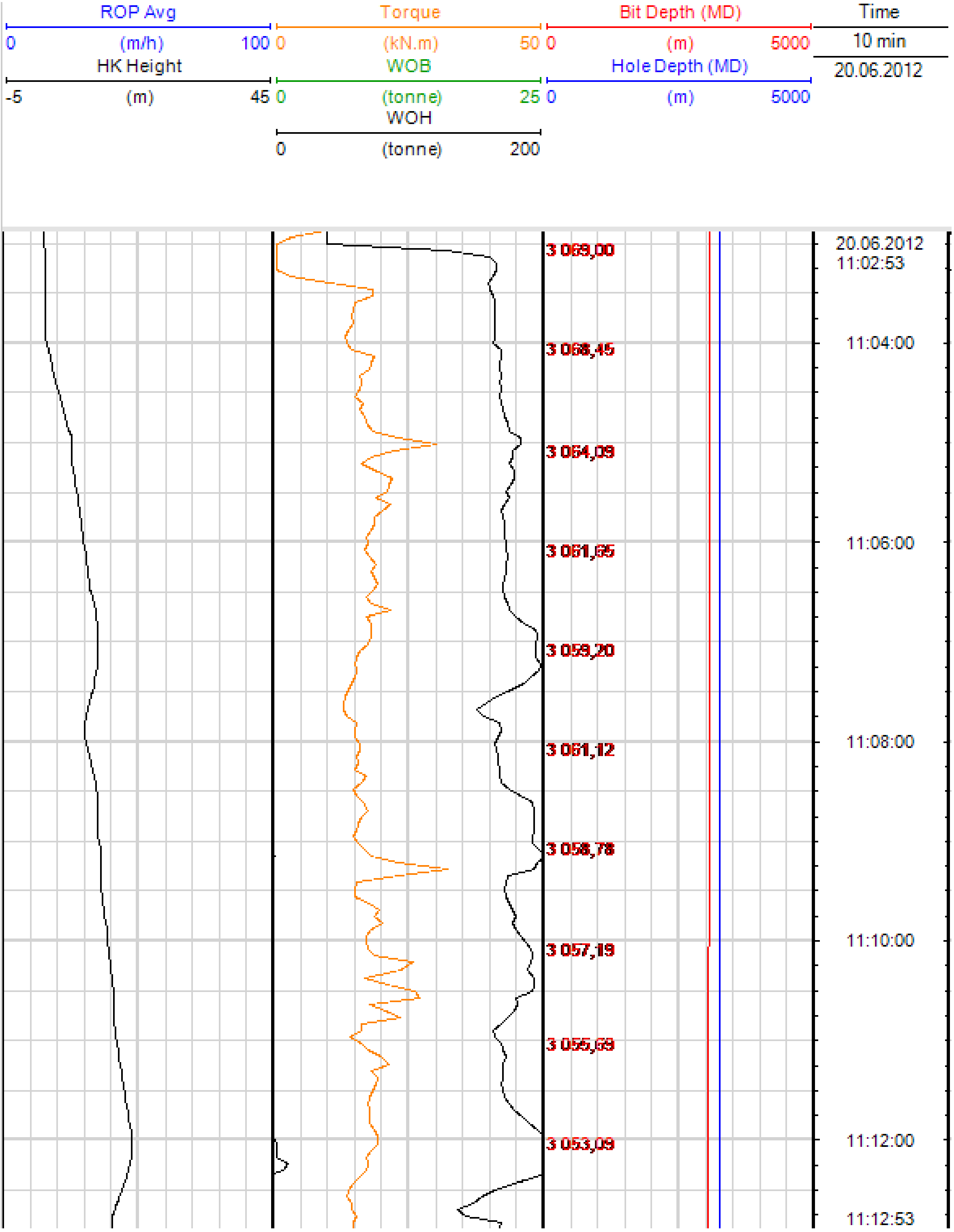

FIGURE A.14: Hook load signal for ledge. Tripping out with rotation.

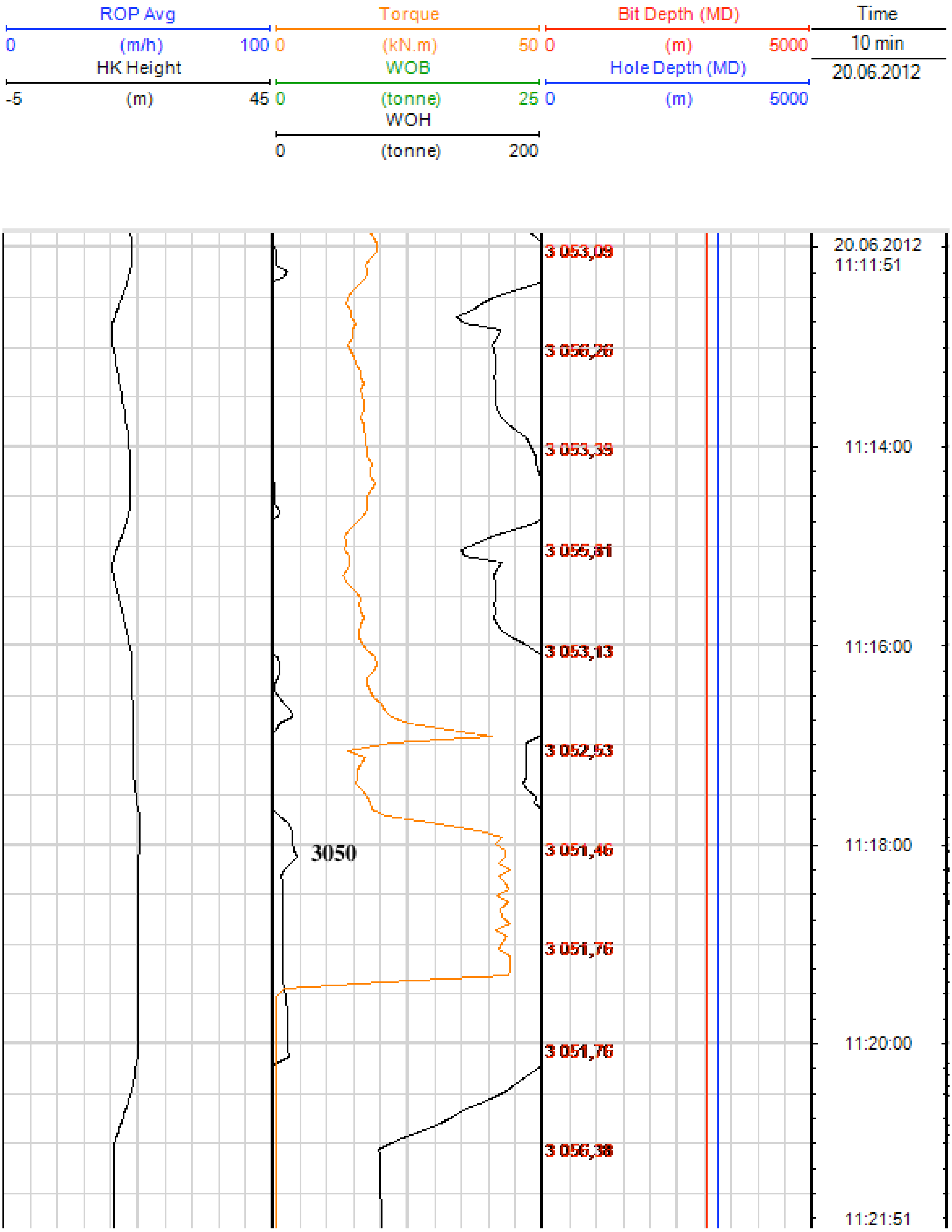

Figure A.15: Hook load signal for ledge. String torqued up and got stuck.

A.3 Well B-3 - Local Dogleg

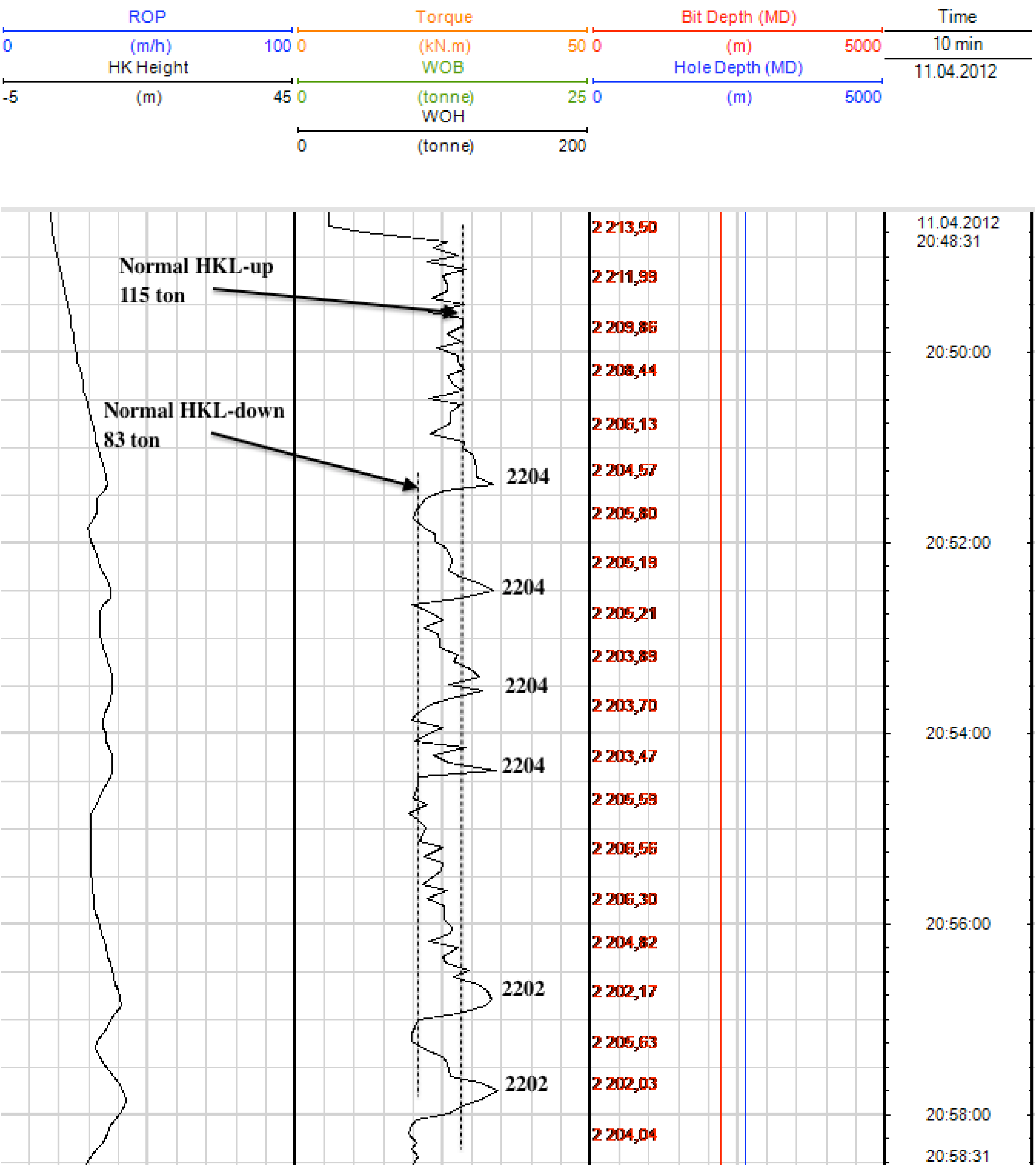

FIGURE A.16: Hook load signal for high local dogleg.

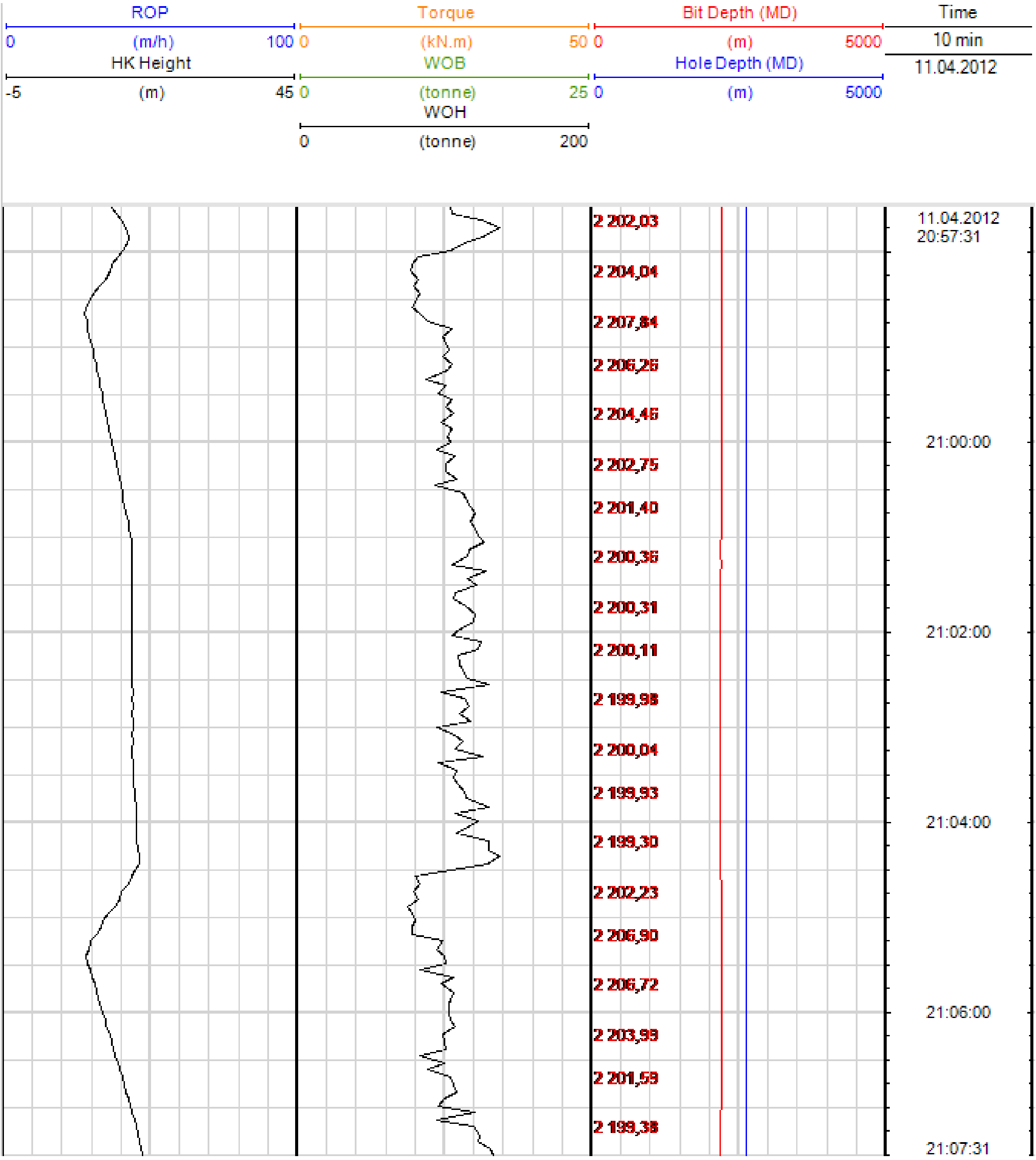

FIGURE A.17: Hook load signal for high local dogleg.

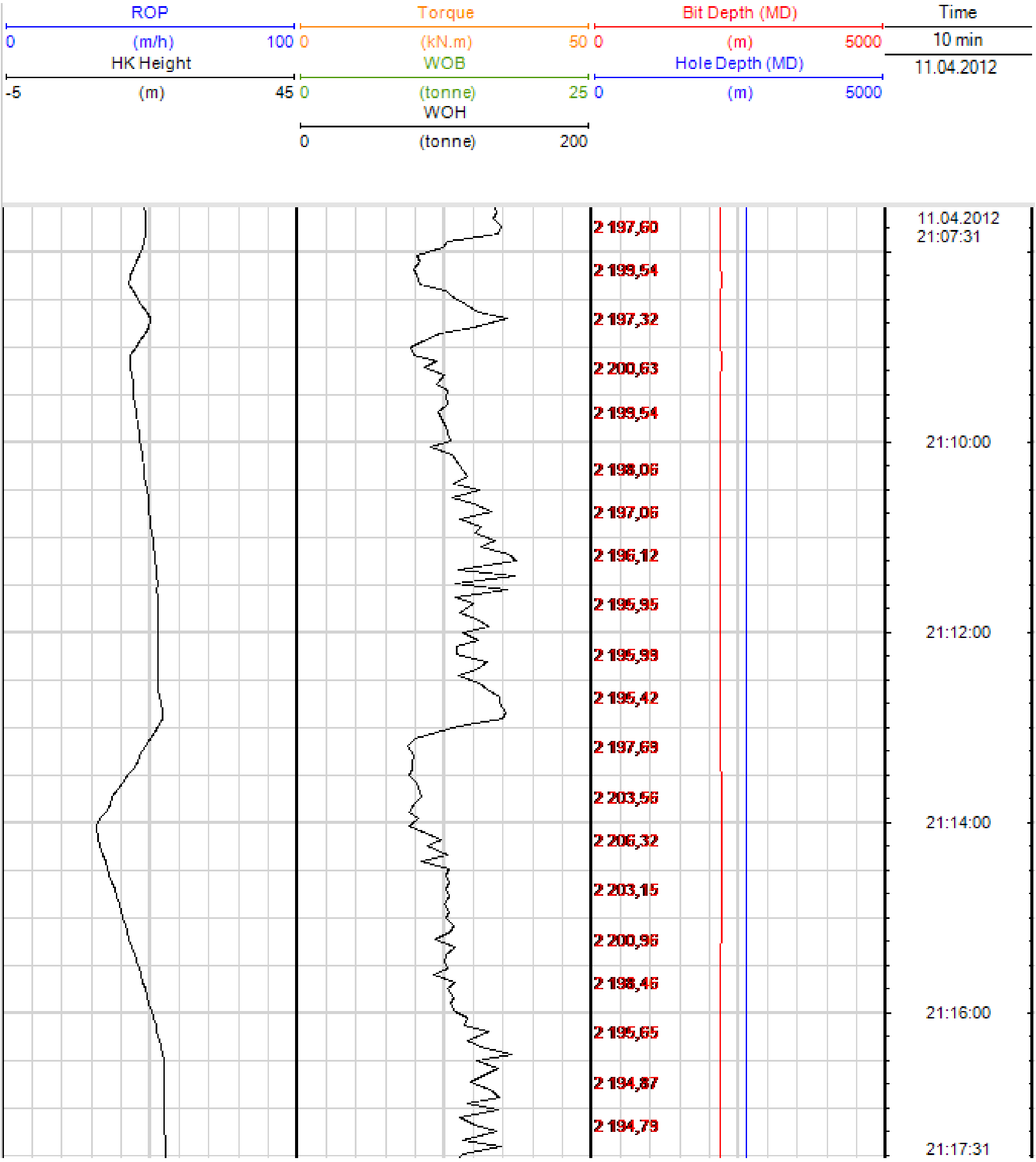

Figure A.18: Hook load signal for high local dogleg.

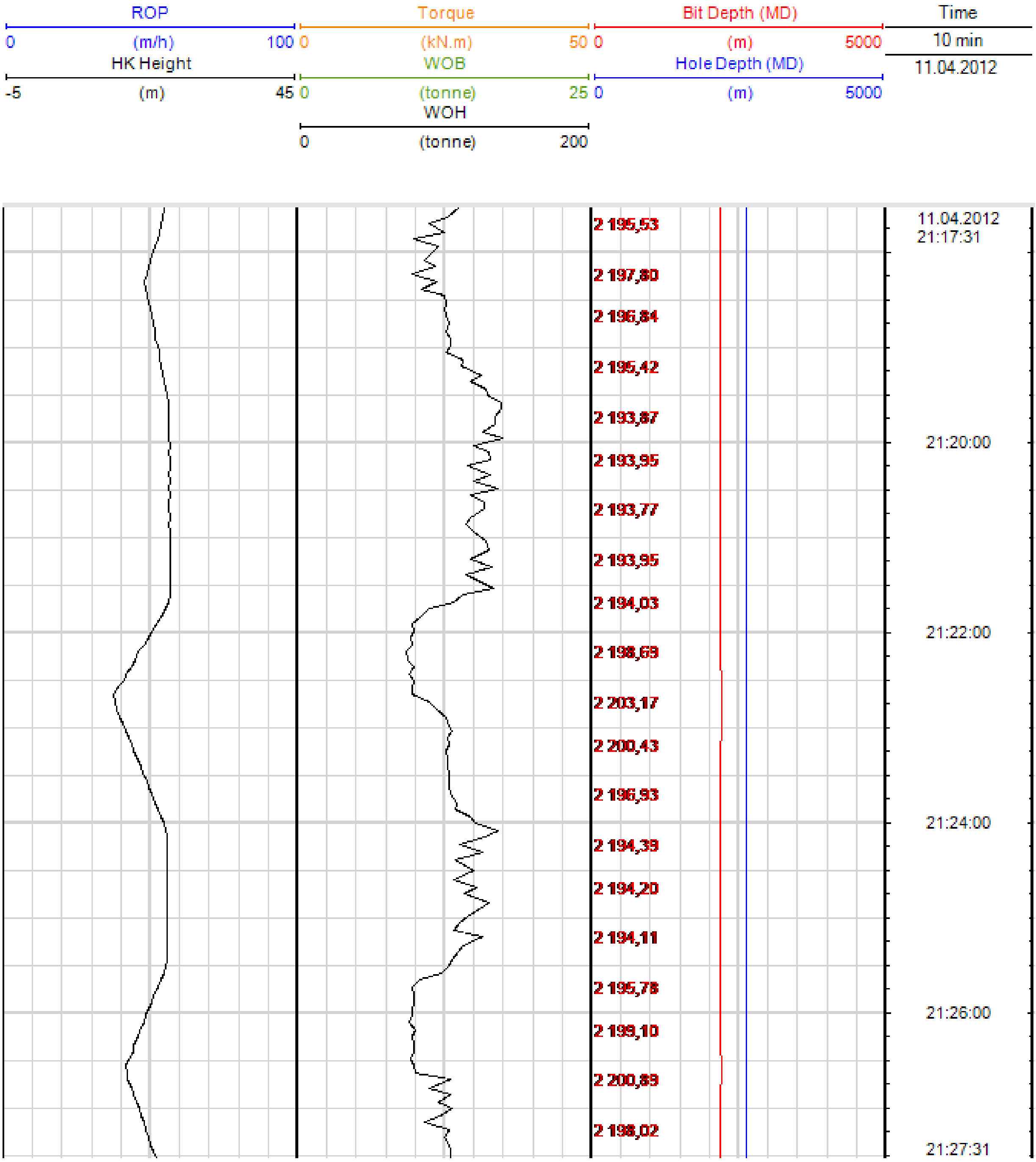

FIGURE A.19: Hook load signal for high local dogleg.

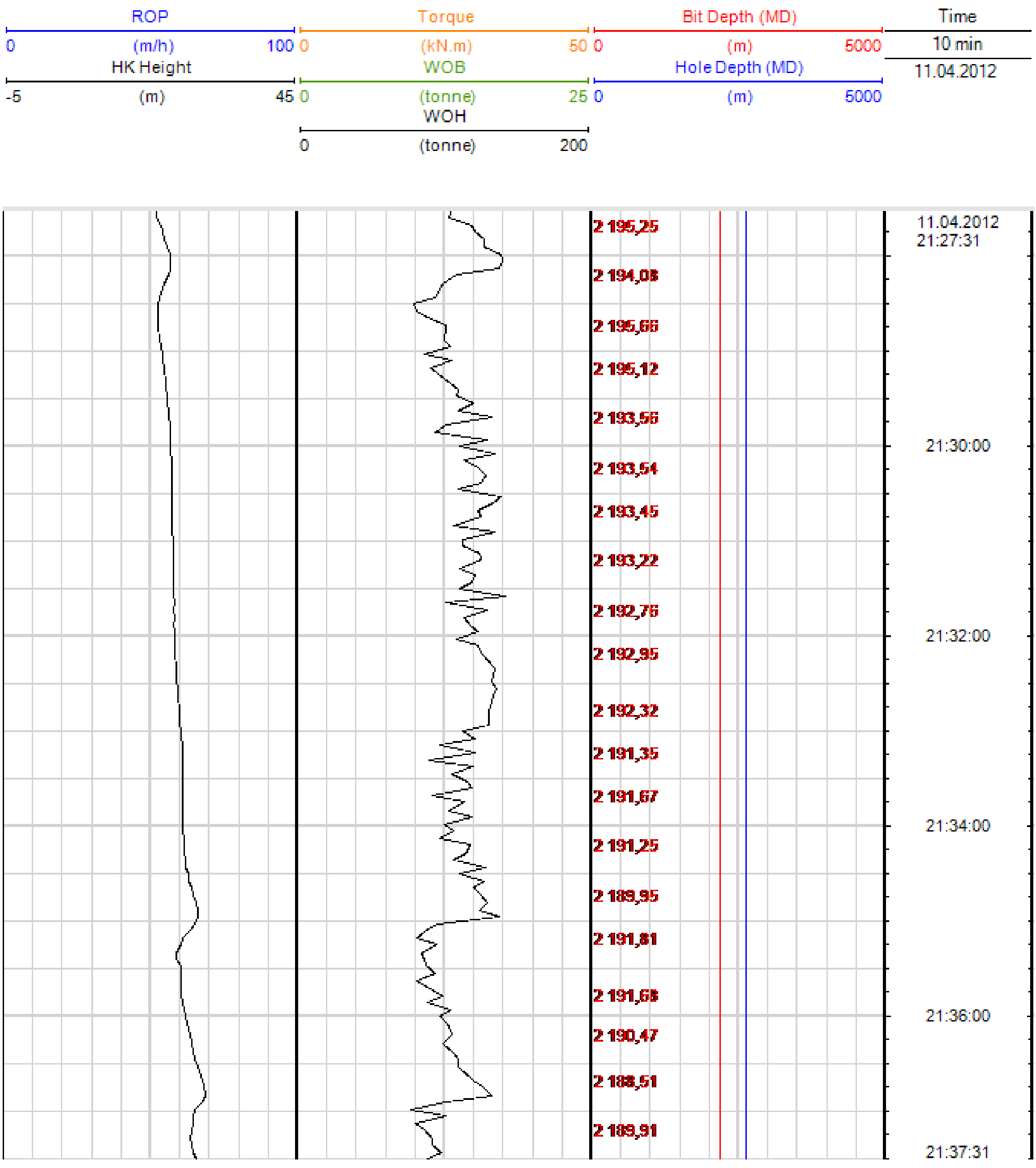

Figure A.20: Hook load signal for high local dogleg.

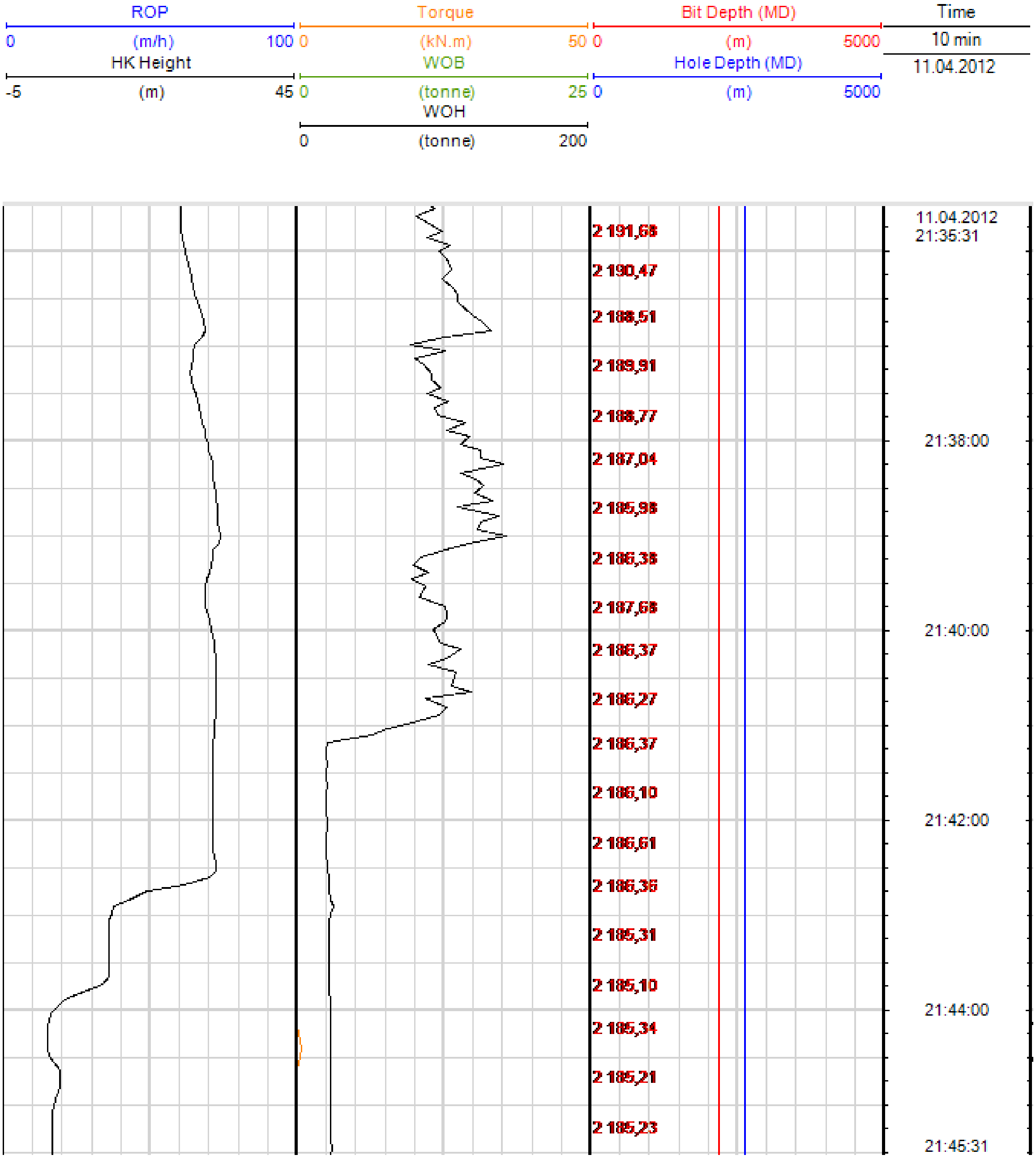

Figure A.21: Hook load signal for high local dogleg.