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Prediction of Failures While Drilling

Daniel Vilhelm Rosland
Andreas Øveraasen Årstad

Petroleum Geoscience and Engineering
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Supervisor: Pål Skalle, IPT

Norwegian University of Science and Technology
Department of Petroleum Engineering and Applied Geophysics

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Besides our advisor, we would like to thank PTS (Center of Petroleum Technology) at NTNU for providing us with a modern workspace, the required software and expertise from several professors. A workspace with modern computer equipment is essential when programming structures of this size.

Developing a failure-predicting program could not have been done without all of the above.

Lastly, we would like to individually thank our project partner for consistent work throughout the semester and for putting in the required effort to finish the project on time.

Summary

Complex drilling operations, high production expenses and a low oil price influence the modern petroleum industry. Reducing the non-productive-time (NPT) during an operation can reduce the production expenses. Drilling, well control and mud equipment is responsible for 21-30 % of the NPT (Contractor, 2010). The industry needs solutions that reduces drilling related NPT. Our solution was to develop a program that predicts failures while drilling. The program reduces NPT by alerting the operator of failures that will occur in the future.

Historical data on NPT during drilling is important when developing a failure-predicting program. Collected historical data was from 427 offshore wells in the Gulf of Mexico. The goal was to match program output with the historical data.

The program was developed to calculate a probability distribution of future failures. The distribution is calculated based on symptoms detected in real-time-drilling-data (RTDD). As for medical diseases, the probability of a drilling related failure changes with the detected symptoms. A symptom can cause a positive or negative event. All symptoms were linked to their events through relationships. The relationships were collected in an ontology that serves as a database for the program.

The program was developed by placing all relationships in a hierarchal structure. Symptoms were placed on the top and failures were placed on the bottom of the hierarchy. Detection of a symptom activates multiple paths leading to failures. The activated paths were added together and presented as a failure distribution. To match the historical failure distribution, the ontology and the complete program were adjusted.

Data from three actual drilling operations were used to test the program. The failures were one case of lost circulation and two cases of motor stalls. Symptoms were detected and collected from End of Well (EoW) reports and RTDD. The program was capable of predicting the two cases of motor stall failures, but the lost circulation failure was only top three.

Based on the successful prediction of motor stalls, the program was verified as logical. The most probable failure was motor stall with a probability of 18 %. The probabilities were not extreme enough, as the most probable failure should have a probability of at least 50 %.

Future work includes adjusting the ontology to make the failure distribution extreme. To optimize the program further, a method that deactivates time and depth dependent symptoms must be developed. More EoW reports and RTDD are required to continue testing the program. By applying these changes, we believe that the program will be able to predict failures and hence reduce drilling related NPT.

Sammendrag

Dagens petroleumsindustri er påvirket av kompliserte boreoperasjoner og resulterende høye kostnader. Høye produksjonskostnader kan reduseres ved å redusere nedetiden (NPT) under en operasjon. Boring, brønnkontroll og slamutstyr står for 21-30 % av all nedetid knyttet til en brønn (Contractor, 2010). Industrien trenger løsninger som reduserer nedetiden knyttet til boring. Vår løsning på hvordan nedetiden kan reduseres var å utvikle et program som predikerer feil. Boreoperasjonen vil kunne endres for å unngå nedetid ved å predikere feil som ville ha inntruffet i fremtiden.

Historiske data om nedetid under boring er viktig når man skal utvikle et predikerende program. Historiske data var samlet fra 427 offshore brønner som ble boret i Mexicogolfen. Målet er at programmet skal stemme overens med historiske data.

Programmet ble utviklet til å beregne en sannsynlighetsfordeling for fremtidige feil basert på symptomer i nåtids boredata (RTDD). Som for medisinske sykdommer vil sannsynligheten for en borerelatert feil endres med mengde detekterte symptomer. Det endelige målet er å ha dataagenter som finner disse symptomene automatisk. Symptomer kan ha negativ og positiv innvirkning på boreoperasjonen. Alle mulige symptomer ble knyttet til deres innvirkning på boreoperasjonen gjennom relasjoner. Relasjonene ble samlet i en ontologi som fungerer som programmets database.

Programmet ble utviklet ved å strukturere alle relasjonene i et hierarki. Symptomer ble plassert på toppen av hierarkiet og borerelaterte feil ble plassert på bunn. Når et symptom utløses vil flere stier som peker til ulike feil bli aktivert. Aktiverte stier blir regnet sammen og presentert som en sannsynlighetsfordeling. Parametere i ontologien og det ferdige programmet ble justert slik at sannsynlighetsfordelingen stemte overens med historisk data.

Data fra tre faktiske boreoperasjoner ble brukt til å teste programmet. Feilene var ett tilfelle av tapt sirkulasjon og to tilfeller av motorstopp. For hvert av tilfellene ble symptomer hentet og detektert fra endelig borerapport (EoW) og RTDD. Programmet var i stand til å predikere de to tilfellene av motorstopp mens tapt sirkulasjon bare ble topp tre i fordelingen.

At programmet predikerte motorstopp som mest sannsynlige feil betyr at programmet og strukturen oppfører seg logisk. Den mest sannsynlige feilen var predikert med 18 % sannsynlighet. Den mest sannsynlige feilen var ikke ekstrem nok da den bør predikeres med en sannsynlighet på vertfall 50 %.

Fremtidig arbeid inkluderer å justere ontologien slik at sannsynlighetsfordelingen blir mer ekstrem. En metode som kan deaktivere tids- og dybdebestemte symptomer når de ikke lengre er relevante for boreoperasjonen må utvikles. Flere EoW rapporter og RTDD av høy kvalitet trengs for å teste programmet ytterligere. Med disse endringene mener vi at programmet vil være i stand til å predikere feil og dermed reduserte borerelatert NPT.

Table of Content

1 Introduction

Complex drilling operations, high production expenses and a low oil price influence the modern petroleum industry. Operators and other actors are forced to re-think and re-evaluate their current operations. Short-term solutions include cutting direct expenditures such as employees, contractors and high-cost, high-risk projects. Long-term solutions include putting time and value into research that can reduce the cost/income ratio. Reducing NPT during an operation can reduce the production expenses. Drilling, well control and mud equipment is responsible for 21-30 % of the NPT (Contractor, 2010).

The objective of this thesis is to develop a program that predicts failures while drilling. The program reduces NPT by alerting the operator of failures that will occur in the future. The final program detects symptoms in the RTDD and produces a probability distribution of future failures. Engineers will be able to make supported, real-time decisions based on the probability distribution of events occurring in the future. Investigating if such a probability model is programmable, and which structure model to use, were goals of the project.

The approach of developing a predicting program includes:

1. **Evaluate previous published knowledge.** To get an idea of already existing information and already attempted approaches.

2. **Expected failures.** Statistical information on expected failures during a drilling operation was collected to know what to expect from the program output.

3. **Obtain a list of all possible relations between concept A and concept B.** Symptoms and the events they cause are referred to as concepts. All concepts were linked together in relationships. Relationships were collected in a list called the ontology.

4. **Developing a failure-predicting program.** The program aims to connect all concept-relationships and calculate the probability of a failure. Microsoft (MS) Excel was used as a programming tool to efficiently store, read and access large sheets of data.

5. **Creating cases.** Real cases where actual failures occurred and symptoms were detected in RTDD were created. Real cases were required to test the program. The program required two types of input when calculating the probability of failures: Static symptoms (ss) and symptoms (s).

    i. **Static Symptoms**. EoW reports were used to point out the occurrence of failures. These reports provided drilling parameters used to calculate static symptoms.
    ii. **Symptoms.** Symptoms were detected in the RTDD. An average window of 12 hours were investigated. Manual detection of symptoms was done in the early stages. Ideally, data agents detects symptoms automatically. Two already developed agents by Rosland & Årstad (2016) shows the detection process.

6. **Presenting the result.** The program produces a failure distribution when symptoms are entered. If the program responds correctly, the failure distribution matches the actual failure. Already at this stage, since no downhole data are available, it can be revealed that determining the real failure type is a challenge.

2 Previous Published Knowledge

To reduce the frequency of offshore accidents, a higher focus on safety and NPT is required by the industry. Numerous computer programs have previously been developed to reduce NPT and the frequency of accidents.

Verdande Technology developed a software called DrillEdge. This was a real time decision support system for the operator. DrillEdge used case-based reasoning (CBR) with RTDD to predict future problems. DrillEdge provided a failure distribution by comparing the current RTDD with previous patterns from drilling operations in the past. (Gundersen, Sørmo, Aamodt, & Skalle, 2013)

SAS (2013) developed a program that identifies NPT problems in the planning stage of a well and detects problems while drilling. According to the developers, the system is "*An advanced analytical model that should be able to predict and provide early warnings about events that will affect the safety and NPT issues*". The program was designed to improve the efficiency of the entire drilling operation. This method differs from DrillEdge as it uses a more mathematical approach. According to themselves, the program have proved to improve the efficiency of a drilling operation by reducing the NPT by 18% and increase foot per day by 12% (SAS, 2013).

Skalle, Aamodt & Laumann (2014) published a paper on ontology for hierarchically models with the goal of reducing the number of drilling failures. The model is based on information and understanding of drilling related failures. The model can be applied in real time and requires no historical cases. The combination of technical and human failures are essential for this model. As failures are rarely caused by one factor, this system validates all symptoms of the well in order to predict failures. According to Skalle, Aamodt and Laumann (2014), this system could be able to predict failures before they happen.

The research by Skalle, Aamodt and Laumann (2014) was the origin of this thesis.

3 Failures

Statistical information on historical failures are necessary to develop a predicting program that resembles reality. This chapter presents the most probable failures while drilling based on historical events. The historical failure distribution was used as a calibrating tool for the program. The motivation for obtaining historical data is to perform a history match of the program output. Modifications were required to make the historical data comparable to the program output.

3.1 Source of Historical Information

Pritchard, Roye & Espinoza-Gala (2012) present historical data related to failures while drilling. The statistics include information from 427 offshore wells located in the Gulf of Mexico between 2004 and 2010. 263 wells were drilled in shallow waters of less than 600 ft. 65 wells were drilled in subsalt deposits more than 3000 ft of water. Subsalt refers to oil reservoirs with overlying salt. The last 99 wells were pre-salt drilled in more than 3000 ft of water.

3.2 Most Probable Failures

The historical failure distribution shows the most probable failures while drilling. Figure 3-1 shows the unmodified historical failure distribution by Pritchard, Roye & Espinoza-Gala (2012).

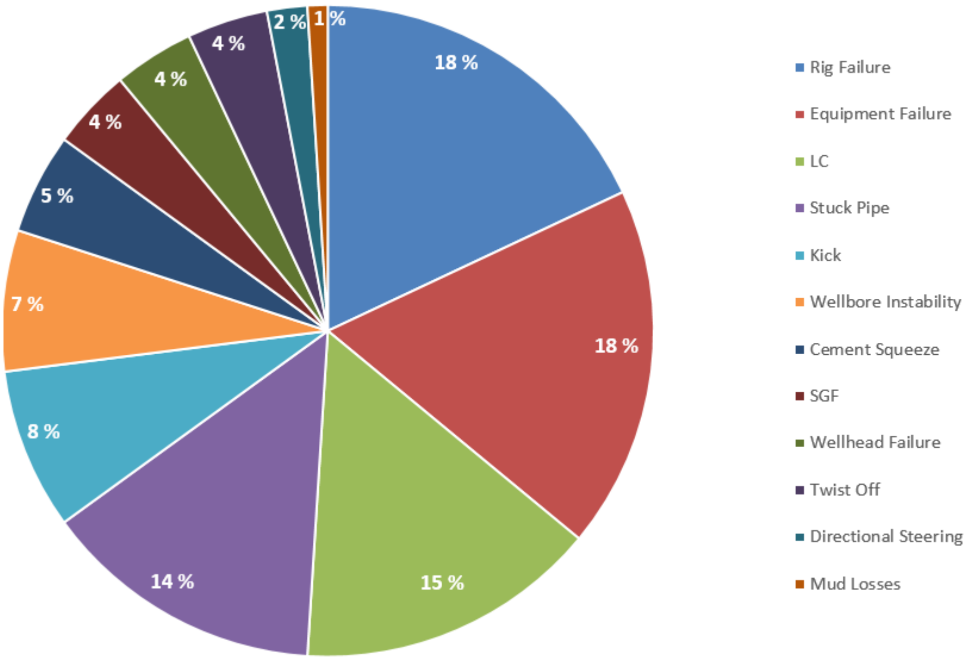


Figure 3-1: Historical failure distribution from 427 offshore wells in the Gulf of Mexico. Data is an average from the period 2004-2007 (Pritchard, Roye, & Espinoza-Gala, 2012).

Figure 3-1 shows a failure distribution in percent of total NPT from offshore wells drilled in the Mexico gulf. Skalle (2016) conducted a modification of the historical data to make it comparable to program output. Figure 3-2 shows the modified historical failure distribution.

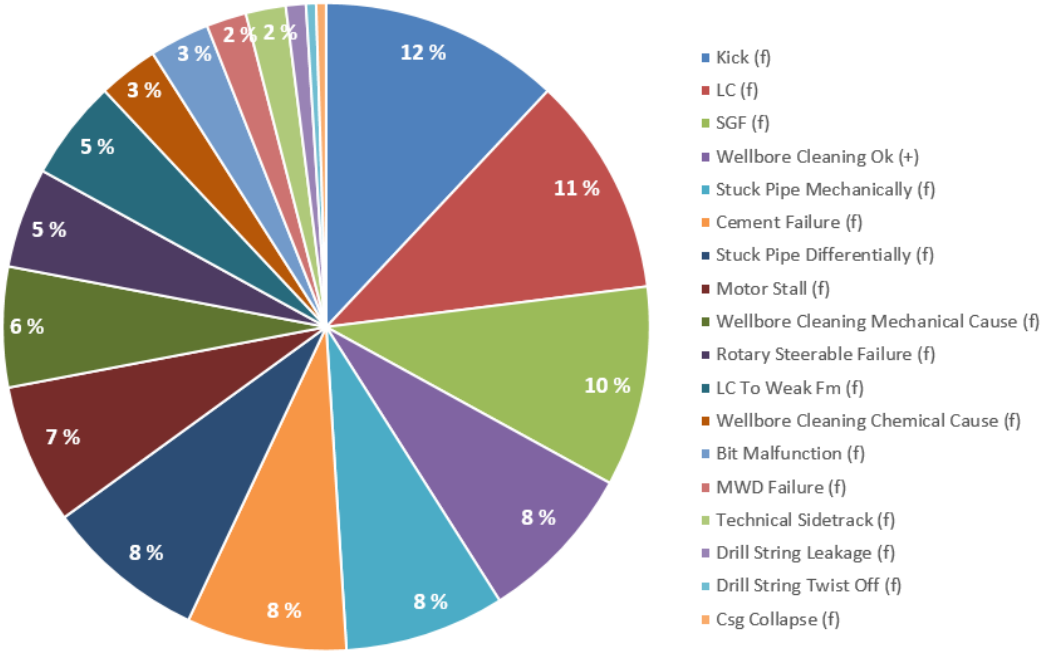


Figure 3-2: Modified historical failure distribution (Skalle, Discussion on modification of historical data, 2016)

Major modifications included:

- Equipment Failure – Removal of Top Drive Failure as part of Equipment Failure and the term renamed to MWD Failure.
- Rig Failure – Removal of the concept as the scope of our project is downhole.
- SGF – Upscaling Shallow Gas Formation to represent the difference in geology from the Gulf of Mexico and the North Sea.
- Wellbore Instability – Splitting the concept in two, a mechanical cause and a chemical cause.
- Directional Steering – Adjusting renaming the concept Technical Sidetrack.
- Cement Squeeze – Made the concept more general and renamed it Cement Failure.

Section 8.1 compares Figure 3-2 with program output.

4 Ontology

According to Wikipedia (2016), Ontology is the philosophical study of the nature of being, becoming, existence or reality, as well as the basic categories of being and their relations. Although ontology as a philosophical enterprise is highly theoretical, it also has practical application in informational science and technology, such as ontology engineering.

Process ontology describes the relationship between inputs and outputs (or concepts) by applying constraints (or relation-strengths) and sequencing the information. Process ontology has the closest relation to the ontology model of this development.

Figure 4-1 shows an example of two ontology relationships.

ECD – (minus) Pore Pressure Low (s) → 0.6 → Well Pressure Too Low (err)

Well Pressure Too Low (err) → 0.8 → Direct Factor Behind Kick (x)

Figure 4-1: Two relationships from the ontology. Upper: Low difference between the equivalent circulating density (ECD) and the pore pressure relates to a low well pressure. Lower: Low well pressure relates to the wellbore failure kick. The relation-strengths are 0.6 and 0.8 respectively.

The relationships shown in Figure 4-1 are two of hundreds relationships in a large database referred to as the ontology. A set of rules and definitions must exist to develop a predicting program based on these relationships.

4.1 Ontology Rules and Definitions

This section presents the rules and definitions that apply for the entire ontology. The rules and definitions exist to make ontology changes easier to apply. For simplicity, rules and definitions are as short and describing as possible.

4.1.1 Introductory Ontology Rules

1. A relationship exist of a left side, a right side and a middle placed percentage.
2. The middle placed percentage, referred to as relation-strength, explains the likelihood of the right side occurring given left side already occurred.
3. In the ontology, numbers 1 through 10 in the relation-strength indicate probabilities 10 through 100 in percentage.
    - In the program, all probabilities are fractions of one.
4. The left and the right side of a relationship are referred to as concepts.
5. The first name of a concept should reflect the main word / its meaning; i.e. Bit Balled, not Balled Bit.
6. A concept name must be as short as possible, but still precise enough to be unique.
7. Every concept must be pre-defined (see; Table A- 2)
8. Concepts are grouped in six entities (see; section 4.1.2).
9. Noun; each word starts with a capital letter.
10. An entity’s symbol bracket should be included when referring:
    - Static Symptoms (ss)
    - Symptoms (s)
    - Internal Parameters (i)
    - Errors (err)
    - Direct/Indirect Factor Behind Failure (x)
    - Failure (f)
11. Direct/Indirect Factor Behind Failure (x) can be referred to as DFBF (x) or IFBF (x) respectively.
12. All relationships should be read from left to right:

ECD – (minus) Pore Pressure Low (s) → 0.6 → Well Pressure Too Low (err)

Read as:

ECD – Pore Pressure Low (s) causes Well Pressure Too Low (err) with the likelihood of 60%.

Alternatively:

There is a 60% likelihood of a low-pressure related well error if an agent that tracks low values of ECD minus pore pressure is positive.

4.1.2 Different Concept Types

Each concept in a relationship has a defined type. This type explains the affect this entity has on the drilling operation. For simplicity, all types of concepts have been categorized into six entities and one combining AND term:

- (ss) – Static symptoms that are present due to drilling parameters.
- (s) – Symptoms that are located in the RTDD.
- (i) – Internal parameters that are non-observable.
- (err) – Errors caused by symptoms or internal parameters.
- (x) – Direct or indirect factors behind failures (DFBF/IFBF).
- (f) – Failures.
- AND – AND statements combines multiple (ss), (s), (i) or (err) concepts into one statement (see; section 4.1.3).

Static symptoms (ss) are known before the program is activated and are calculated based on drilling parameters from the drilling plan or EoW reports. Data agents scanning the RTDD detect symptoms (s). In early stages of development, the symptoms were found manually in the RTDD. Internal parameters (i), Errors (err), DFBF/IFBF (x) and Failures (f) are non-observable parameters. Detection of symptoms provide information about non-observable parameters. Failures (f) are intended to, as an end-result of this research project, to either be predicted or explained.

The relationship between these six types are one-directional. The following path rules exist:

1. (ss) can point to (ss), (s), (i), (err), AND and (x) concepts.
2. (s) can point to (s), (i), (err), AND and (x) concepts.
3. (i) can point to (i), (err), AND and (x) concepts.
4. (err) can point to (err), AND and (x) concepts.
5. (x) can point to (x) and (f) concepts.
6. AND can point to (ss), (s), (i), (err), AND and (x) concepts.
7. All paths must go through the (x) entity before reaching a (f).

Figure 4-2 shows an example of how these entities are related:

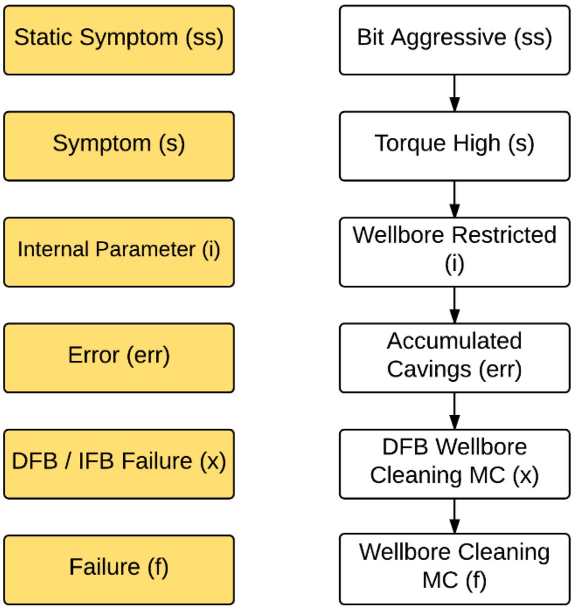


Figure 4-2: Relationship between the six entities. A path starts with symptoms and ends with failures. Arrows indicate the allowed direction of information flow.

4.1.3 The AND Concept

The combining AND concept requires additional rules due to the difference in application. Sometimes multiple concepts are required for an error or failure to be possible. The likelihood of an error or a failure may change when multiple concepts occur at once. The AND concept was added to the ontology to combine multiple concepts.

Figure 4-3 shows an AND relationship:

ECD – (minus) Collapse D Low (s) AND Shale Brittle (i) → 0.6 → Cavings Blocky (i)

Figure 4-3: An AND relationship. Shale Brittle (i) is required on the left side for ECD - Collapse D Low (s) to relate to Cavings Blocky (i). The relation-strength is 0.6.

The following rules applies for AND statements:

1. Can exist of two, three or four concepts.
2. Are only true if all individual concepts are true.
3. Can be a combination of equal entities or a combination of different entities.
4. The order of the concepts are chosen alphabetically.
5. All the rules stated in section 4.1.1 also applied to the AND statement.
6. All relationships can be read in normal order (see; rule 12 section 4.1.1)
7. When including prior probability (PP) (see; section 4.2) to AND statements, the lowest PP of the involved concepts should be used. The likelihood of the lowest one will dominate, as the statement is only as strong as its weakest contribution.
8. Only one relationship in an expanded series can be true at once (See; Expansion of Concepts below).

Expansion of Concepts

A single concept can be expanded into an AND statement consisting of multiple concepts. Expansion is done if adding concepts changes the relation-strength. Figure 4-4 shows expansion of Cuttings Concentration High (i) into an AND statement.

Cuttings Concentration High (i) → 0.2 → Accumulated Cuttings (err)

Cuttings Concentration High (i)
AND Cuttings Bed Erosion Low (s) → 0.6 → Accumulated Cuttings (err)

Figure 4-4: Expansion of Cuttings Concentration High (i). Upper: Single relationship. Lower: Cuttings Bed Erosion (s) are added to the left side as the relation-strength increases from 0.2 to 0.6. The lower AND statement is only true if both individual concepts are true.

Adding Cuttings Bed Erosion Low (s) to the left side in Figure 4-4 increases the likelihood of Accumulated Cuttings (err) from 20% to 60%.

4.1.4 The Current State of the Ontology

Development of the ontology was done by applying the rules and definitions from sections 4.1.1, 4.1.2 and 4.1.3 to all concepts and relationships (Skalle, Ontology, 2016). New information on drilling related failures continuously changes the ontology. Appendix A presents the current state of the ontology.

Precise definitions were developed for all concepts (Skalle, Ontology, 2016). Definitions help determine if the concept is true or false. Table A- 2 shows all concepts and their definitions.

Information provided in chapter 4 was necessary for developing the program (see; chapter 6).

4.2 Prior Probability

The program require entered symptoms to provide a failure probability distribution of next failure. The historical data is presented as a failure probability distribution. Entering all program symptoms are necessary to compare program output with historical data. A factor that includes the likelihood of occurrence are required to compare historical data and program output. The solution was to add a factor called prior probability (PP).

Relation-strengths represents the likelihood of concept B occurring given concept A already occurred (see; section 4.1.1). PP represents the likelihood of concept B (or concept A) occurring given no other information. The program output is comparable to historical data if all symptoms are entered and all PPs are included. When testing the program on real cases the PPs were naturally removed.

The PPs are defined as a factor of one and can be sub-divided as (Skalle, Ontology, 2016):

- 1.0 – Event occurs often every well section
- 0.5 – Event occurs seldom every well section
- 0.1 – Event occurs often every well
- 0.05 – Event occurs seldom every well
- 0.01 – Event occurs every 10th well

Table 4-1 shows PP of three concepts.

Table 4-1: PP of three concepts. Activity of drilling occurs 10 times more frequently than casing erosion and 20 times more frequently than erratic torque.

PP	**Concept**
1,00	Activity of Drilling (s)
0,10	Casing (csg) Erosion (i)
0,05	Torque Erratic (s)

Figure 4-5 shows where PPs are added in the relationships.

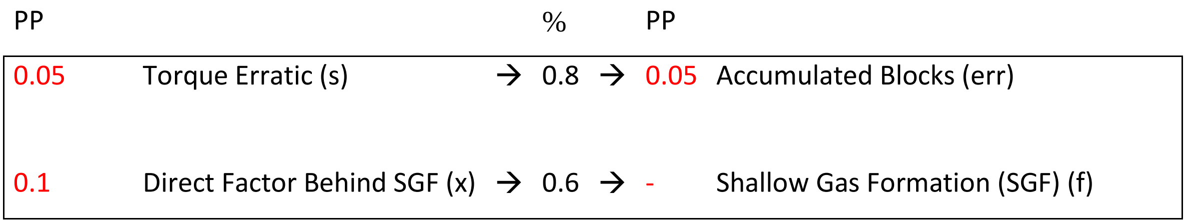


Figure 4-5: Two relationships with PPs in red numbers. Values 0.8 and 0.6 represent the relation-strengths for upper and lower relationships respectively.

The program output and historical data was compared when adding PP and entering all symptoms. Tuning of the program output was required to obtain a sufficient history match. The end of all paths in the program, the failures, such as shallow gas formation SGF (f), does not require a PP factor.

5 Agents

Symptoms (s) are detectable in the RTDD. In an ideal model, one agent exist for every symptom (s). Third party programmers are constantly developing new agents. Two agents have already been developed (Rosland & Årstad, 2016). These agents read RTDD and detect:

- ECD – (minus) Pore / Collapse / Fracture Pressure Low/High (s)
- Erratic Torque (s)

Matlab was used to develop and test the agents.

5.1 ECD Agent

Changing well pressure causes the original mud weight to change. This mud weight is called equivalent circulating density (ECD). To maintain stable drilling it is important to know the difference between the ECD and the pressure-boundaries (pore, collapse and fracture pressure). The equation for ECD is:

$$ECD = \rho_{mud} + \frac{\Delta P_{annulus} + \Delta P_{cuttings} + \Delta P_{surge,swab} + \Delta P_{rotation} + \Delta P_{acceleration}}{gz} \tag{5.1}$$

Neglecting the effect of cuttings transportation, rotation of the drill string and acceleration simplifies Equation 5.1:

$$ECD = \rho_{mud} + \frac{\Delta P_{annulus} + \Delta P_{surge,swab}}{gz} \tag{5.2}$$

Contributions from annular pressure change ($\Delta P_{annulus}$) and surge/swab pressure change ($\Delta P_{surge,swab}$) were calculated individually. The annular change is related to the pressure change from circulation while the surge and swab pressure change is related to pipe movement. The agent use the following RTDD to calculate ECD:

- Mud Density In (MDI)
- Running Speed Up (RSU)
- Running Speed Down (RSD)
- Measured Depth (DMEA)
- Vertical Depth (DVER)

Pressure boundaries were extracted from the EoW reports and created in a separate Matlab file. The agent finally applies Equation 5.2 on the RTTD and compares the calculated ECD and the pressure boundaries. Figure 5-1 shows how the agent operates.

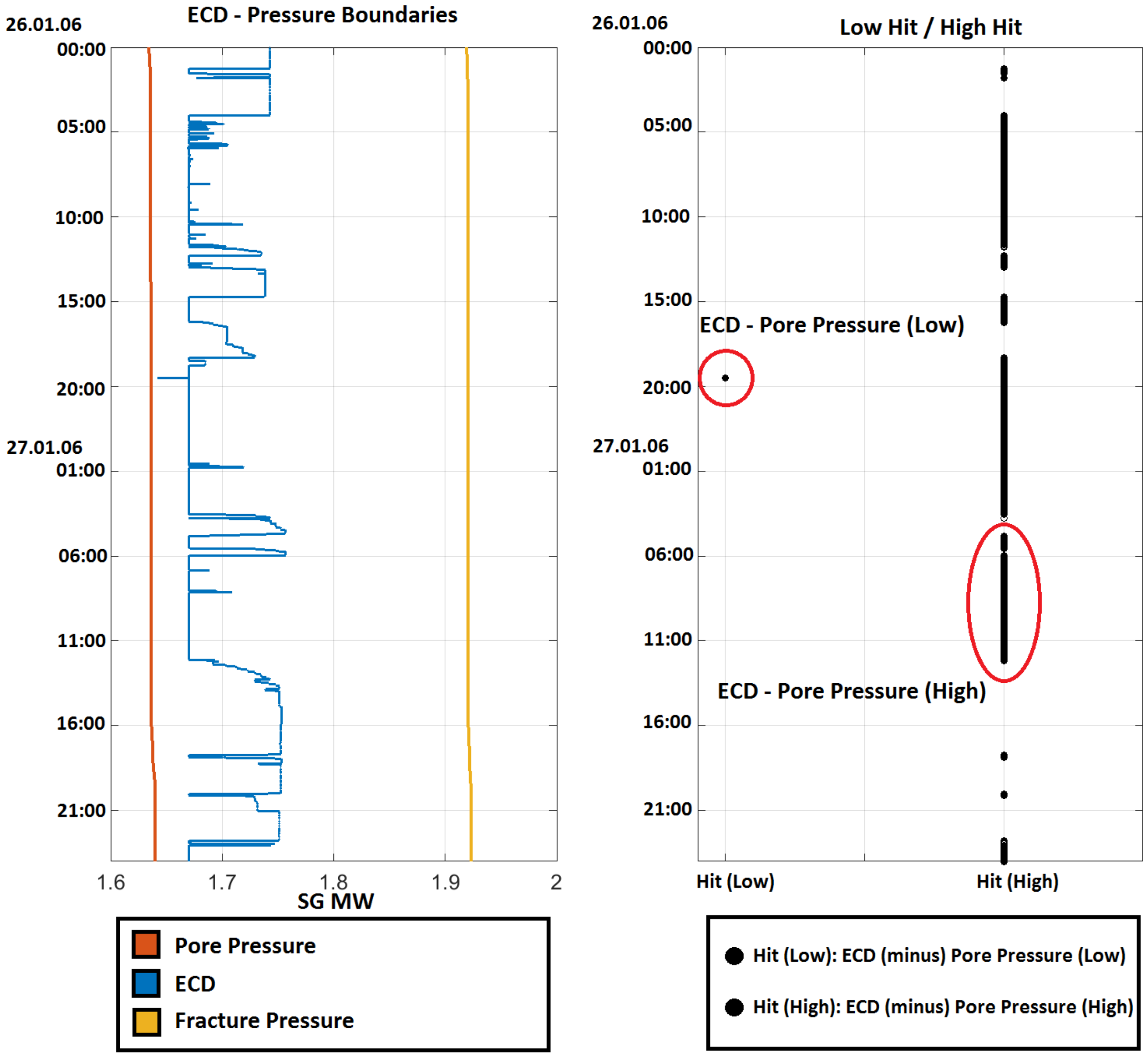


Figure 5-1: ECD Agent raw output. Left: Calculated ECD vs. extracted pressure boundaries. Right: Detected agent hits from left figure. Red circles are included to highlight some hits (Rosland & Årstad, 2016).

Figure 5-1 shows an occurrence of low difference between ECD and pore pressure at 19:50. A red circle on Hit (Low) indicates the hit. High differences occurred multiple times as seen by the continuous hits on Hit (High). Low and high hits are defined as a difference of significance for the operation. The operator allows the difference to be small (high or even low) when not drilling or tripping in manage-pressure drilling (MPD) mode. MPD drilling is the reason why multiple Hit (High) occurred in Figure 5-1. The two symptoms, ECD – Pore Pressure (High/Low) (s) would be true in this example.

Appendix B-1 presents the complete Matlab agent. Case 1 in section 7.3 shows actual use of the agent.

5.2 Erratic Torque Agent

The bottom hole assembly (BHA) experiences vibrations when drilling and reaming. Severe BHA vibrations can damage tools and hence cause NPT. Torque is required when drilling and experience show that erratic torque can cause severe BHA vibrations (Hughes, 2010). Reducing the likelihood of damaging the BHA is the motivation for developing an Erratic Torque agent.

Torque (TRQ) is measured while drilling and exists as a parameter in the RTDD. The goal was to develop an agent that monitors the torque while drilling and alerts the user when erratic torque occurs. The challenge was to recognize drilling and reaming periods. Weight on bit (WOB) and rotations per minute (RPM) was monitored to identify drilling periods.

Periods of erratic torque were determined based on the difference between present torque value and the previous torque value. The torque was defined as erratic if the difference exceeded a pre-defined threshold. Thresholds also exists for WOB and RPM to determine drilling periods. Equation 5.3, 5.4 and 5.5 shows the relevant equations.

$$\Delta Torque = Torque_i - Torque_{i-1} > Threshold \tag{5.3}$$

$$WOB > 0 \tag{5.4}$$

$$RPM > 0 \tag{5.5}$$

A manual interpretation referred to as tagging was performed before running the agent on RTDD. Tagging includes localizing erratic torque periods manually by looking at the RTDD. Figure 5-2 shows manual tagging of erratic torque.

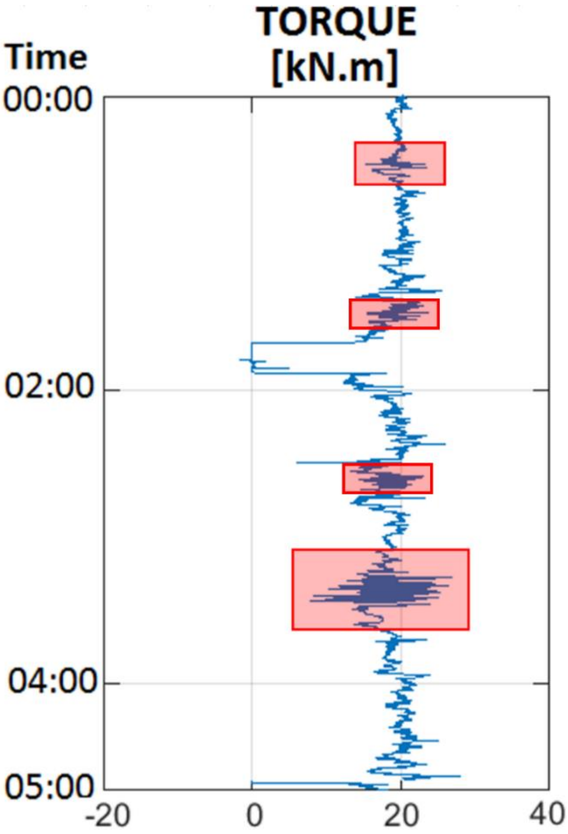


Figure 5-2: Manual tagging of the torque for a 5-hour period. Red boxes indicate erratic torque periods (Rosland & Årstad, 2016).

Equation 5.2 is applied to the torque data when the agent detects activity of drilling or reaming based on WOB and RPM. Figure 5-3 shows the raw agent output.

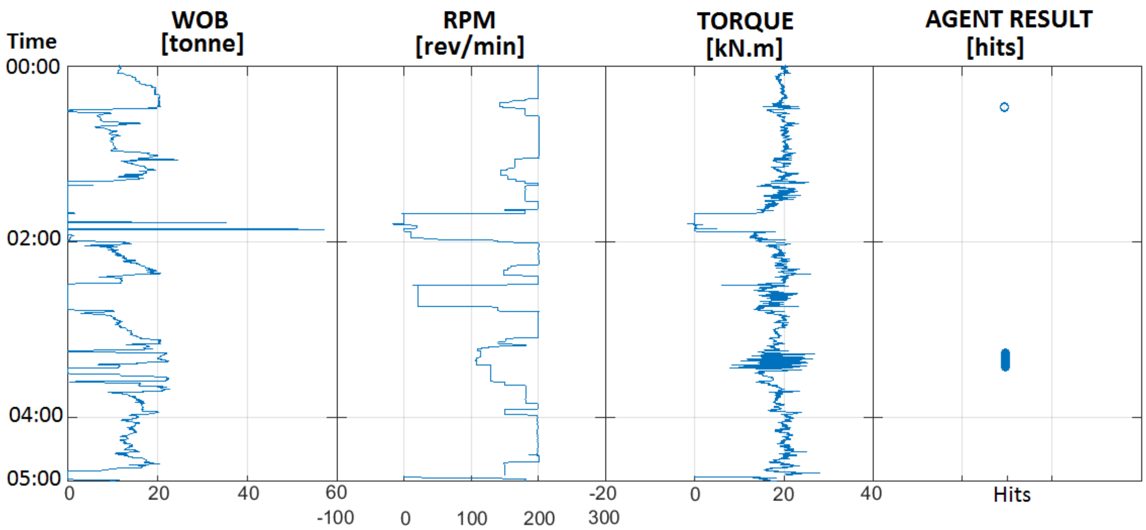


Figure 5-3: Raw output from running the agent with a torque threshold of 4 kN.m on a 5-hour period (Rosland & Årstad, 2016).

Figure 5-3 shows that the agent registered hits at approximately 00:30 and 03:15. Both periods are part of the manual tagging in Figure 5-2. The agent did not detect all the erratic torque periods from the manual tagging due to low WOB or RPM. Hits detected by the agent are transformed into Erratic Torque (s) hits in the input file.

Appendix B-2 presents the complete Matlab agent. The cases in sections 7.3, 7.4 and 7.5 show actual use of the agent.

6 Development of the Program

The goal was to develop a failure-predicting program. Information from the ontology (see; chapter 4) was used to calculate a probability distribution of the next failure. The development process is explained in sub-divided sections:

- The Idea
- Use of the Ontology
- Creating and Connecting Paths
- Integration of the Model
- Prior Probability
- Tuning of the Program
- Early Stages vs. Late Stages of Development

The entire project including the ontology, the input file, the program and the output file is referred as the model. The program developed in MS Excel is referred to as the program.

6.1 The Idea

The goal was to develop a failure-predicting model. The model includes a program that calculates the probability of potentially upcoming failures based on observed drilling parameters and symptoms. The program was developed on a database consisting of multiple relationships. These relationships were connected in a hierarchy. When a symptom is detected while drilling, the program returns an updated probability distribution. The initial idea was to connect relationships in a hierarchal structure.

According to UnixSpace (2016) "*the hierarchical data model organizes data in a tree structure. There is a hierarchy of parent and child data sections. This structure implies that a record can have repeating information, generally in the child data sections.*"

Figure 6-1 shows how a hierarchical data model organizes data.

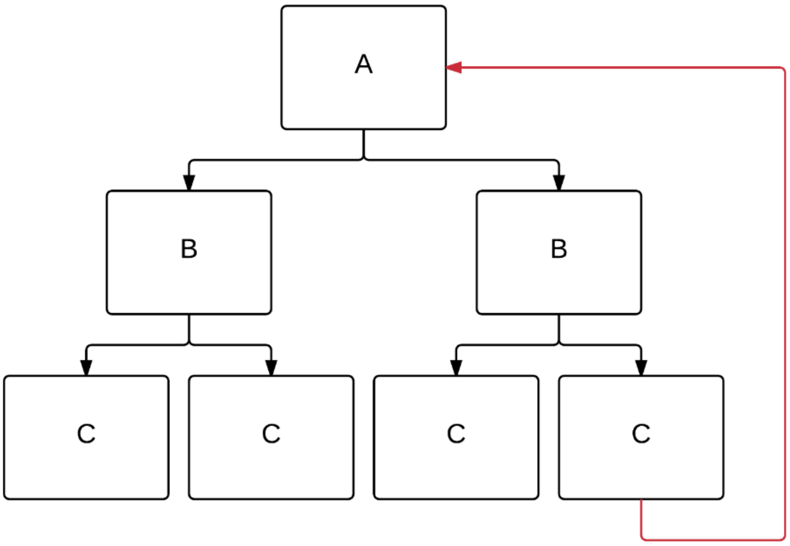


Figure 6-1: A hierarchy of parent (top) and children (below) data sections. Black arrows represent possible flows of information. The red arrow represents information flowing backwards (UnixSpace, 2016).

The idea was to put symptoms at the top and failures at the bottom of the hierarchy. Concepts were initially allowed to provide information backwards (shown by the red arrow in Figure 6-1), but this approach was later rejected due to programming issues (see; section 9.1 Development Method). Arrows in Figure 6-1 have two properties: a path and a relation-strength. These properties were provided by the ontology.

6.2 Use of the Ontology

This section explains how the ontology was used to support development of the program. The relationships in the ontology were used to create paths leading from symptoms to failures. The rules listed in chapter 4.1.1 were applied to the entire program. Important use of the ontology included:

- A relationship is one directional.
    - In early stages of development the relationships were bi-directional. In later stages it was necessary to make them one directional, the process is shown below:

Step 1 Relationships were divided by "causes" and "caused by":

	→ Causes	← Caused by	
A	0.8	0	B
A	0.7	0.2	C

Step 2 Relations were collected in three columns:

A	0.8	B	
A	0.7	C	
B	0	A	(invalid)
C	0.2	A	

Step 3 Opposite relations were added as all relations were considered bi-directional:

A	0.8	B	
A	0.7	C	
C	0.2	A	
B	0.8	A	(caused by)
C	0.7	A	(caused by)
A	0.2	C	(caused by)

Step 4 Removed all invalid relations. Concepts that points to another concept higher in the hierarchy (a failure that points to an error) was considered invalid relations and removed. Based on this, a new ontology was created that treated relationships as one directional.

    - In reality, some concepts provide information upwards in the hierarchy. Some information was lost when applying this one directional approach.
- All relationships contain a relation-strength.
    - Expressed as percentage in fractions of one (0.1 = 10%...1=100%)
- Skalle (2016) provided two equations for calculating the path-strengths and the failure-strengths.
- Path-strength is defined as the product of all relation-strengths of path i (Skalle, Building and testing ontology, 2016):

$$Path\ Strength = \prod (Relation\ Strength)_i \tag{6.1}$$

- Failure-strength is defined by as the sum of all path-strengths leading to failure j divided by the total path-strengths (Skalle, Building and testing ontology, 2016):

$$Failure\ Strength = \frac{\sum (Path\ Strength)_j}{\sum (Path\ Strength)_{total}} \tag{6.2}$$

- A failure distribution is a visual presentation of all the failure-strengths.
- The ontology is constantly adjusted and expanded. Adjusting the ontology cannot require major changes to the program.
    - For programming purposes this mean that the code should be kept as general as possible. A structure that runs even though small parts are changed was developed.

The bullet points above were applied when creating and connecting paths to form the program.

6.3 Creating and Connecting Paths

The main development process included creating paths and connecting them in a hierarchy. MS Excel was chosen as the programming platform. MS Excel allows storage and easy access to large databases. Each cell can include multiple calculations and if-statements which are essential when creating and connecting paths in a hierarchy. The process of creating and connecting paths are presented in five sub-divided paragraphs:

- Single Path
- Multiple Paths
- AND Series
- Loops
- Efficiency

Single Path

A path consists of two or more concepts connected to each other through causal relation-strengths. The right side concept in a relationship will have a pre-defined likelihood of occurring given the left side concept already occurred. This likelihood is referred to as relation-strength. Figure 6-2 shows how a single A to B relationship was programmed in MS Excel, exemplified by;

Water Depth High (ss) → 0.6 → Well Complex (i)

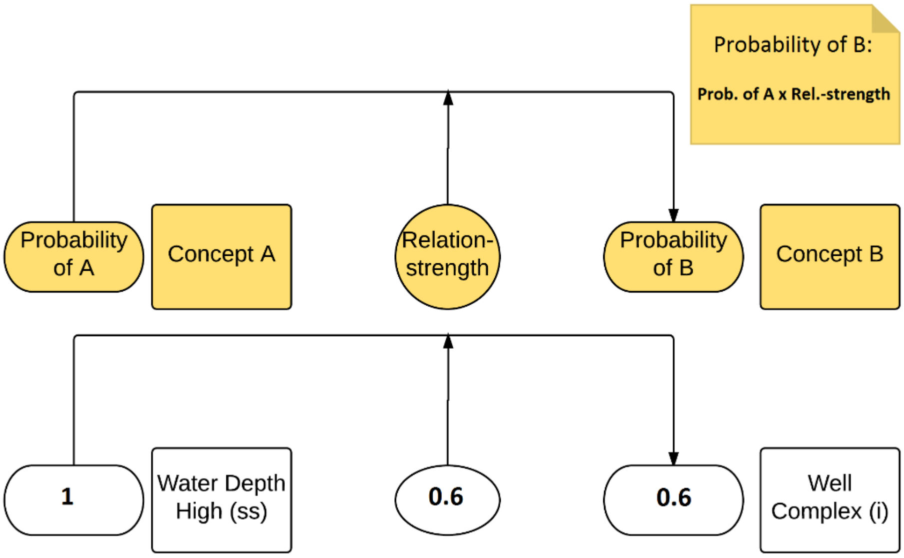


Figure 6-2: The process of programming a single relationship in MS Excel. The lower figure show an example of this process. All probabilities are now fractions of 1 (1 = 100 %). This figure does not include PP.

Symptoms were defined as true or false. A true/false value indicates that the symptom occurred with a probability of 1/0. Figure 6-2 shows that the static symptom Water Depth High (ss) occurred and is given the probability of one. The probability of Well Complex (i) becomes 0.6 due to the relation-strength of 0.6.

The next step was to expand the single relationship by connecting concept B to concept C. Figure 6-3 show the process of expanding a single relationship into a path.

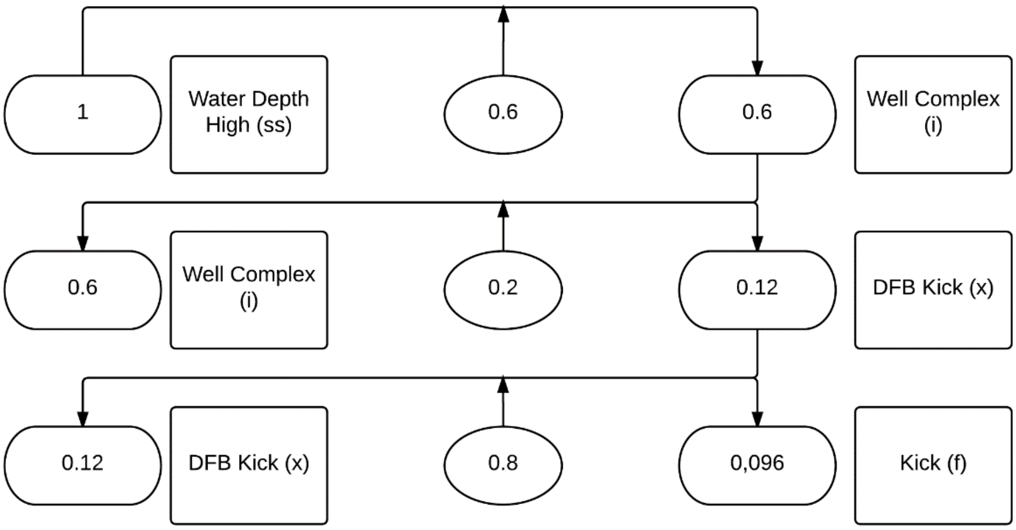


Figure 6-3: The process of expanding a single relationship (A to B) into a path (symptom to failure). The path starts with the static symptom Water Depth High (ss) and ends with the failure Kick (f).

The example in Figure 6-3 provides information about the likelihood of a kick occurring. The calculated path-strength was 0.096. A path always starts with a symptom and ends with a failure. Any types of entities can be represented. The minimum length of a path was initially two concepts but after introducing the collector entity DFBF/IFBF (x), it increased to a minimum of three concepts (symptom, DFBF/IFBF and failure). The maximum length that occurred in the program was eight concepts.

Multiple Paths

The path in Figure 6-3 is straightforward. Many concepts in the ontology pointed towards multiple causes. The next step was to expand the paths to include all causes. Figure 6-4 show how a complex hierarchy network looks.

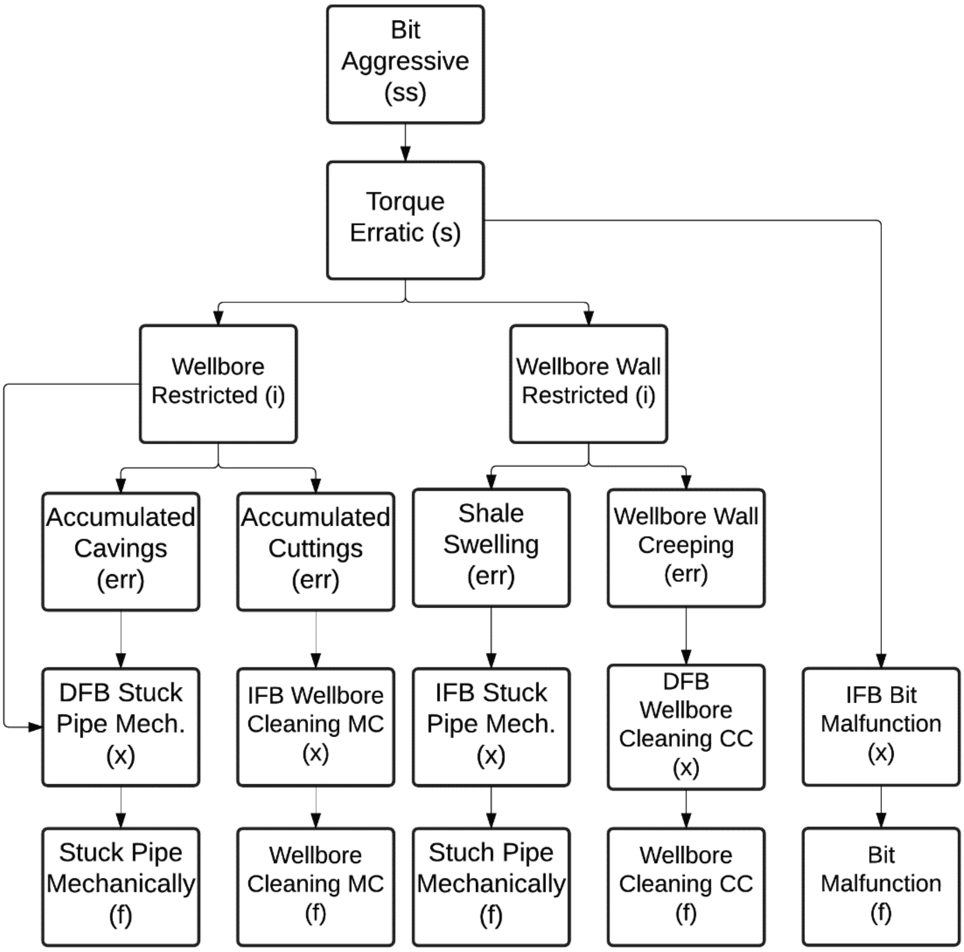


Figure 6-4: A complex hierarchy network. Concepts points to multiple causes. Arrows indicate paths. MC/CC (Mechanical/Chemical Cause).

Manually developing the network in Figure 6-4 was time consuming. To avoid re-development of the network at every change of model, a flexible approach explained later in this chapter was used (see; chapter 6.3, Efficiency).

AND Series

The AND statement (see; section 4.1.3) required additional rules to those applied in Figure 6-3. The following AND statement of concepts A, B and C is used to explain the additional rules:

$$(\mathbf{A}\ \text{ AND }\ \mathbf{B}\ \text{ AND }\ \mathbf{C}) \rightarrow \mathbf{D}$$

The rules applied were:

- All concepts must have a probability greater than zero for the cause to be valid.
    - **A**, **B** and **C** must be greater than zero for **D** to be true.
- If the statement is re-arranged to, **A** → (**B** AND **C** AND **D**), all concepts on the right side are given identical probabilities equal the probability of **A** multiplied by the relation-strength (see; Equation 6.3).

$$Prob\ (B) = Prob(C) = Prob(D) = Prob(A) * Relation\ strength \tag{6.3}$$

- If (**A** AND **B** AND **C)** → **D** The probability of **D** is determined as the average of all individual concepts (see; Equation 6.4).

$$Prob\ (D) = \frac{Prob(A) + Prob(B) + Prob(C)}{3} \tag{6.4}$$

Rule 8 in section 4.1.3 describes the expansion of a concept. This expansion requires an if-statement. If an expanded AND series is true, all lower versions of that series are automatically false. This is shown in figure Figure 6-5 when (**A** AND **B** AND **C**) is true, (**A** AND **B**) and (**A**) become false. Figure 6-5 shows how AND statements were programmed using if-statements.

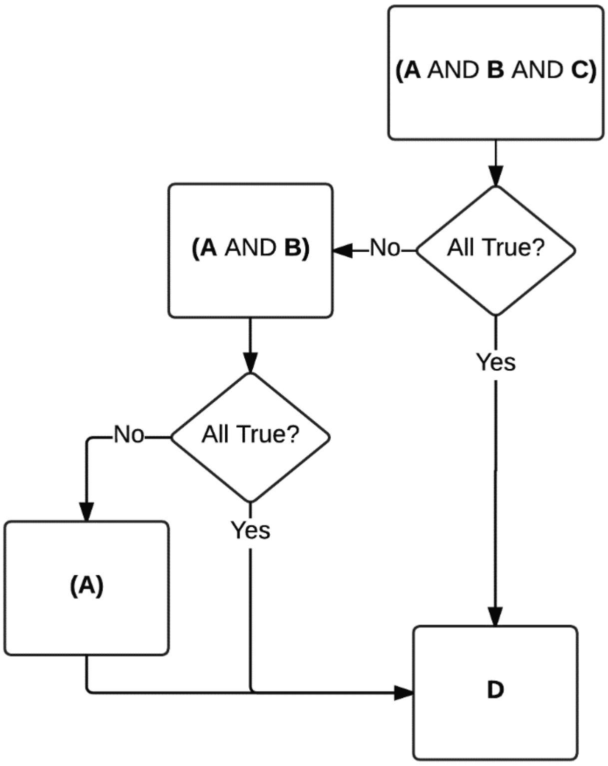


Figure 6-5: Handling AND statements using IF-statements. All versions of the series are pointing at the identical concept D. Square boxes are concepts. Diamond boxes are if-statements. Arrows are paths.

Figure 6-5 shows that only the largest version of competing AND series contributes toward the result. All lower versions are ignored (are false) if a higher relationship is true. The single relationship **A - D** applies only if all higher version of the AND series are false.

Loops

Initially the rules applied to the ontology (see; section 4.1.1) stated that concepts were bidirectional. From a programming point of view, this became a problem. Loops occurred when information was allowed to flow forwards and backwards. The red arrow in Figure 6-1 show the occurrence of a loop. This loop would cause the probability of concept A to increase towards infinity. Relationships were therefore arranged in one direction. Lower entities could no longer effect entities of a higher level (failures could no longer provide information backwards in the hierarchy). Applying a one directional approach was necessary but resulted in lost information.

Efficiency

Due to low efficiency when creating paths manually, a more efficient solution was necessary. The solution was to summarize all contributions toward concepts early instead of summarizing all the failures in the end. This summation could be done as path-strengths are calculated as a product (See; Equation 6.1). The amount of paths that had to be created manually were reduced as shown in Figure 6-6.

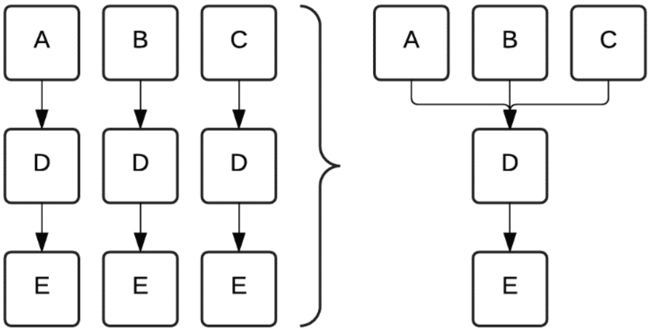


Figure 6-6: Summation of contributions towards concept D. Left: Three paths created manually. Right: One path where the three contributions towards D are summarized. Squares indicate concepts and arrows paths.

Figure 6-6 shows that the initial approach (left) required six relationships (arrows) while the new approach required four relations (arrows). The result from the new approach was a more efficient way to create paths manually.

The final program structure is included as a separate MS Excel file (see; Appendix D).

6.4 Integration of the Model

The complete model consists of three parts:

- Input File
- Program
- Result File

The program requires symptoms from the input file to calculate the failure distribution. The result file presents the failure distributions as pie charts. From a commercial point of view, only the input file and the result is necessary for the user. Figure 6-7 shows an overview of the model.

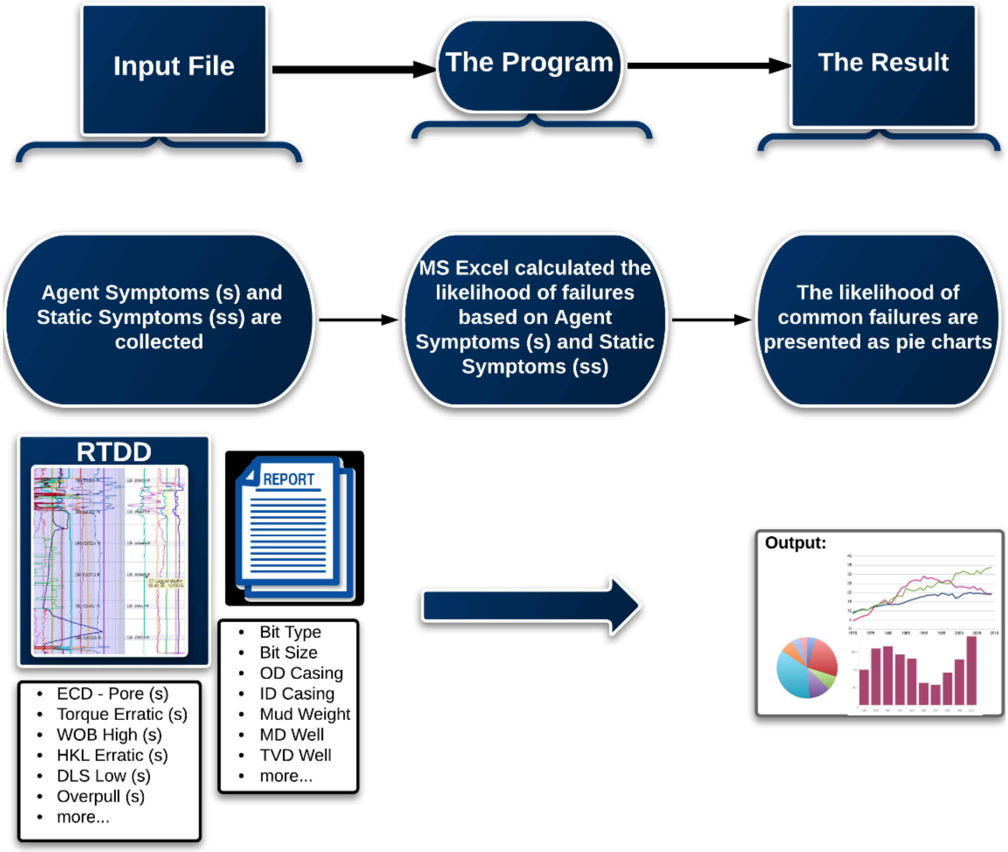


Figure 6-7: Overview of the model. Information flow is presented as arrows in three versions.

Input File

The input file contains all symptoms (true or false). The program obtains one value for each symptom. Static symptoms are known before drilling starts. Agents find RTDD symptoms during drilling. Whenever an agent registers a hit in the input file, the program file automatically updates accordingly. The input file is based on data obtained prior to and during drilling. Data required by the input file include:

- EoW Report
- RTDD
- Well Geometry

Section 7.1 explains how the data was used to determine symptoms.

Result File

The result file obtains the failure-strengths from the program. The file provides two types of result:

- **Case based failure distribution**
  This failure distribution includes symptoms that were active for a specific case.
- **General failure distribution**
  This failure distribution includes all symptoms and all PPs. A history match was performed on the general failure distribution.

Chapter 8 presents case based and general failure distributions.

6.5 Prior Probability

Tuning of the final program was required to match the historical data (see; chapter 3.2). The process of tuning involved adjusting the effect that one single concept or path had on the program output. The tuning process was repeated until the program output matched the historical data. PP (see; chapter 4.2) was added to all concepts except failures to make the result comparable to historical data. Chapter 6.6 discusses the tuning process.

It was believed that enabling all symptoms and including their occurrence likelihood, referred to as PP would cause the program output to match the historical data. Initially this was not the case, so relation-strengths and number of relations had to be changed.

Figure 6-8 shows how PP were added into the already existing program structure in Figure 6-3.

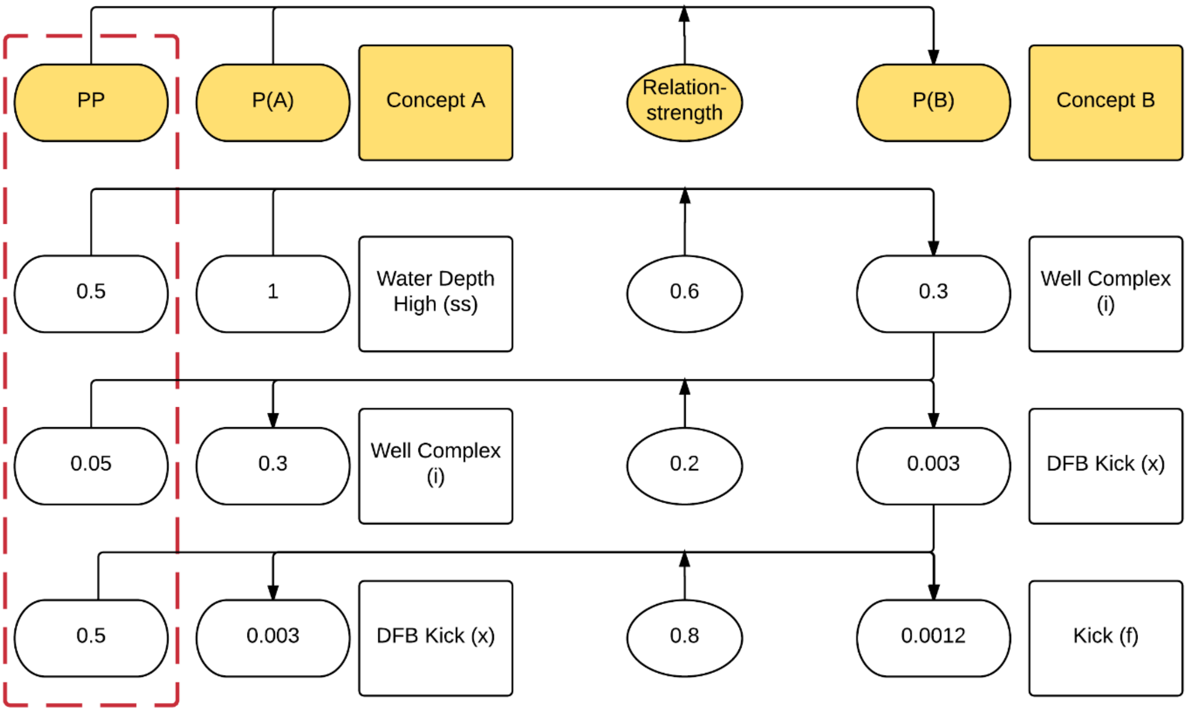


Figure 6-8: One path including PPs. Dotted line box: the addition of PP to already existing program structure.

Even though PPs only appear on the left side in Figure 6-8 they are effectively multiplied by all concepts as all right side concepts are repeated in the rows below. Figure 6-8 shows that Water Depth High (ss) has a PP of 0.5. Therefore, Water Depth High (ss) has a 0.5 probability of occurring if no other information is available. The new version of Equation 6.1 for estimating path-strength became:

$$Path\ Strength = \prod (Relation\ Strength_i * PP) \tag{6.3}$$

In Figure 6-8 the probability of Well Complex (i) is multiplied by a PP of 0.5 and reduced to 0.3 (in Figure 6-3 the probability of Well Complex (i) was 0.6). Equation 6.3 was only applied when tuning and comparing the program output to historical data.

6.6 Tuning of the Program

Tuning of the program was the final stage of model development. The tuning process resembles a history-matching process by comparing the program output to historical data. All symptoms were activated when comparing data. Concepts were multiplied by PP to make the program resemble a failure distribution.

The next steps were to change parameters within the program. Changes were made to:

1. Concepts (adding)
2. Relation-Strengths
3. Prior Probabilities

Changes were prioritized as shown above. It was preferred to add concepts (read; introduce more information) instead of changing relation-strengths and PPs.

Concepts
The ontology was constantly changed during program development. Concepts were verified and falsified. Some concepts dominated the result and some concepts were neglected. Concepts were added when a specific failure were underrepresented. A concept would only be removed if its relationship was falsified. Adding information was the preferred approach.

Relation-Strengths
Relation-strengths between the concepts were adjusted when a failure was wrongly represented and no new concepts could be added or removed. Relation-strengths were increased when the specific failure was underrepresented and decreased when the failure was overrepresented. Small changes to multiple relation-strengths instead of large changes to a few was the preferred approach.

Prior Probabilities
PPs were adjusted when a failure was wrongly represented and the relation-strengths could not be changed. Changing PPs were a simple process and did not require any changes to the program structure. An allowed range for the PPs were defined in section 4.2. The tuning process caused some of the PPs to deviate from the already defined ranged.

All changes to the program and the ontology were logical. Section 8.1 presents the final comparison of the program output and the historical data.

6.7 Early Stages vs. Late Stages of Program

The program changed multiple times during the development. Some pre-defined rules were rejected and some rules were added. This section summarizes important changes that were applied to the program from early stages to late stages.

- The initial ontology was changed multiple times during development. Major changes to the ontology often required major changes to the program structure.
- In early stages, all relationships were bidirectional. Later relationships were restricted as one directional to void the occurrence of loops (see; section 6.3). In practice this restriction meant that some information was lost as concepts low in the hierarchy could not provide information upwards in the hierarchy.
- In early stages, all the paths were created manually. In later stages, all contributions toward the same concept were added to reduce the total amount of paths. The new approach was time efficient and reduced the size of the program structure.
- In early stages, the expanding AND series (see; section 6.3) contained no restrictions. It was later realized that for expanding (competing) AND relations, only one relationship should be true. The alternative would of course overestimate the corresponding failure.
- PPs were introduced after the first version of the program became available. PPs allowed tuning of the program.
- When tuning the program it was discovered that the number of paths toward failures affects the program output. Because of this, the new DFBF/IFBF (x) entity was added next to all failures. Scaling the relation-strength of the (x) entity indirectly changed the number of paths towards the failure. The new addition made tuning more efficient.

The development process required multiple workovers because of the changes above.

7 Cases

To verify if program output resembles reality it is required to test it on real cases. This will approve or falsify the current state of the program. These cases also represent the real purpose of the development, to estimate the likelihood of drilling related failures before they happen. Some cases have all necessary data available while some cases have little data available. The quality of the test is related to the variety and quantity of available data. The cases were divided into three quality-classes:

- Type 1 – Cases where the failure is detectable in the RTDD and all necessary data is available.
- Type 2 – Cases where the failure is detectable in the RTDD but necessary data to predict the failure is missing. Type 2 failures require educated guesses where necessary data is missing.
- Type 3 – Cases where the failure is not detectable in the RTDD. Type 3 require educated guesses where important data is missing and where the failure occurred.

Multiple type 3 cases were found and rejected due to missing information on the failure. Three type 2 cases were found and have been created:

1. Lost Circulation failure in well C-147 (Type 2)
2. Motor Stall failure in well A-148 (Type 2)
3. Motor Stall failure in well C-147 (Type 2)

Full reports on these cases are presented in sections 7.3, 7.4 and 7.5 respectively.

7.1 Available Data

The amount of data available to the public is limited and the quality of the data is varying. EoW reports and RTDD were acquired in cooperation with anonymous operators companies. Available data is presented in declining order of importance:

- EoW Report
- RTDD
- Well Survey
- Other Information

7.1.1 EoW Report

The EoW report is the main source of information. It includes most, if not all of the drilling parameters available when drilling in real time. These drilling parameters are used to calculate Static Symptoms (ss). The accuracy of the symptoms are directly related to the accuracy in the EoW report. Modern reports include greater details as reporting and other NPT reducing data is important in a cost cutting industry.

Unfortunately, according to Oljedirektoratet (2015), a national law states that well data such as EoW reports can be held private for 20 years after well completion. Because of this law, most of the available reports are old with poor quality. Good quality EoW reports can cause type 1 cases while poor quality reports can cause type 2 cases.

Two EoW reports were available for this project, one for well C-147 and one for well A-148. As the time window is 12 hours, the drilling parameters were assumed constant from start to finish in all cases. Drilling parameters are continuously updated in a real case.

7.1.2 RTDD

Agents require RTDD to detect Symptoms (s). A case is automatically type 3 if RTDD is not available. As one goal was to monitor RTDD, it was important to find as many cases of type 1 or 2 as possible. Educated guessing, referred to as estimating, was required where parts of the RTDD was missing. Estimating includes assuming that some data agents are positive in a time prior to failure. Figure 7-1 shows example of RTDD.

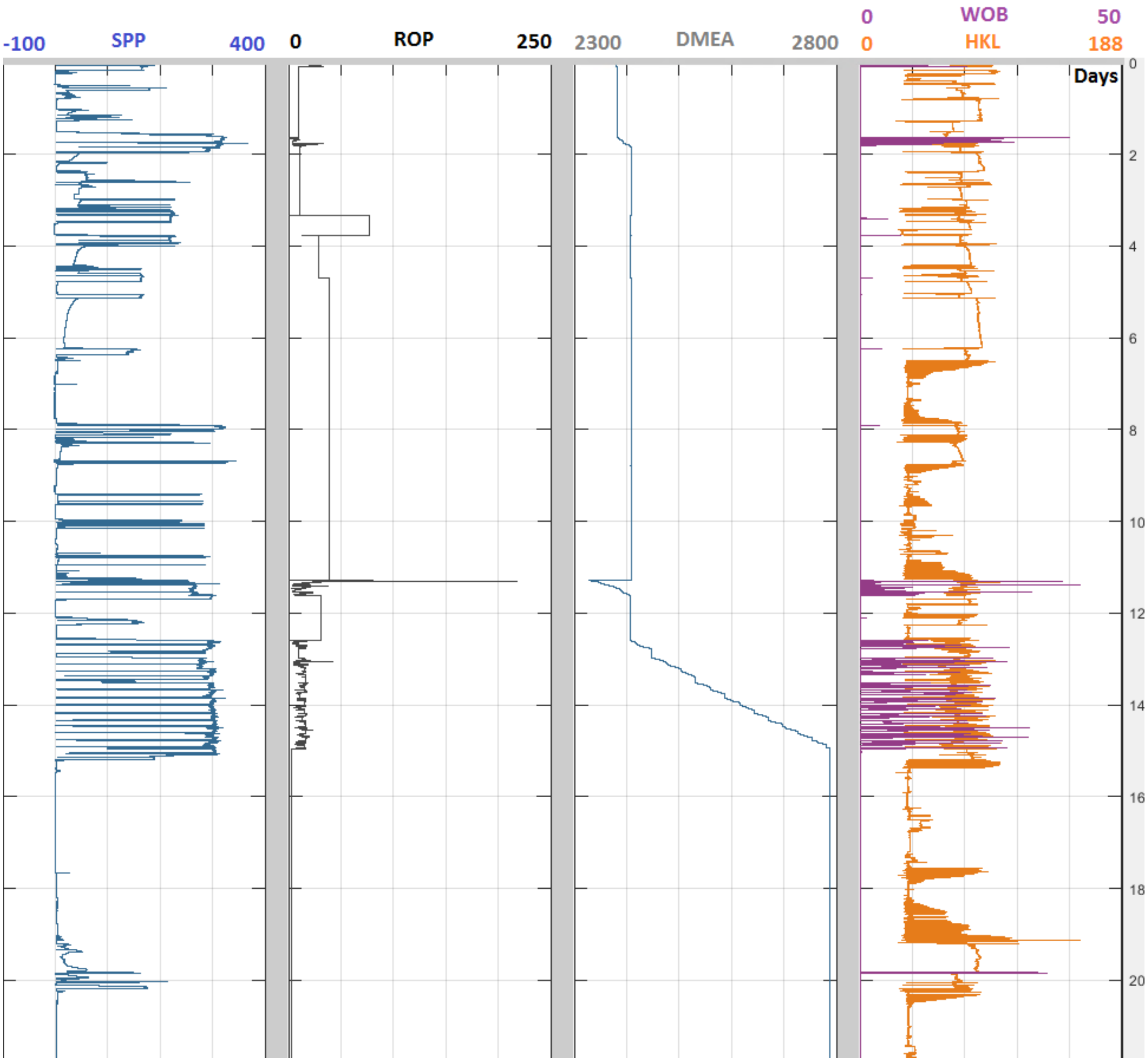


Figure 7-1: 22 days of RTDD – From left to right: Stand Pipe Pressure (SPP), Rate of Penetration (ROP), Measured Depth (DMEA), Weight on Bit (WOB) and Hook Load (HKL). Vertical axis is time in days (Operator, RTDD, 2006) (Raknes, 2014).

RTDD can include up to 78 different logs (see; Appendix C). A Matlab script developed by Verdande Technology was used to visualize and handle RTDD (Raknes, 2014). RTDD was available for all sections in well C-147 and for the 8 1/2” section in well A-148.

7.1.3 Well Survey

A detailed well survey and well schematics describes the well geometry. Build-ups and drop-offs can cause severe forces on the borehole wall and casing. Because of this, the well geometry and the well components affect the probability of a failure. Well survey and well schematics provide information such as:

- Well inclinations, azimuths, N/S and E/W deviations
- Measured Depth (MD) and True Vertical Depth (TVD)
- Casing setting depths
- Casing types and sizes
- Open hole zones

Depth for mid build-ups and drop-offs are determined based on the information above. Well survey and well schematics were included as part of the EoW reports for C-147 and A-148.

7.1.4 Other Information

Other information that was useful when predicting failures included:

- Experience from drilling surrounding wells and similar wells. This experience can be correlated to match the current well.
- Geology reports which are useful to determine the presence of fractures, boundaries, special formations and other formation related issues.
- Incident reports from surrounding and similar wells which can prevent repeating mistakes.

Well A-148 was side-tracked into A-148T. Information from A-148T was correlated and applied to A-148. A detailed geology report was available for well A-148.

7.2 Case Template

A case template was created to make the process of creating cases smooth and streamlined. The template provides preinstalled formulas for calculating static symptoms from drilling parameters. The template was created in MS Excel and integrated into the probability program. MS Excel allows the user to store RTDD figures, add interpretations and handle large amounts of data easily. The template was divided into four sheets, namely:

- Sheet #1: Well Description
- Sheet #2: RTDD
- Sheet #3: Well Survey
- Sheet #4: Input File

Sheet #4 includes an interpretation of the information provided in Sheet #1 – Sheet #3.

Sheet #1: Well Description

General information about the case, such as:

- Well name, failure number, failure type, well section, time of occurrence and a summary of the events prior to failure, during failure and after failure.
- Well schematics to provide information about the construction.
- Pressure plots, boundaries, mud weight (MW) and ECD (if available).

Sheet #2: RTDD

Includes figures and interpretation of RTDD. The RTDD were used to manually find symptoms (s). In a real case, agents detect symptoms (s). The RTDD was generally presented as:

- **Overview of RTDD**
  explains the situation and highlights important events prior to failure (for example 24 hours – a week prior to failure).
- **Narrow interpretation of RTDD**
  interpretation of the last 6 - 12 hours of RTDD. The narrow selection provides details about the events prior to failure.

Presentation of RTDD was in macro and micro perspective. Table 7-1 shows common logs included in the RTDD. Table C- 1 shows all logs represented in the RTDD.

Table 7-1: Common logs included in the RTDD. Block Position (BPOS), Mud Flow In (MFI), Torque (TRQ). Additional logs are included in column four when needed.

		MFI	
	BPOS	SPP	
DMEA	HKL	WOB	TRQ

Sheet #3: Well Survey

Well survey was included when available in the EoW report. Survey data was plotted as:

- MD vs. Inclination
    - Determines mid build-up and drop-off depths.
- MD vs. Azimuth
- MD vs. Dog Leg
    - Determines sections with severe dogleg (DLS).
- TVD vs. N/S and E/W
    - Provides information about the bit location relative to the rig.

Complete survey data was available for wells C-147 and A-148.

Sheet #4: Input File

Combines and prepares information provided in Sheet #1, 2 and 3. The input file automatically transforms drilling parameters into Static Symptoms (ss) hits. Symptoms (s) are detected manually in the interpretation of RTDD in Sheet #2. The process of determining symptoms are shown below:

1. Drilling parameters are listed in a pre-defined table (see; Table 7-2).
2. Formulas inside the table use these parameters to calculate static symptoms (ss).
3. The formulas determine if a static symptom occurred or not (true or false). The static symptoms are listed in a table (see; Table 7-3).
4. The manual interpretation of symptoms (s) in the RTDD are collected in a table (see; Table 7-4). Symptoms (s) are detected (is true) in the RTDD.
5. All symptom hits (true values) are provided to the program.

The current state of the input file is static. Static means that when a symptom is entered, it remains active until removed. When testing cases, all symptoms within the time window are entered at once. In a real case, symptoms would be entered as they occurred and removed when they no longer affect the operation. Manually changing the state of symptoms every second in a 12-hour period is time consuming. To resemble a realistic scenario, all time windows were divided into three periods, namely:

- Long Period: 12 hrs prior to failure to nine hrs prior to failure.
- Middle Period: nine hrs prior to failure to six hrs prior to failure.
- Short Period: six hrs prior to failure to seconds before the occurrence.

A timeline that shows these periods and how they affect the program output can was produced. The case template provided in section 7.2 was used to create cases in sections 7.3, 7.4 and 7.5. The cases were one lost circulation failure and two motor stall failures. The amount of information presented declines with the cases:

- Case 1 includes an explanation of how all symptoms were determined.
- Case 2 only includes some explanation of how symptoms were determined.
- Case 3 includes no explanation of how symptoms were determined.

Such decline was necessary to present multiple cases within the time of the project.

7.3 Case 1: Lost Circulation

Sheet #1: Well Description

Well C-147 was drilled in 2005/2006. The well entered the reservoir horizontally. The well was drilled and completed in managed pressure drilling (MPD) mode.

General Information

Provided in the EoW report (Operator, EoW Report, 2006).

Well Name:	C-147
Failure Type:	Lost Circulation (LC) (Type 2)
Failure No:	LC #1
Section:	12 1/4"
Depth of Occurrence:	2407 m MD / 1750 m TVD
Time of Occurrence:	27.01.2006 19:30
NPT	264 hours (approximately)

Summary Prior to Failure

Summary of events prior to the failure:	The 12 1/4" section was drilled using OBM in MPD mode where the choke was adjusted to keep the BHP close to the pore pressure. It was drilled using a mud motor and 8 1/2" PDC bit with 10 5/8" x 12 1/4" reamer wings. This equipment was used because a regular bit would not pass the rotating BOP. The 12 1/4" hole was drilled from 2383 m MD with 3000 lpm, 130 RPM. BHP was adjusted to 310 bars by the choke. At 2407 m MD while reaming one single, the BHP was gradually increased to prepare the well for the high pressure Shetland Zone.
Summary of events during the failure:	After increasing the BHP to 315 bars, the pressure dropped and 10 m3 mud was lost into formation. The losses were then stabilized by reducing the BHP. A loss free rate was established with 2800 lpm and BHP at 311 bar (ECD = 1.82 SG EMW).
Summary of events after the failure:	A Versa Pack pill was tried set and squeezed into formation at 2225 m MD. This pill serve the purpose of plugging the leak. A dynamically FIT was performed to 1.88 SG EMW, but another 17 m3 mud was lost at 1.854 SG EMW. Another pill of 6m3 was then mixed and squeezed into formation. A new dynamically FIT was performed after the plug had set up, but the pressure still leaked off at 1.86 SG EMW. The hole was then logged again to find the loss area. It was expected to find a resistivity peak due to the 2nd pill, but no resistivity change was seen. A total of 100 m^3 mud was lost to formation. It was decided to kill the well.

Well schematics were located in the EoW report and are shown in Figure 7-2. The schematics were improved due to poor quality. The schematics provide easy-to-read information about the well construction. The point of failure occurred after drilling only 48 m MD, it is thus a close distance between the 13 3/8” casing shoe and the point of failure. Detailed well survey is presented in Sheet #3.

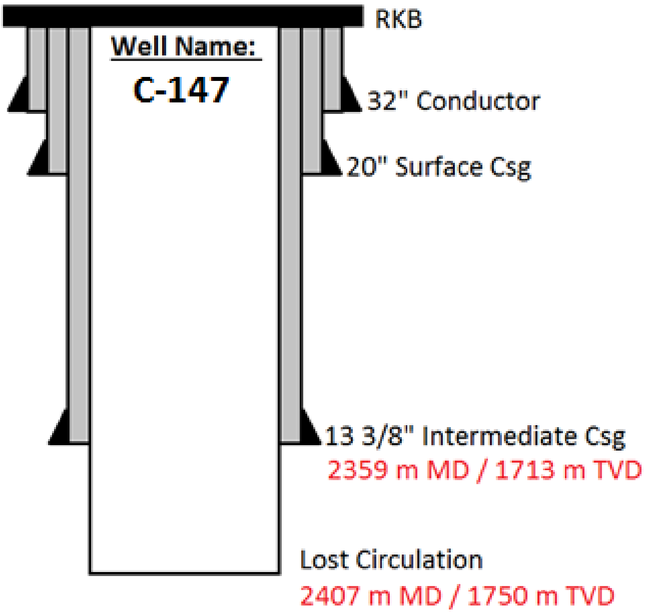


Figure 7-2: Well schematics for well C-147. Black writing indicates casing types, casing sizes and point of failure. Red indicate depths. Free after (Operator, EoW Report, 2006).

Detailed pressure plots were included in the EoW report. Figure 7-3 shows a plot of pressure (SG EMW) vs TVD (m).

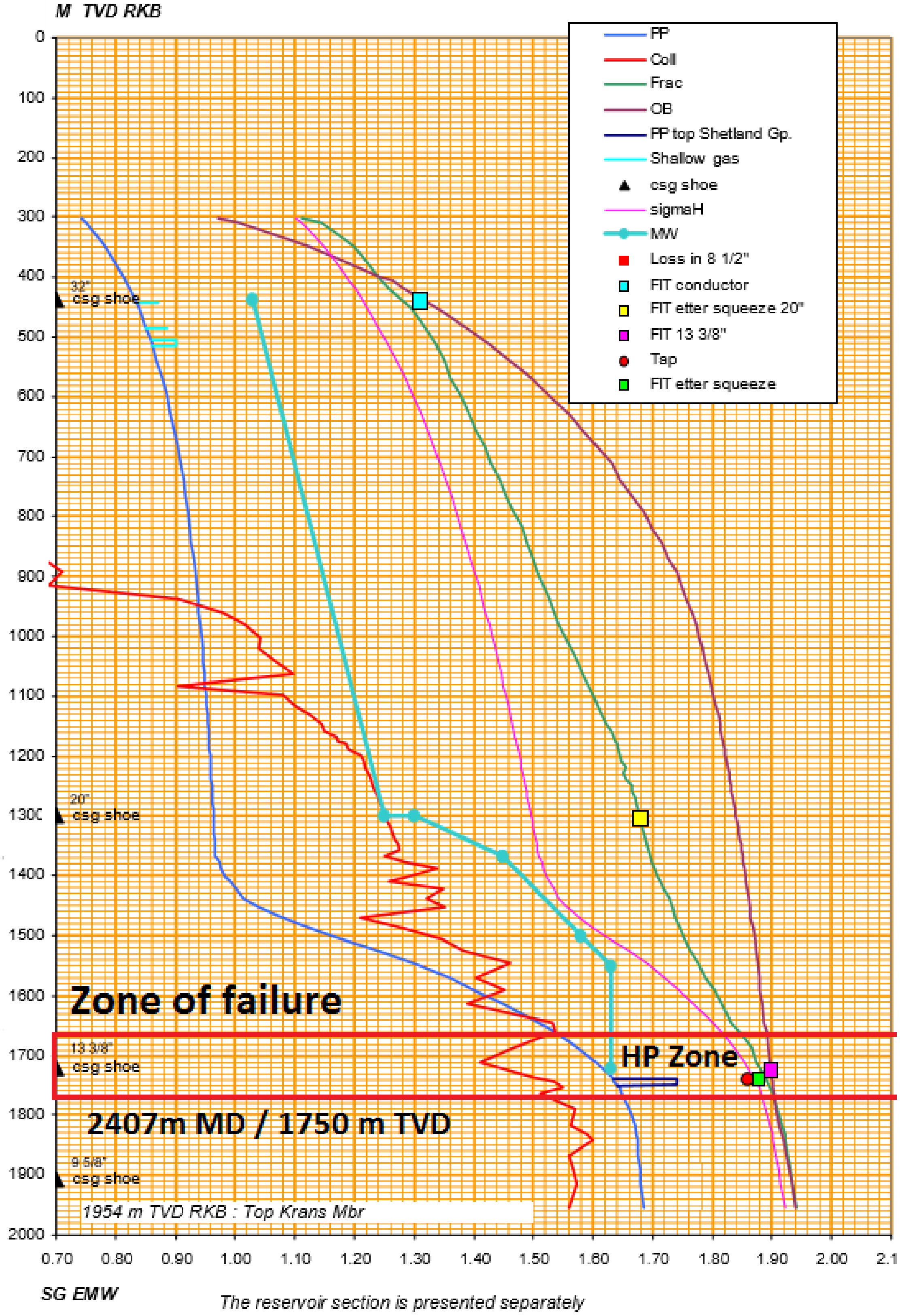


Figure 7-3: Pressure Plot for well C-147. Blue line: Pore pressure boundary. Red Line: Collapse boundary. Cyan line: Mud weight. Pink Line: Sigma H. Green Line: Fracture boundary. Brown Line: Overburden pressure boundary. Free after (Operator, EoW Report, 2006).

The MW was allowed close to the pore pressure boundary as drilling was done in MPD mode. Notice the pressure increase in the high-pressure (HP) zone where the pore pressure increased by 0.1 SG EMW. It was at this depth that the well pressure was increased and the formation started leaking. Square boxes indicate different formation integrity tests (FIT). The Shetland Group consist of high-pressure shale (NORLEX, 2016). Formation symptoms were detected based on this information about the formation and the pressure regime.

Sheet #2: RTDD

All figures of RTDD includes drafted ideas and key points of interest that is described in detail later.

RTDD is presented in the following order:

- 24 hours prior to failure.
- Interpretation of last 12 hour prior to failure.
- Manual symptom detecting from the last 12 hours of RTDD.

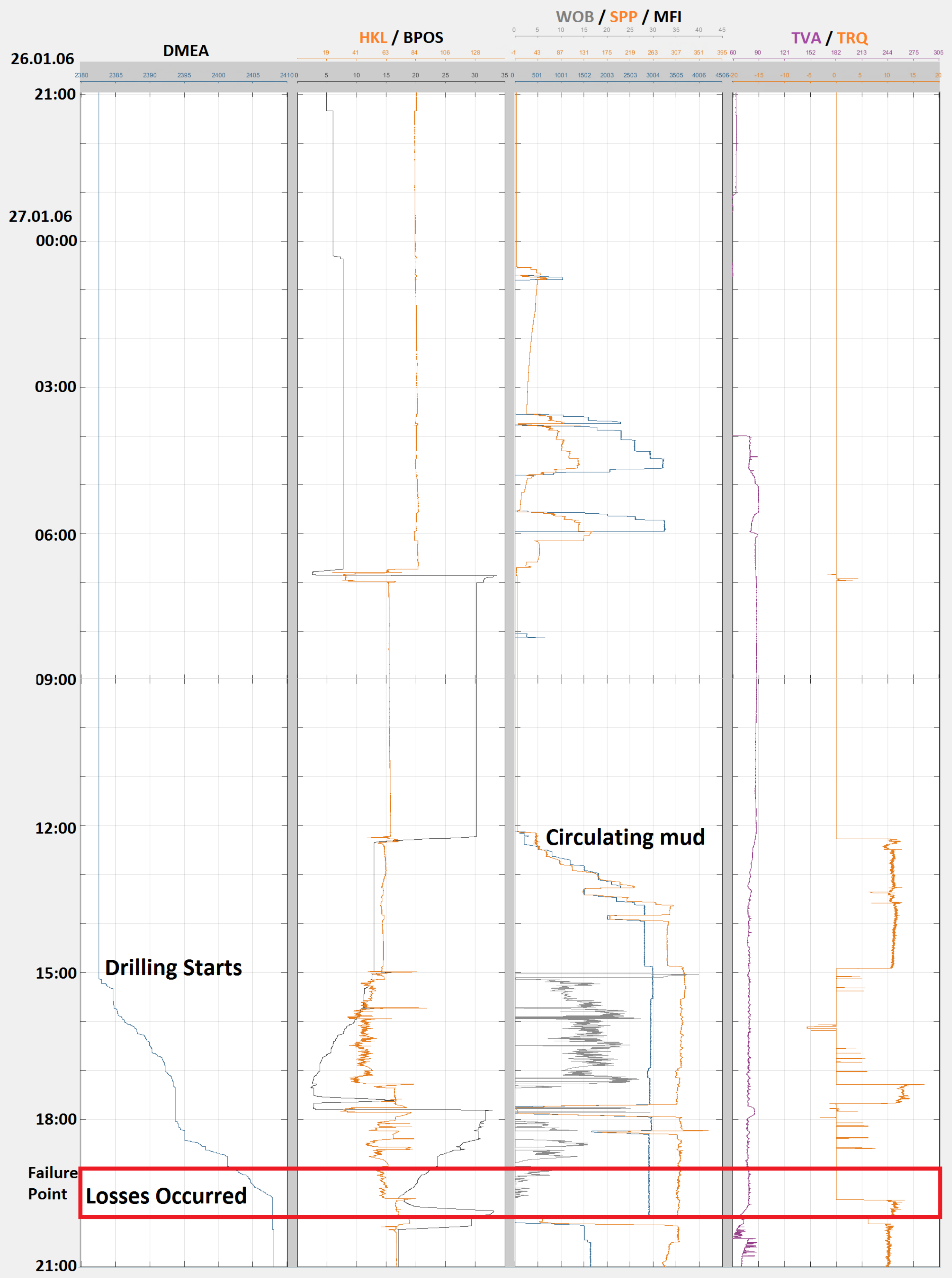


Figure 7-4: RTDD 24 hour prior to failure. Black writing is comments. Red box indicate the period where LC occurred (Raknes, 2014), free after (Operator, RTDD, 2006).

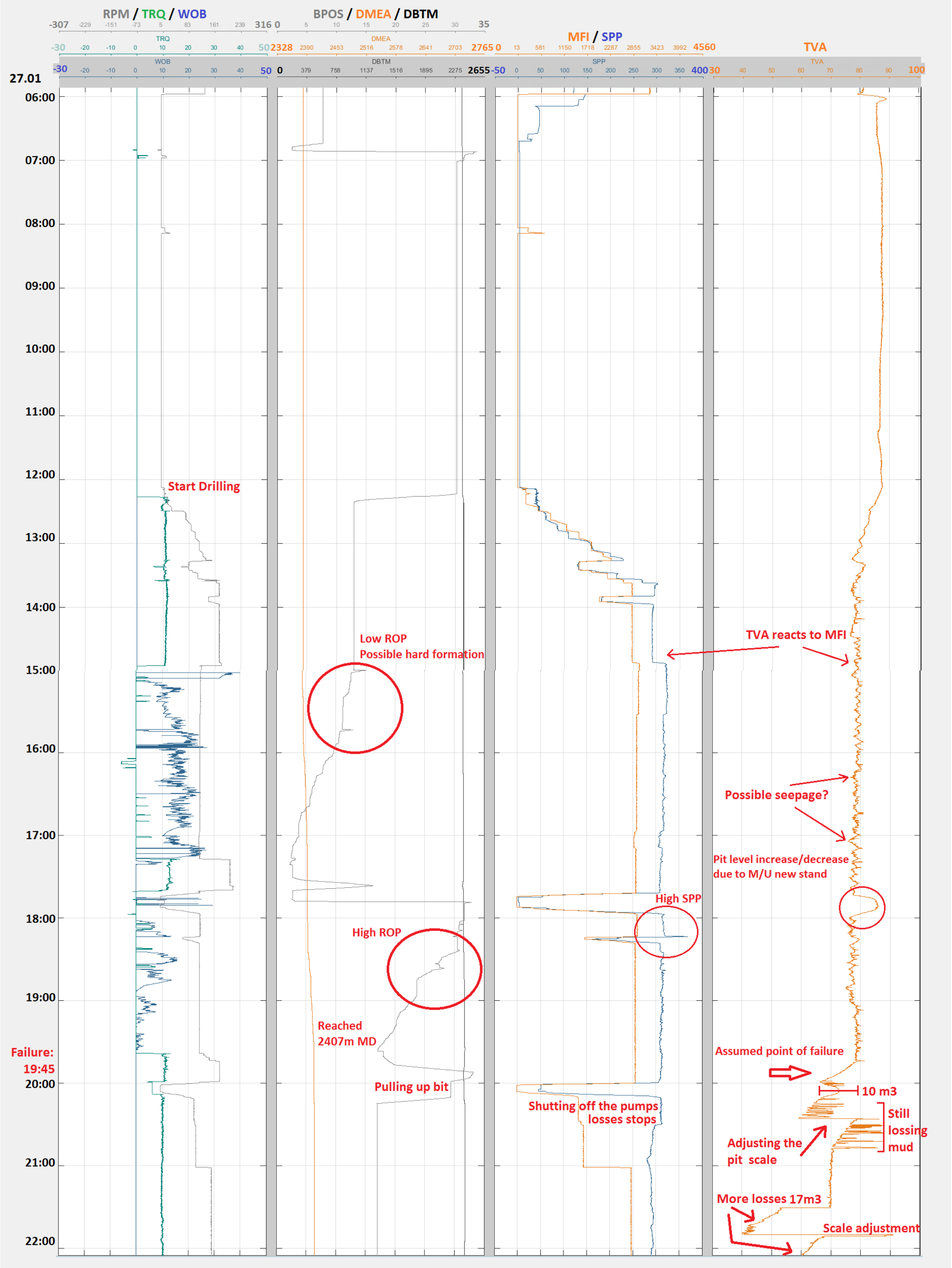


Figure 7-5: Interpretation of the RTDD. 12 hours prior to failure. Red writing indicate comments (Raknes, 2014), free after (Operator, RTDD, 2006).

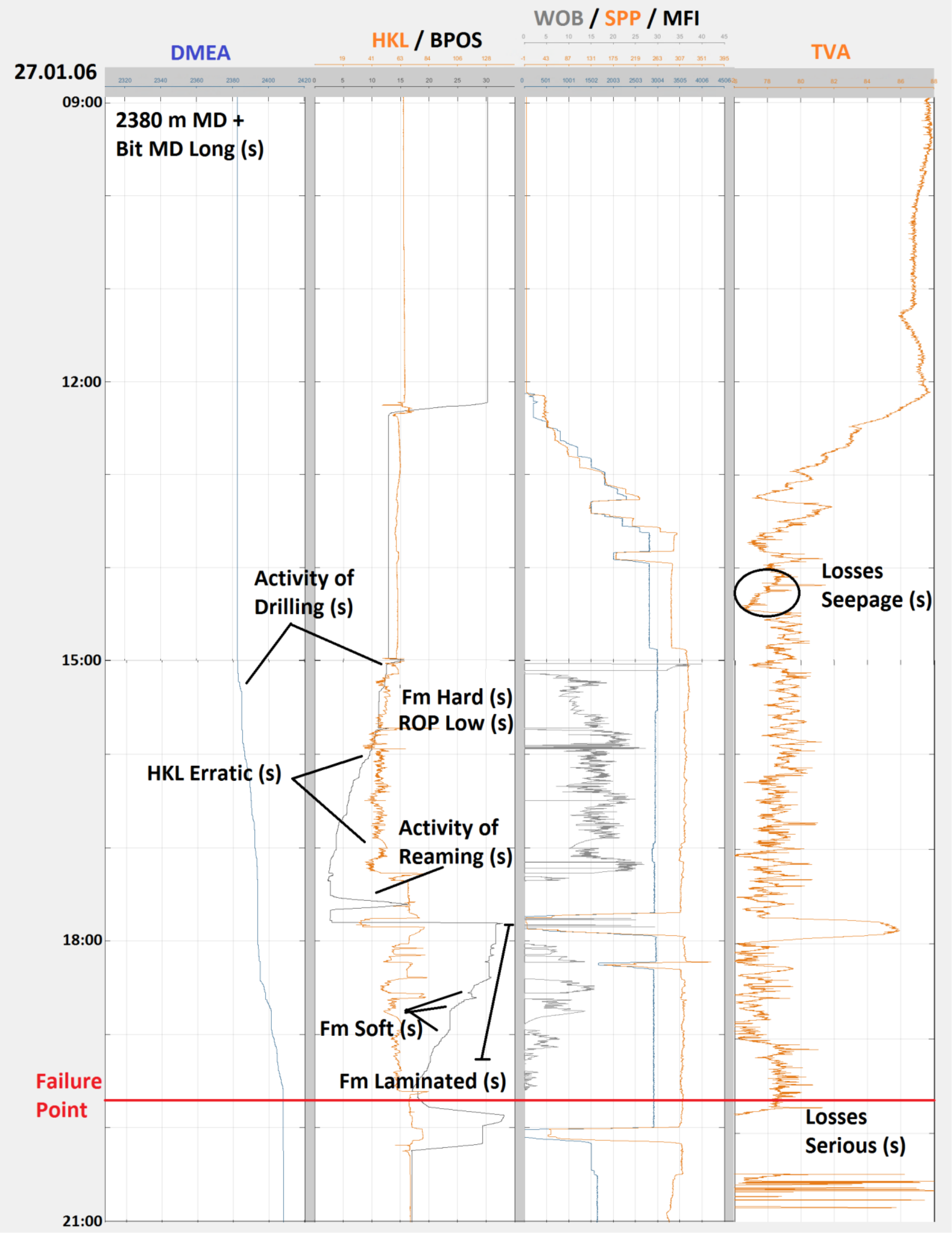


Figure 7-6: Symptom (s) detecting in the RTDD. 12 hours prior to failure. Only the earliest occurrence of each symptom is included. Ten symptoms were detected in the RTDD, these are shown in black writing (Raknes, 2014), free after (Operator, RTDD, 2006).

Table 7-4 summarize the symptoms detected in Figure 7-6.

Sheet #3: Well Survey

Complete gyro-measured well survey was available for C-137. The survey included the following data:

- Measured Depth (m)
- Inclination (deg)
- Azimuth (deg)
- TVD (m)
- North / South (m)
- East / West (m)
- Dog Leg (deg/30m)

Figure 7-7 shows how mid build-ups were found by plotting MD vs. inclination.

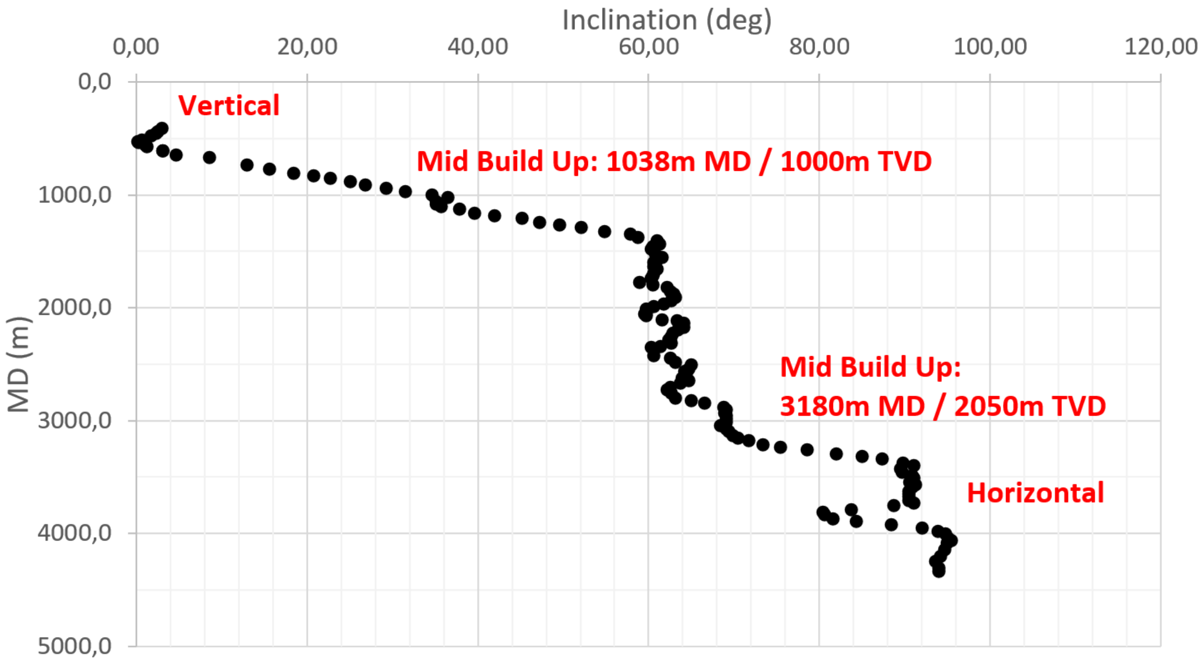


Figure 7-7: Well Survey. Measured Depth (m) vs. Inclination (deg). Build-up periods are included in red. Free after (Operator, EoW Report, 2006).

Figure 7-8 shows the calculated dogleg for the entire well section.

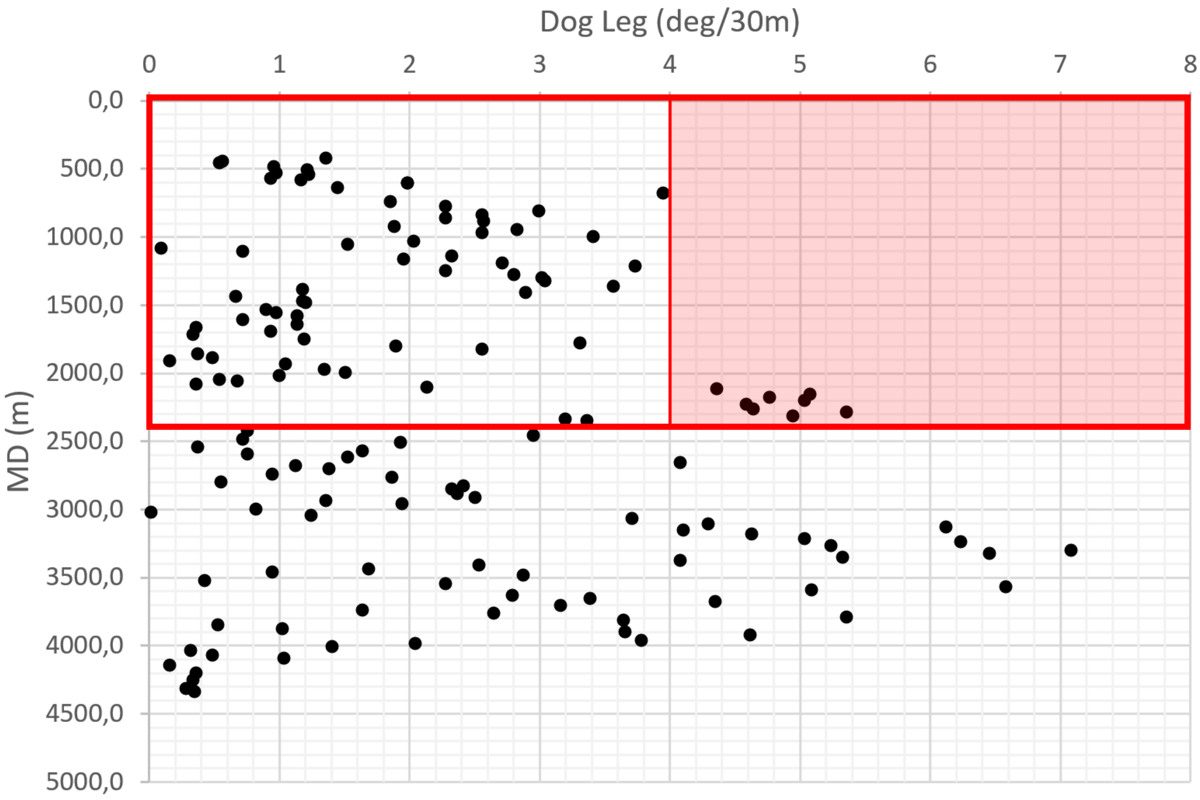


Figure 7-8: Measured Depth (m) vs Dog Leg (deg/30m). Large red box indicates area of interest for Case 1: Depth down to point of failure (2407 m MD). Transparent box indicates values with dogleg severity (DLS) (Dog leg > 4 deg/30 m). Free after (Operator, EoW Report, 2006).

Dogleg is considered severe (DLS) when the well path changes more than 4 degrees every 30 m. This zone for Case 1 is indicated by the transparent red box in Figure 7-8.

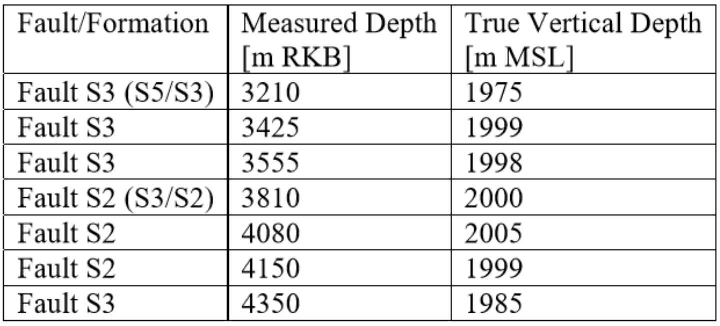
Sheet #4: The Input File

For Case 1, the origin of all drilling parameters, static symptoms (ss) and symptoms (s) are explained in detail.

Drilling Parameters and Static Symptoms (ss)

The drilling parameters are used to calculate the static symptoms (ss). All drilling parameters are presented below. The origin of each parameter is presented in a bracket.

- **Bit Type:** Shear Bit – PDC BHA delivered by Smiths Bits (EoW).
- **Bit Size (Previous section):** 17 ½” – Found in the well schematics (Figure 7-2).
- **Bit Size (Present section):** 12 ¼” – 10 5/8” x 12 ¼” reamer wings (Figure 7-2).
- **Bit Teeth Length:** 2.0” – Common value in PDC Shear Bits by Smiths Bits (Assumed).
- **Fm Above Csg Shoe is Charged**: No – No information in EoW (Assumed).
- **Fm Special Expected:** No – No information in EoW (Assumed).
- **Fm Boundary Expected:** No – Boundary expected at 2200m MD and 2411m MD. No boundary expected in current scope (EoW).
- **Fm Fault Expected:** No – Faults expected below point of failure (Figure 7-9).



Fault/Formation	Measured Depth [m RKB]	True Vertical Depth [m MSL]
Fault S3 (S5/S3)	3210	1975
Fault S3	3425	1999
Fault S3	3555	1998
Fault S2 (S3/S2)	3810	2000
Fault S2	4080	2005
Fault S2	4150	1999
Fault S3	4350	1985

Figure 7-9: Location of faults. Interpreted from well data and seismic data (Operator, EoW Report, 2006).

- **Fm Permeable Expected:** No – No information in EoW (Assumed).
- **Erosion Wellbore Factor:** 1.1 – No information in EoW (Assumed).
- **ID Casing (Previous):** 12.35” – 13 3/8” P-110, 72 lbs/ft casing (Figure 7-2).
- **Losses Expected:** No – No information in EoW. Drilling in MPD (Assumed).
- **MD Build/Drop Upper:** 3405’ MD – Midpoint of upper Build-up (Figure 7-7).
- **MD Build/Drop Lower:** 10433’ MD – Midpoint of lower Build-up (Figure 7-7).
- **MD Casing Shoe (Previous):** 10433’ – Found in the well schematics (Figure 7-2).
- **MD Water Depth:** 708’ – (EoW).
- **MD Well:** 7897’ – Current well depth at point of failure (Figure 7-2).
- **Mud Type:** OBM – Drilling with Paratherm OBM (EoW).
- **Mud Water Activity:** 0.91 – No information in EoW (Assumed).
- **Mud Weight:** 13.35 ppg – (Figure 7-3).
- **Mud YP:** 18 lb/100ft^2 – No information in EoW (Assumed).

- **OD Casing (Previous):** 13 3/8" – P-110, 53.5 lbs/ft casing (Figure 7-2).
- **OD Stab:** 0.00 – No stab present (EoW).
- **OD Drill Collar:** 8" – (EoW).
- **OD Drill Pipe:** 5" – (EoW).
- **Shallow Gas Expected:** No – Shallow gas sands at 1084 m MD to 1090 m MD and 1492 m MD to 1508 m MD. No evidence within the current scope (EoW).
- **TVD Well:** 5725" – Found in the well schematics / well survey (Figure 7-2).
- **Volume Cement (Previous 13 3/8" cement job):** 453 bbl – Total pumped cement. (EoW).
- **Volume Annulus (Previous 13 3/8" casing):**

$$V_{ann} = L_{casing} * \left(HoleSize^2 - OD_{casing}^2\right) * \frac{\pi}{4} \tag{7.1}$$

$$V_{ann} = 2740\ ft * (17.5''^2 - 13.375''^2) * \frac{\pi}{4} \tag{7.2}$$

$$V_{ann} = 455\ bbl$$

- **Volume Nipple Casing (Previous 13 3/8" casing):**

$$V_{5m,nipple} = 5m * \left(ID_{casing}^2\right) * \frac{\pi}{4} \tag{7.3}$$

$$V_{5m,nipple} = 3.17\ bbl$$

- **Volume Rat Hole:**

$$V_{3m\,rat\,hole} = 3m * HoleSize^2 * \frac{\pi}{4} \tag{7.4}$$

$$V_{3m\,rat\,hole} = 3.91\ bbl$$

- **Volume Cement Theoretical** (Volume Annulus + 300 m into previous casing + 5 m nipple + 3 m rat hole):

$$V_{cement,theoretical} = V_{ann} + V_{ann,300} + V_{5m,nipple} + V_{3m\ rat\ hole} \tag{7.5}$$
$$= 455\ bbl + 163\ bbl + \ 3.17\ bbl + 3.91\ bbl$$

$$V_{cement,theoretical} = 623\ bbl$$

Volume Cement Pumped:	453	bbl
Volume Theoretical Needed:	623	bbl

- **Weighting Material:** Barite – No information in EoW (Assumed).
- **Well Inclination:** 62.3 deg – Average of last hundreds of meters based on survey (Figure 7-7)

Table 7-2 shows the complete list of drilling parameters.

Table 7-2: Drilling parameters as used in the input file for calculation of Static Symptoms (ss). Red values are raw inputs. Oil Field Unit (OFU), Supp (Supported by).

Drilling Parameters	**OFU Value**	**Unit**	**SI Value**	**Supp.**
Bit Type	Shear Bit	-	Shear Bit	EoW
Bit Size (Previous)	17,5	in	0,44	Figure 7-2
Bit Size (Present)	12,25	in	0,31	Figure 7-2
Bit Teeth Length	2	in	0,05	Assumed
Fm Above Csg Shoe is Charged	No	-	No	Assumed
Fm Special Expected	No	-	No	Assumed
Fm Boundary Expected	No	-	No	EoW
Fm Fault Expected	No	-	No	EoW
Fm Permeable Expected	No	-	No	EoW
Erosion Wellbore Factor	1,1	-	1,1	Assumed
ID Csg	12,35	in	0,31	Figure 7-2
Losses Expected	No	-	No	EoW
MD Build/Drop Upper	3405	ft	1037,84	Figure 7-7
MD Build/Drop Lowest	10433	ft	3179,98	Figure 7-7
MD Csg Shoe	7805	ft	2378,96	Figure 7-2
MD Water Depth	708	ft	215,8	EoW
MD Well	7897	ft	2407,01	Figure 7-2
Mud Type	OBM	-	OBM	EoW
Mud Water Activity	0,91	-	0,91	Assumed
Mud Weight	13,35	ppg	1,6	Figure 7-3
Mud YP	18	lb/100 ft^2	8,53	Assumed
OD Csg	9,63	in	0,24	Figure 7-2
OD Stab	0	in	0	Assumed
OD DC	8	in	0,2	EoW
OD DP	5	in	0,13	EoW
Shallow Gas Expected	No	-	No	EoW
TVD Well	5725	ft	1744,98	Figure 7-2
V Cement (Pumped)	453	bbl	53,91	EoW
V Cement Theoretical	623,68	bbl	74,15	Equation 7.5
V Annulus	454,99	bbl	54,14	Equation 7.1
Weighting Material	Barite	-	Barite	Assumed
Well Inclination	62,3	^{0}	62,3	Figure 7-7

Table 7-3 shows the resulting static symptoms (ss) calculated from the drilling parameters in Table 7-2.

Table 7-3: Static symptoms (ss) calculated from drilling parameters. Column two shows the symptom definition. 11 static symptoms were registered.

Static Symptoms (ss)	Definition	Hit
Bit Aggressive (ss)	Bit Teeth Length > 15 mm	1
Bit Type Shear Bit (ss)	When Bit Type = Shear Bit	1
Build/Drop Section Inside Csg (ss)	(MD Csg Shoe - MD Build/Drop Upper) > 0	1
Build/Drop Section Inside Open Hole (ss)	(MD Csg Shoe - MD Build/Drop Lower) < 0	0
Cement V/Theoretical V Low (ss)	(Volume Cement) / (Volume Cement Theoretical) < 1.5 - 1.25 - 1.0	1
Csg Ann Slot Narrow (ss)	(Bit Size (Previous) - OD Csg) < 4 - 3 - 2	0
Fm Above Charged (ss)	Yes = 1; Increasing res pressure due to natural fractures in the formation	0
Fm Boundary Expected (ss)	Yes = 1; Formation boundaries expected based on geology reports	0
Fm Fault Expected (ss)	Yes = 1; Fault/s expected based on geology reports	0
Fm Permeable Expected (ss)	Yes = 1; Drilling in the reservoir or a small permeable zone with length > 10 m	0
Fm Special Expected (ss)	Yes = 1; Special formation expected	0
Losses Expected (ss)	Yes = 1; Losses expected based on geology reports	0
Mud Water Activity High (ss)	Aw > 0.8 - 0.85 - 0.9	1
Mud Water Activity Low (ss)	Aw < 0.8 - 0.7 - 0.6	0
Mud Weight High (ss)	MW > 1.5 - 1,65 - 1,8 kg/l	1
Mud Weighting Material Is Barite (ss)	Weighting Material = Barite	1
Mud YP High (ss)	Mud YP > 15 - 25 - 35 Pa	1
OBM (ss)	Mud Type = OBM	1
Shallow Gas Expected (ss)	SGE = Yes; Challenging to drill through. Avoid by moving the rig	0
Stabilizer Undergauge (ss)	(Bit Size (Current) - Near Bit Stab Size) < 0.02 m	0
Water Depth High (ss)	Water Depth > 300 - 500 - 700 m	0
WBM (ss)	Mud Type = WBM	0
Well Depth High (ss)	Well TVD > 2000 - 3000 - 4000 m	0
Well Depth Shallow (ss)	Well TVD < 2000 - 1500 - 1000 m	1
Well Inclination High (ss)	Well Inclination > 60 deg	1
Well Inclination Low (ss)	Well Inclination < 30 deg	0
Well Inclination Medium (ss)	30 < Well Inclination < 60 deg	0
Well Length High (ss)	MD Well > 3000 - 4000 - 5000 m MD	0
Well Openhole Long (ss)	(MD Well - MD Csg Shoe) > 400 - 750 - 1 000 m MD	0
Wellbore - DC Dia Small (ss)	(Bit Size (Current) - OD DC) < 4 - 3 - 2 in	0
Wellbore - DP Dia Small (ss)	(Bit Size (Current) - OD DP) < 3 - 2 - 1 in	0

If a symptom has occurred, (is true) a red one in Table 7-3 (column three) indicates it. If it has not occurred, (is false) a zero indicates it. From the raw data, we were able to define 11 static symptoms (ss) in Case 1.

Symptoms (s)

This section includes all symptoms (s) that occurred prior to the failure. Normally the 12-hour period prior to failure was divided in three periods (long, middle and short). For early testing purposes, this period of which the symptoms can occur will not be sub-divided. That means that all symptoms (s) that occurred 12 hours prior to failure will be included.

First, two already developed agents were used to show how agents detects symptoms (s) in a real case. Then, the manual interpretation of RTDD in Figure 7-6 were used to determine the remaining symptoms (s). The agents were:

- ECD Agent
- Erratic Torque Agent

ECD Agent

This agent detects four symptoms:

- ECD – Pore Pressure (High) (s)
- ECD – Pore Pressure (Low) (s)
- ECD – Collapse Pressure (Low) (s)
- ECD – Fracture Pressure (Low) (s)

Separate agents determine ECD High (s) and ECD Low (s) symptoms.

The raw output from running the agent on a 12-hour interval is shown in Figure 7-10.

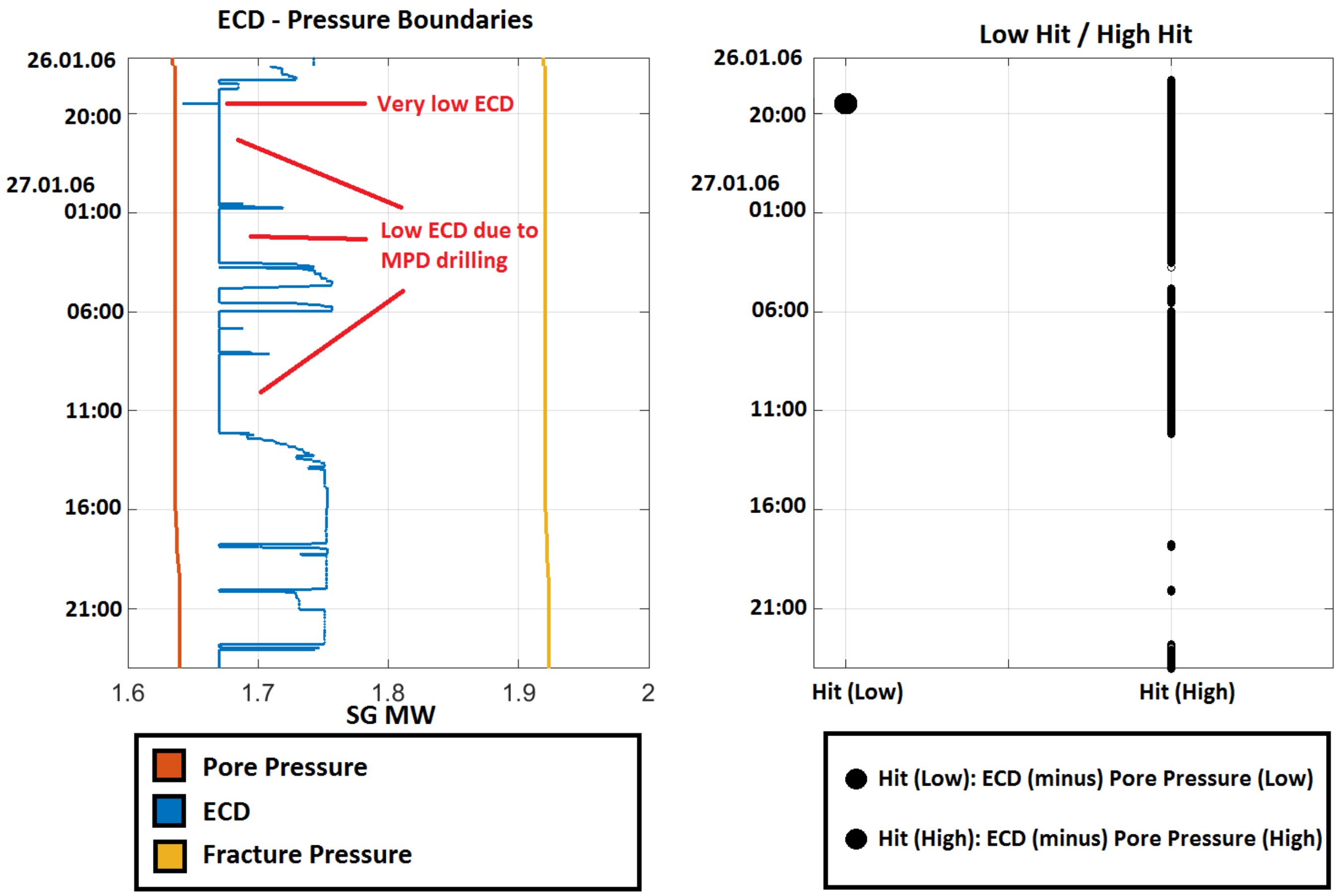


Figure 7-10: Left: ECD and existing pressure boundaries (SG MW) vs. time (hrs). Right: The agent's raw output vs. time (hrs). Red writing is interpretation. Two types of hits can occur: Hit (Low) indicates that the difference is low. Hit (High) indicates that the difference is large but still close.

The left part of Figure 7-10 shows that the ECD is far from the fracture pressure boundary in the current window. The collapse pressure boundary were always below the pore pressure boundary in this case. Because of this, the agent registered no hits for ECD – Frac D Low (s) or ECD – Collapse P Low (s) symptoms.

The right part of Figure 7-10 shows multiple Hit (High) and one Hit (Low) at 19:50. These hits were related to the pore pressure boundary. The ECD is close to the pore pressure boundary. The agent transforms the result into ECD – Pore P Low/High (s) symptom hits in Table 7-4

Erratic Torque Agent

This agent detects one symptom:

- Erratic Torque (s)

Torque High (s) and Torque Cumulative High (s) are determined by separate agents.

Figure 7-11 shows the raw output from running the erratic torque agent on a 12 hour interval.

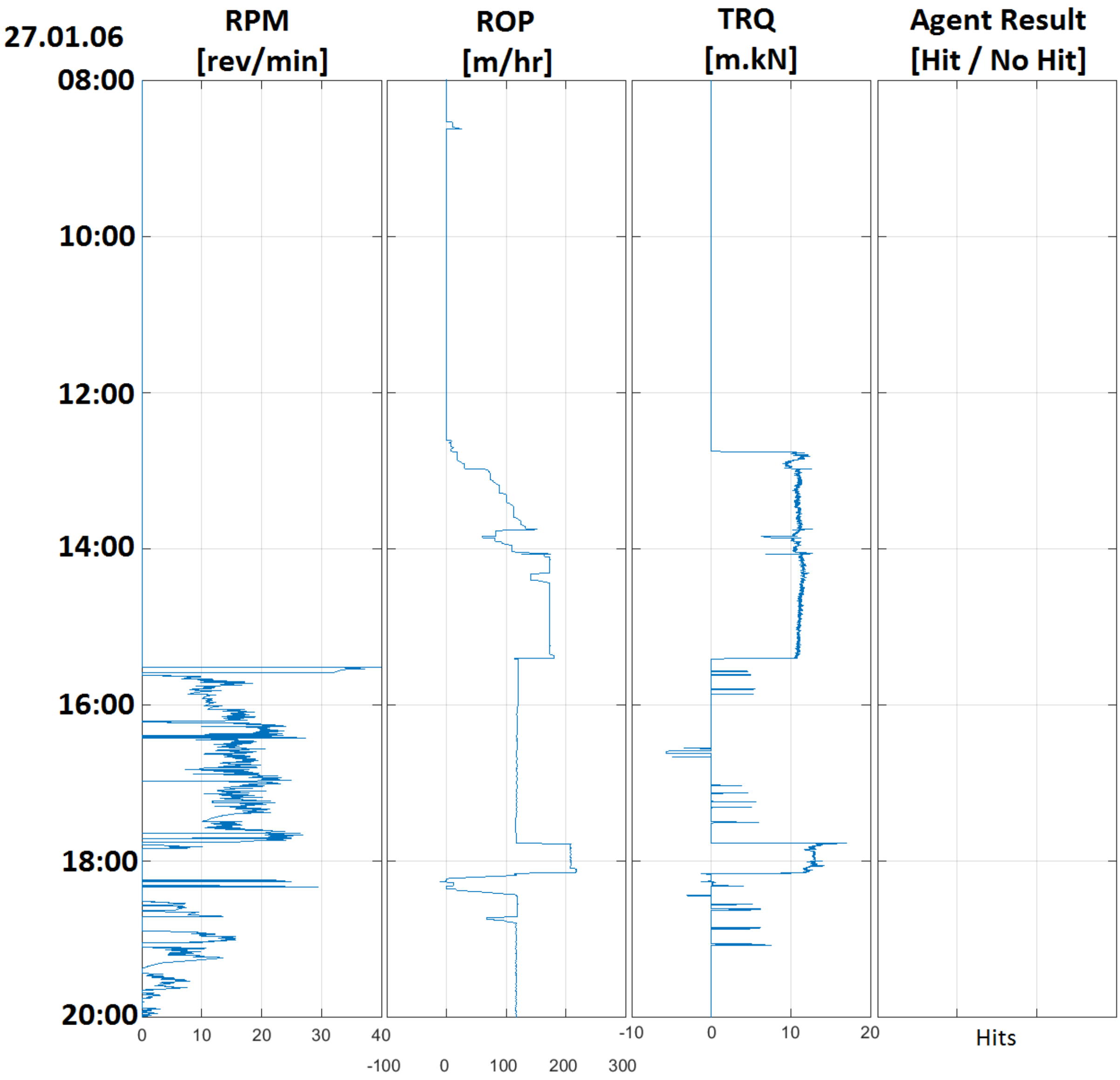


Figure 7-11: Raw agent output from RTDD 12 hours prior to failure in case 1. Fourth column shows no agent hits.

Column four in Figure 7-11 shows no hits by the agent. Erratic Torque (s) was given a false value (a zero) in Table 7-4. This correlated with the manual interpretation.

The results from Figure 7-10 and Figure 7-11 and the manual interpretation from Figure 7-6 are summarized in Table 7-4. RTDD in Figure 7-6 supported 10 symptoms (s). The EoW report and survey supported three symptoms. Already developed agents supported two symptoms. The results are summarized in Table 7-4.

Table 7-4: Summary of all symptoms (s). Supported information is referred to as "Supp". Insufficient data is indicated as "Estimated". 15 symptoms were activated.

Symptoms (s)	Date	Time	Hit	Supp
Activity of Directional Drilling (s)	-	-	1	EOW
Activity Of Drilling (s)	27.jan	-	1	RTDD
Activity Of Reaming (s)	27.jan	17:45	1	RTDD
Activity of Tripping In (s)			0	RTDD
Activity of Tripping Out (s)			0	RTDD
Bit MD Long (s)	27.jan	-	1	RTDD
Cavings On Shaker (s)			0	Estimated
Cuttings Initial Concentration High (s)			0	Estimated
Cuttings Initial Concentration Low (s)			0	Estimated
DLS High (s)	27.jan	-	1	Survey
ECD - Collapse D Low (s)	-	-	0	Real Agent
ECD - Frac D Low (s)	-	-	0	Real Agent
ECD - Pore D High (s)	27.jan	-	1	Real Agent
ECD - Pore D Low (s)	27.jan	19:50	1	Real Agent
ECD High (s)	-	-	0	Estimated
ECD Low (s)	-	-	0	Estimated
Fm Hard (s)	27.jan	15:30	1	RTDD
Fm Hard Stringer (s)	-	-	0	RTDD
Fm Laminated (s)	27.jan	18:30	1	RTDD
Fm Soft (s)	27.jan	18:50	1	RTDD
HKL Erratic (s)	27.jan	16:30	1	RTDD
HKL Signature Wellbore Restricted (s)	-	-	0	Estimated
HKL Signature Wellbore Wall Restricted (s)	-	-	0	Estimated
Losses Seepage (s)	27.jan	14:30	1	RTDD
Losses Serious (s)	27.jan	19:45	1	RTDD
Motor Stall Signature (s)	-	-	0	Estimated
MSE Cumulative High (s)	-	-	0	Estimated
MSE High (s)	-	-	0	Estimated
Mud Motor On (s)	27.jan	-	1	EOW
Overpull (s)	-	-	0	RTDD
Pressure Spike (s)	-	-	0	RTDD
ROP Low (s)	27.jan	15:30	1	RTDD
RPM String On (s)	-	-	0	RTDD
Side Force High (s)	-	-	0	Estimated
Sliding Mode (s)	-	-	0	RTDD
SPP High (s)	-	-	0	RTDD
Time Long (s)	-	-	0	EOW
Took Weight (s)	-	-	0	RTDD
Torque Cumulative High (s)	-	-	0	RTDD
Torque Erratic (s)	-	-	0	Real Agent
Torque High (s)	-	-	0	RTDD
Tripping Speed High (s)	-	-	0	RTDD
WOB High (s)	-	-	0	Estimated
Csg Ann P High (s)	-	-	0	Estimated
Mud LGSC High (s)	-	-	0	Estimated
Pore P Increasing (s)	-	-	0	Estimated

Appendix A-3 presents definitions of the symptoms (s). The program output with the symptoms from Table 7-3 and Table 7-4 entered are shown in chapter 8.2.1.

7.4 Case 2: Motor Stall (1)

Sheet #1: Well Description

A-148 was drilled in 2005. A-148 is an 8 ½” side-track of S-148. Severe hole-problems with A-148 led to another side-track, A-148T2. Failure occurred while drilling A-148 8 ½” section.

General Information (Operator, EoW Report, 2005)

Well Name:	A-148
Failure Type:	Motor Stall (Type 2)
Failure No:	Motor Stall #1
Section:	8 ½ “
Depth of Occurrence:	6075 m MD / 2855 m TVD
Time of Occurrence:	02.01.2005 19:30
NPT	Direct NPT occurred as slower drilling the following two days after tool failure. Indirect NPT is related to the hole-problems when RIH with the new tool. It is not possible to estimate direct NPT but indirect NPT was approximately 192 hours.

Summary Prior to Failure

Summary of events prior to the failure:	Drilled S-148 8 ½” section from 5208 m MD to 6057 m MD. Communication with RSS tool was lost. Drilled ahead horizontally to 7044 m MD. TD was changed to 7393 m MD, open hole was plugged and A-148 8 ½” side-track was drilled at 5120 m MD. Drilling from 5120 m MD to 5845 m MD were influenced by hard stringers with adjacent soft shale. Due to this a slight deviation from well path occurred. At 5845 m MD the AC motor on the DDM (derrick drilling machine) had to be changed. BHA was pulled back into the 9 5/8" csg shoe while repairing the DDM. While tripping back in pack off tendencies, increased circulation and cleaning caused a malfunctioning of the MWD tool. Re run with new MWD tool.
Summary of events during the failure:	Drilling ahead from 5845 m MD a series of long and hard stringers were drilled. From 6068 m MD to 6133 m MD a massive hard formation was drilled with an average ROP of 2 m/hr. A combination of WOB and RPM was used to reduce stick-slip in this zone but at 6075 m MD the RSS tool stopped transmitting.
Summary of events after the failure:	The inclination and azimuth achieved at this depth was sufficient to hit the reservoir. Drilling was therefore continued. However, at 6221 m MD the BHA inclination dropped and further drilling would not result in hitting TD. POOH to change RSS tool. When tripping in, the hole was in such a bad shape that drilling could not continue and a side-track was performed at 5608 m MD. A-148T2 was drilled to TD and completed.

Figure 7-12 shows improved well schematics for well A-148.

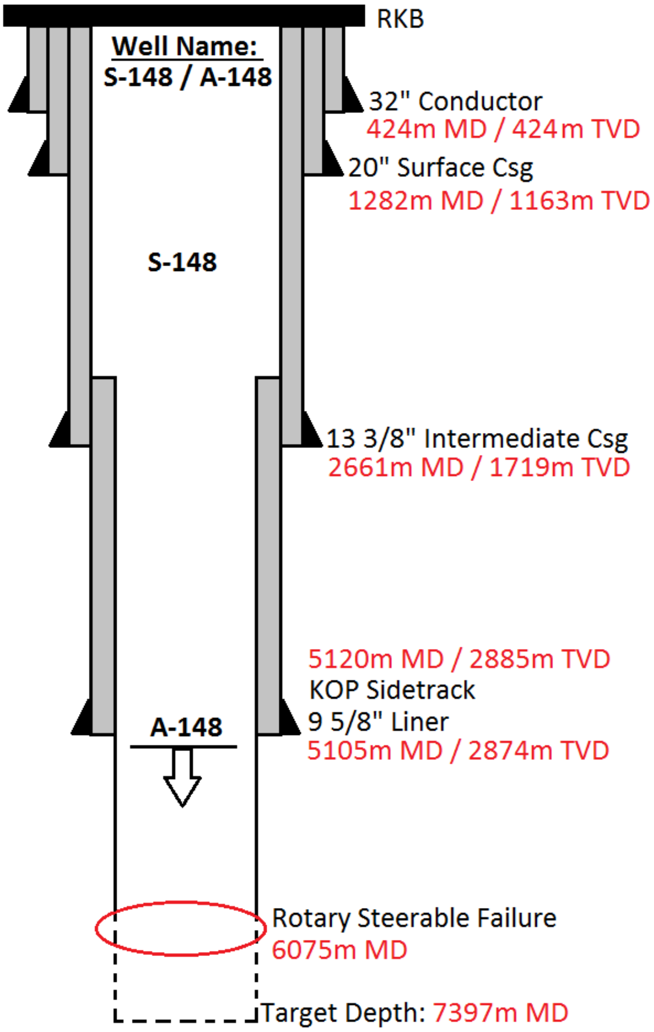


Figure 7-12: Improved well schematics. Improvements were made as the EoW report presented the schematics as a table and not a figure. Free after (Operator, EoW Report, 2005).

Hard stringers with adjacent soft rock were observed prior to failure. Figure 7-13 shows stratigraphy and a cross section of the formation to support the understanding of the complex structure.

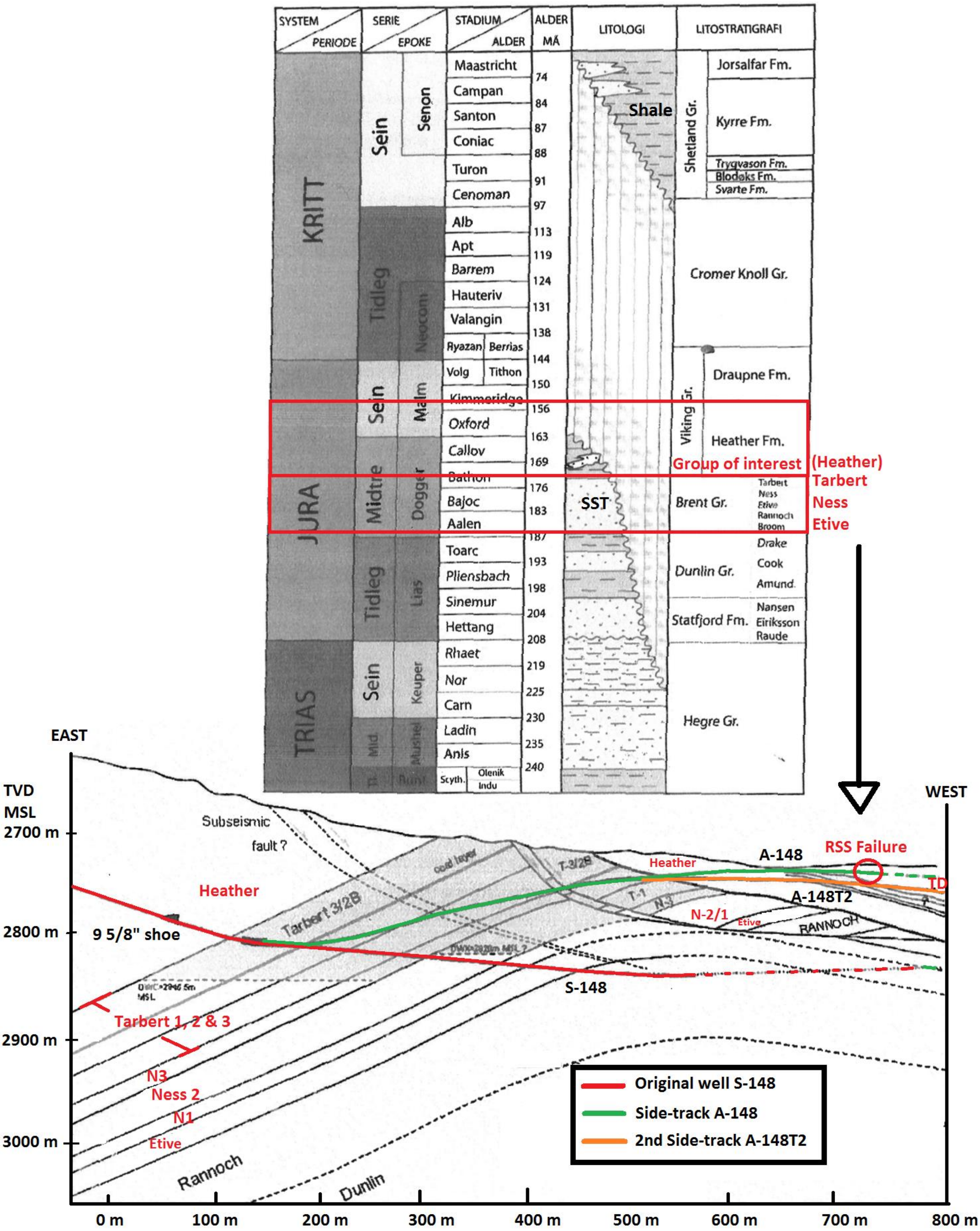


Figure 7-13: Top: Depth based stratigraphy of the formation. Bottom: East/West cross section of the formation. Free after (Operator, EoW Report, 2005).

Figure 7-13 shows that A-148 is drilled through the Tarbert formation, the upper Ness formation and the Heather formation. Prior to failure, the well was drilled through Tarbert 1 and 2 and Ness 3 but mainly the Heather formation. According to the geology sections in the EoW report, the formation consist mainly of sandstone but with limestone layers. Figure 7-14 shows a pressure plot of the formation.

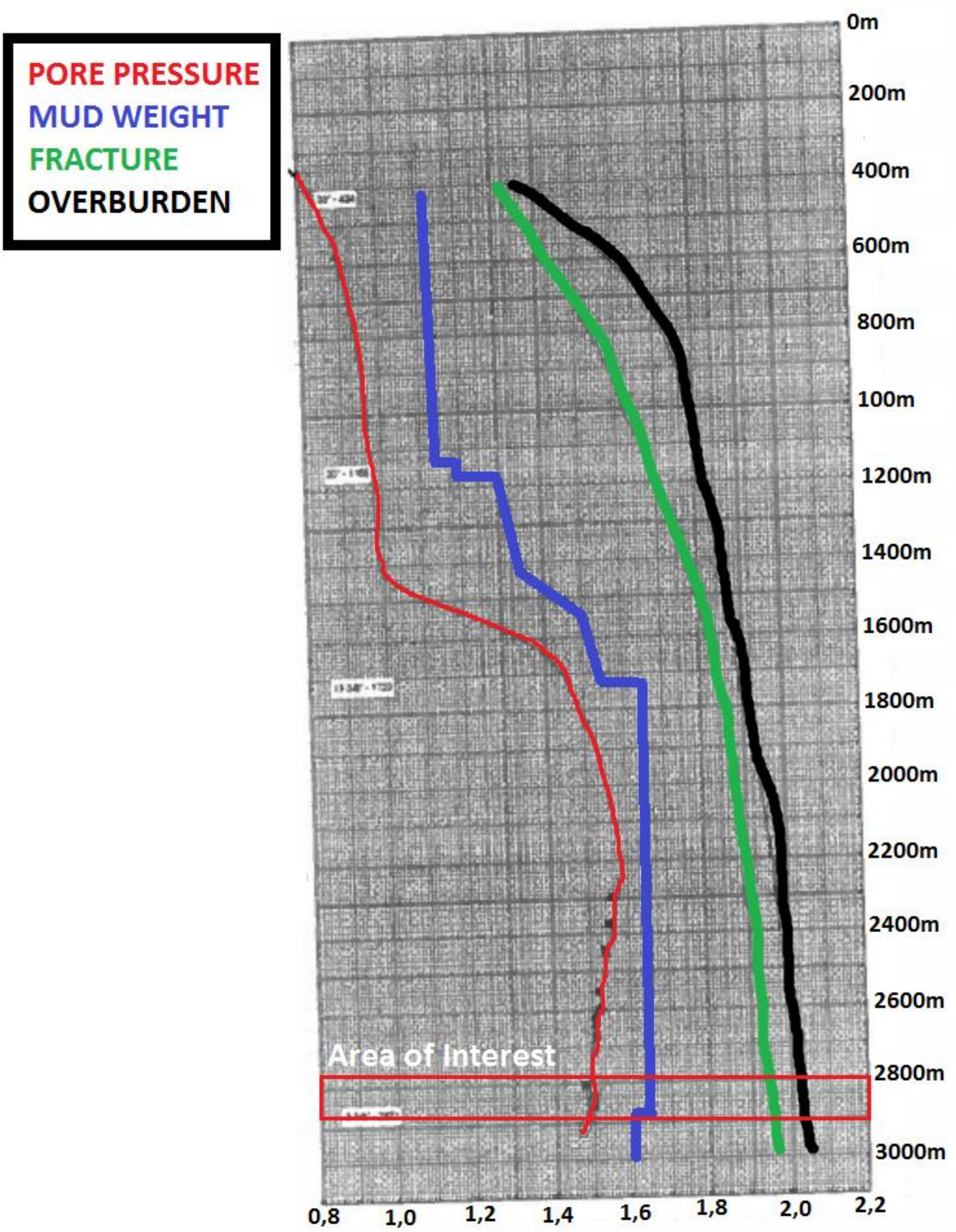


Figure 7-14: Pressure (S.G MW) vs. TVD (m). Drawings were added as the original image was unclear. Free after (Operator, EoW Report, 2005).

Sheet #2: RTDD

RTDD is presented in the following order:

- One week prior to failure.
- Interpretation of last 12 hour prior to failure.
- Manual symptom detecting from the last 12 hours of RTDD.

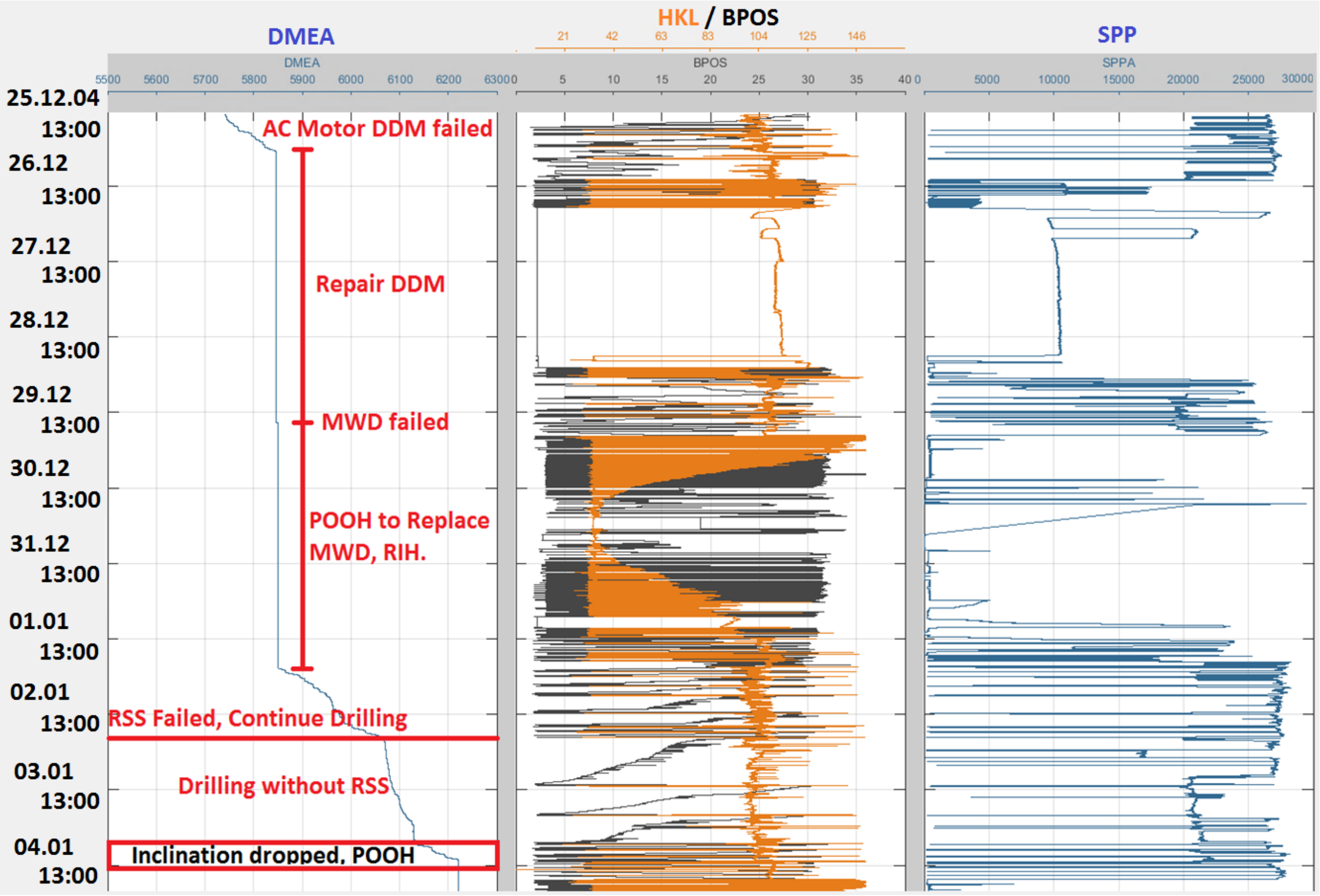


Figure 7-15: One-week summary of RTDD prior to failure. Explanation of important events were added in red. The point of failure occurred at 13:00. (Raknes, 2014), free after (Operator, RTDD, 2005)

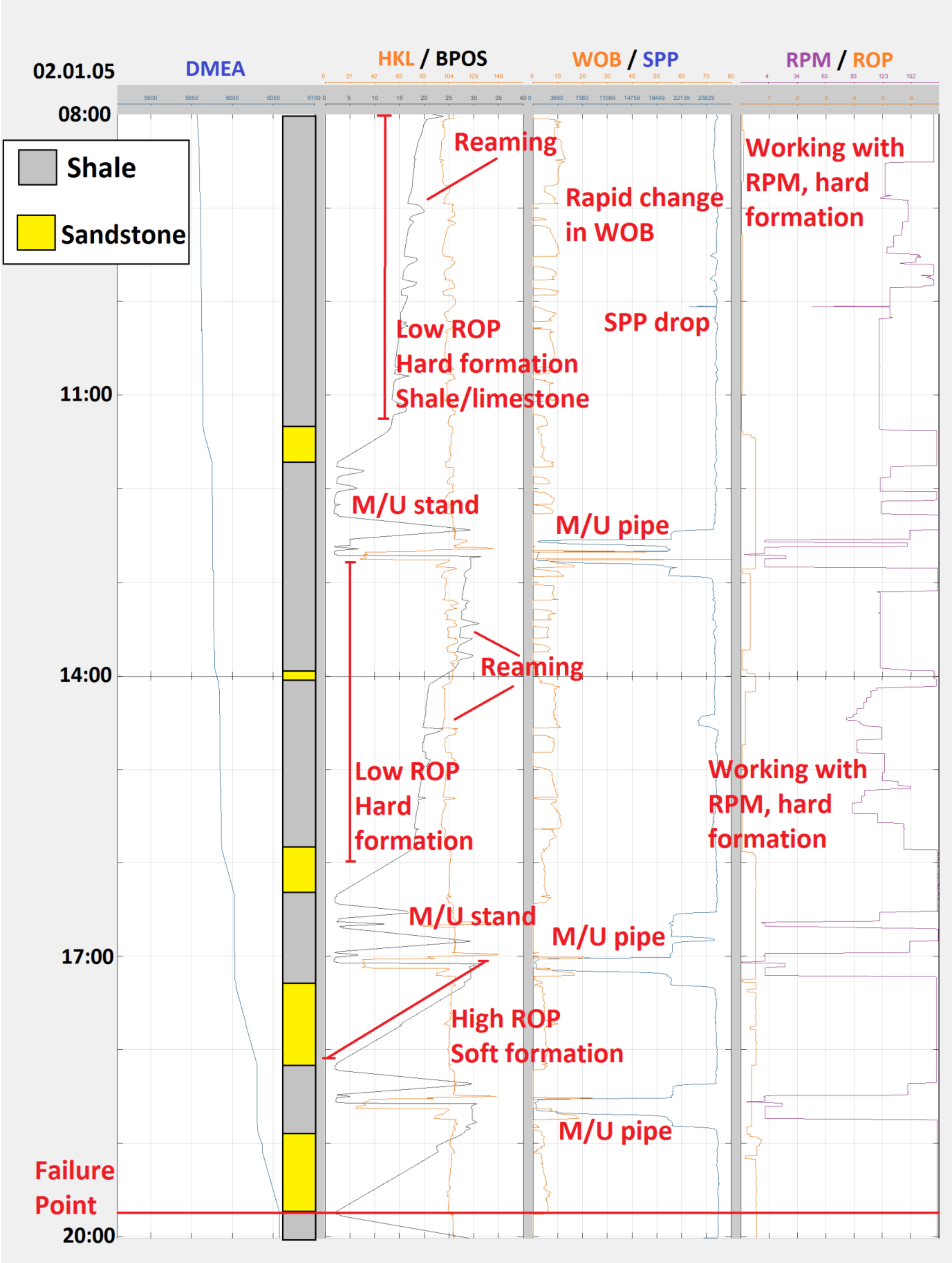


Figure 7-16: 12 hours interpretation of RTDD. Comments were added in red. (Raknes, 2014), free after (Operator, RTDD, 2005)

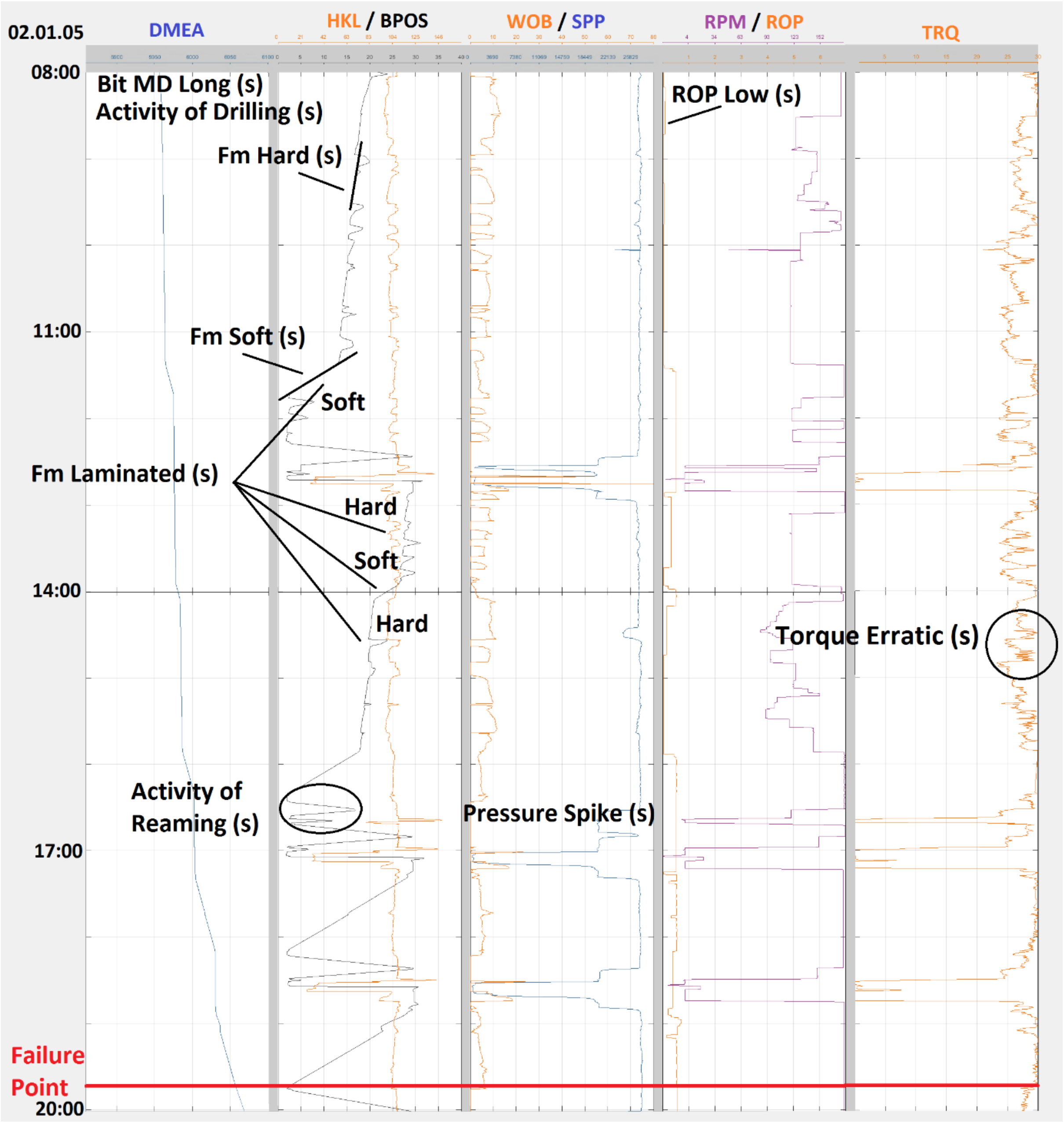


Figure 7-17: Detection of symptom (s) in the RTDD 12 hours prior to failure. Only the earliest occurrence of each symptom is included. Nine symptoms were detected in the RTDD, these are indicated in black writing. (Raknes, 2014), free after (Operator, RTDD, 2005).

Table 7-7 summarizes the symptoms (s) detected in Figure 7-17.

Sheet #3: Well Survey

MWD was conducted to obtain survey that included:

- Measured Depth (m)
- Inclination (deg)
- Azimuth (deg)
- TVD (m)
- North / South (m)
- East / West (m)
- Dog Leg (deg/30m)

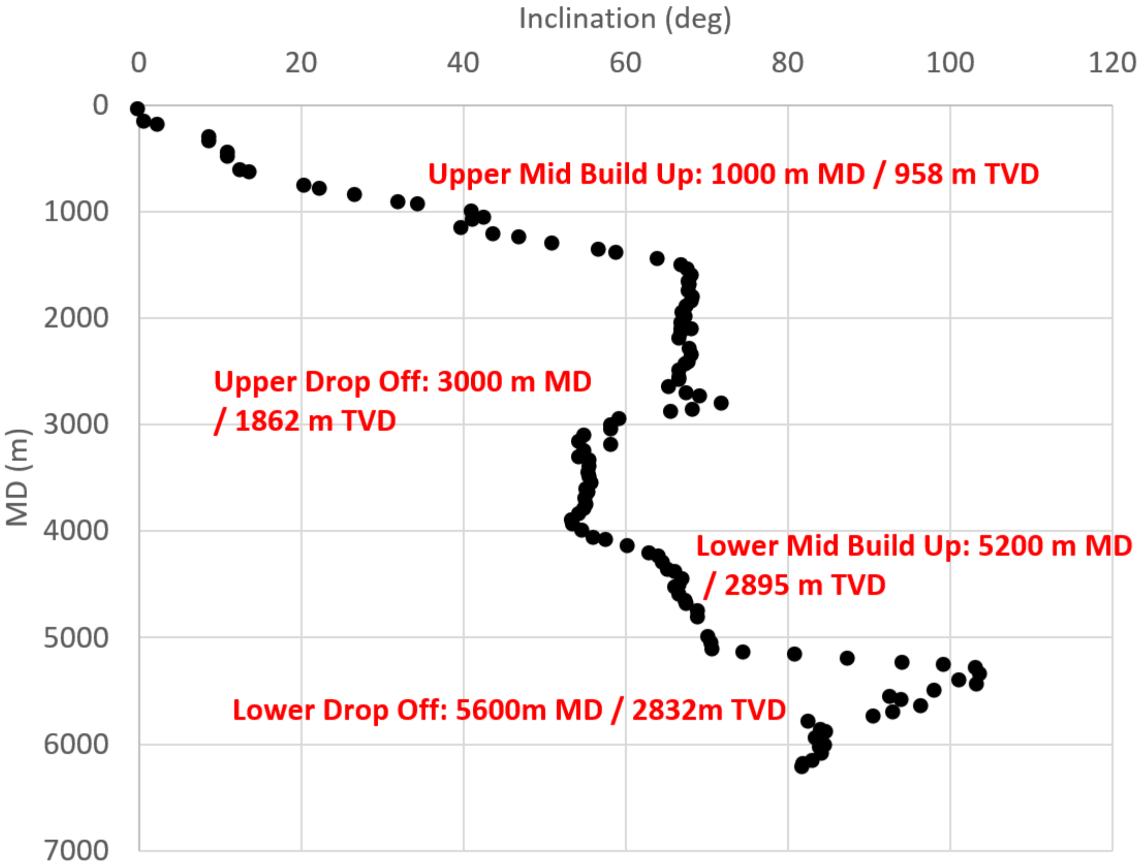


Figure 7-18: Well Survey. Measured Depth (m) vs. Inclination (deg) for well A-148. Mid build-up and mid drop-off was estimated based on the halfway point of increasing data and decreasing data respectively. Free after (Operator, EoW Report, 2005).

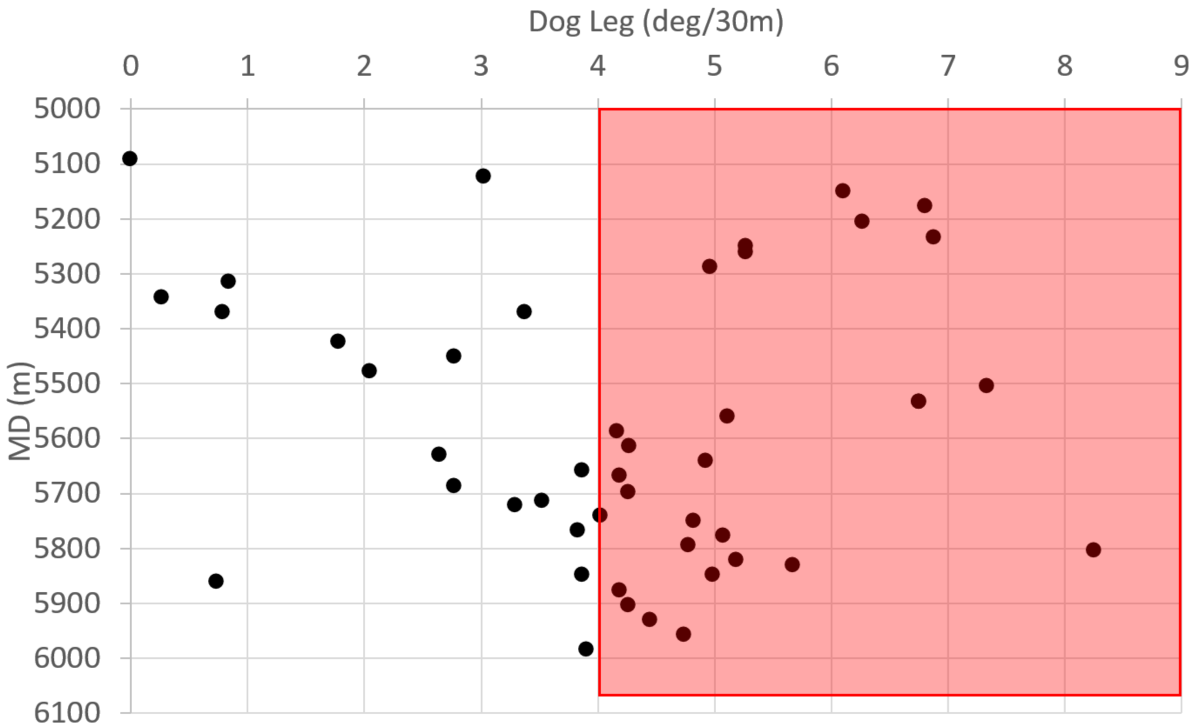


Figure 7-19: Measured Depth (m) vs Dog Leg (deg/30m) for well A-148. Large red box indicates the area of interest for case #2. Transparent box indicates values with DLS. Free after (Operator, EoW Report, 2005).

Sheet #4: The Input File

The input file includes:

- Drilling Parameters
    - Static Symptoms (ss)
- Symptoms (s)
    - Automatic detection by agents
    - Manual detection

Drilling Parameters and Static Symptoms (ss)

Table 7-5 shows drilling parameters from the EoW report for well A-148.

Table 7-5: Complete list of drilling parameters. Columns from left to right: Drilling parameter name, OFU value, OF unit, SI value, supported or not. (Operator, EoW Report, 2005).

Drilling Parameters	**OFU Value**	**Unit**	**SI Value**	**Supp.**
Bit Type	Shear Bit	-	Shear Bit	EoW
Bit Size (Previous)	12,25	in	0,44	Figure 7-12
Bit Size (Present)	8,5	in	0,22	Figure 7-12
Bit Teeth Length	2	in	0,05	Assumed
Fm Above Csg Shoe is Charged	No	-	No	Assumed
Fm Special Expected	No	-	No	Assumed
Fm Boundary Expected	No	-	No	Figure 7-14
Fm Fault Expected	Yes	-	Yes	Figure 7-14
Fm Permeable Expected	No	-	No	Figure 7-14
Erosion Wellbore Factor	1,1	-	1,1	Assumed
ID Csg	8,54	in	0,22	Figure 7-12
Losses Expected	No	-	No	EoW
MD Build/Drop Upper	17060	ft	5200	Figure 7-18
MD Build/Drop Lowest	18373	ft	5600	Figure 7-18
MD Csg Shoe	16748	ft	5105	Figure 7-12
MD Water Depth	711	ft	216,7	EoW
MD Well	19931	ft	6075	Figure 7-12
Mud Type	OBM	-	OBM	EoW
Mud Water Activity	0,91	-	0,91	Assumed
Mud Weight	13,41	ppg	1,6	Figure 7-14
Mud YP	18	lb/100 ft^2	8,53	Assumed
OD Csg	9,63	in	0,24	Figure 7-12
OD Stab	0	in	0	Assumed
OD DC	5	in	0,13	EoW, HWDP instead of DC
OD DP	5	in	0,13	EoW, 5” & 6 5/8”
Shallow Gas Expected	No	-	No	EoW, only present at 500m MD
TVD Well	9367	ft	2855	EoW
V Cement (Pumped)	453	bbl	53,91	EoW
V Cement Theoretical	675	bbl	80,33	EoW, calculations
V Annulus	601,7	bbl	71,6	EoW , calculations
Weighting Material	Other	-	Other	Assumed
Well Inclination	84	^{0}	84	Figure 7-18

Static Symptoms (ss) are calculated automatically from the drilling parameters in Table 7-5. Table 7-6 shows the resulting static symptoms (ss).

Table 7-6: Static Symptoms (ss) calculated based on drilling parameters. 15 static symptoms were registered. (Operator, EoW Report, 2005).

Static Symptoms (ss)	Definition	True
Bit Aggressive (ss)	Bit Teeth Length > 15 mm	1
Bit Type Shear Bit (ss)	When Bit Type = Shear Bit	1
Build/Drop Section Inside Csg (ss)	(MD Csg Shoe - MD Build/Drop Upper) > 0	1
Build/Drop Section Inside Open Hole (ss)	(MD Csg Shoe - MD Build/Drop Lower) < 0	1
Cement V/Theoretical V Low (ss)	(Volume Cement) / (Volume Cement Theoretical) < 1.5 - 1.25 - 1.0	1
Csg Ann Slot Narrow (ss)	(Bit Size (Previous) - OD Csg) < 4 - 3 - 2	0
Fm Above Charged (ss)	Yes = 1; Increasing res pressure due to natural fractures in the formation	0
Fm Boundary Expected (ss)	Yes = 1; Formation boundaries expected based on geology reports	0
Fm Fault Expected (ss)	Yes = 1; Fault/s expected based on geology reports	1
Fm Permeable Expected (ss)	Yes = 1; Drilling in the reservoir or a small permeable zone with length > 10 m	0
Fm Special Expected (ss)	Yes = 1; Special formation expected	0
Losses Expected (ss)	Yes = 1; Losses expected based on geology reports	0
Mud Water Activity High (ss)	Aw > 0.8 - 0.85 - 0.9	1
Mud Water Activity Low (ss)	Aw < 0.8 - 0.7 - 0.6	1
Mud Weight High (ss)	MW > 1.5 - 1,65 - 1,8 kg/l	0
Mud Weighting Material Is Barite (ss)	Weighting Material = Barite	0
Mud YP High (ss)	Mud YP > 15 - 25 - 35 Pa	1
OBM (ss)	Mud Type = OBM	1
Shallow Gas Expected (ss)	SGE = Yes; Challenging to drill through. Avoid by moving the rig	0
Stabilizer Undergauge (ss)	(Bit Size (Current) - Near Bit Stab Size) < 0.02 m	0
Water Depth High (ss)	Water Depth > 300 - 500 - 700 m	1
WBM (ss)	Mud Type = WBM	0
Well Depth High (ss)	Well TVD > 2000 - 3000 - 4000 m	1
Well Depth Shallow (ss)	Well TVD < 2000 - 1500 - 1000 m	0
Well Inclination High (ss)	Well Inclination > 60 deg	1
Well Inclination Low (ss)	Well Inclination < 30 deg	0
Well Inclination Medium (ss)	30 < Well Inclination < 60 deg	0
Well Length High (ss)	MD Well > 3000 - 4000 - 5000 m MD	1
Well Openhole Long (ss)	(MD Well - MD Csg Shoe) > 400 - 750 - 1 000 m MD	1
Wellbore - DC Dia Small (ss)	(Bit Size (Current) - OD DC) < 4 - 3 - 2 in	0
Wellbore - DP Dia Small (ss)	(Bit Size (Current) - OD DP) < 3 - 2 - 1 in	0

Symptoms (s)

It was not possible to use the ECD agent as MFI data was missing in the RTDD for well A-148. The Erratic Torque agent was used to detect Erratic Torque (s) symptoms. Remaining symptoms were found by manual inspection of the RTDD in Figure 7-17. Figure 7-20 shows the raw output from running the Erratic Torque agent on Case 2 RTDD.

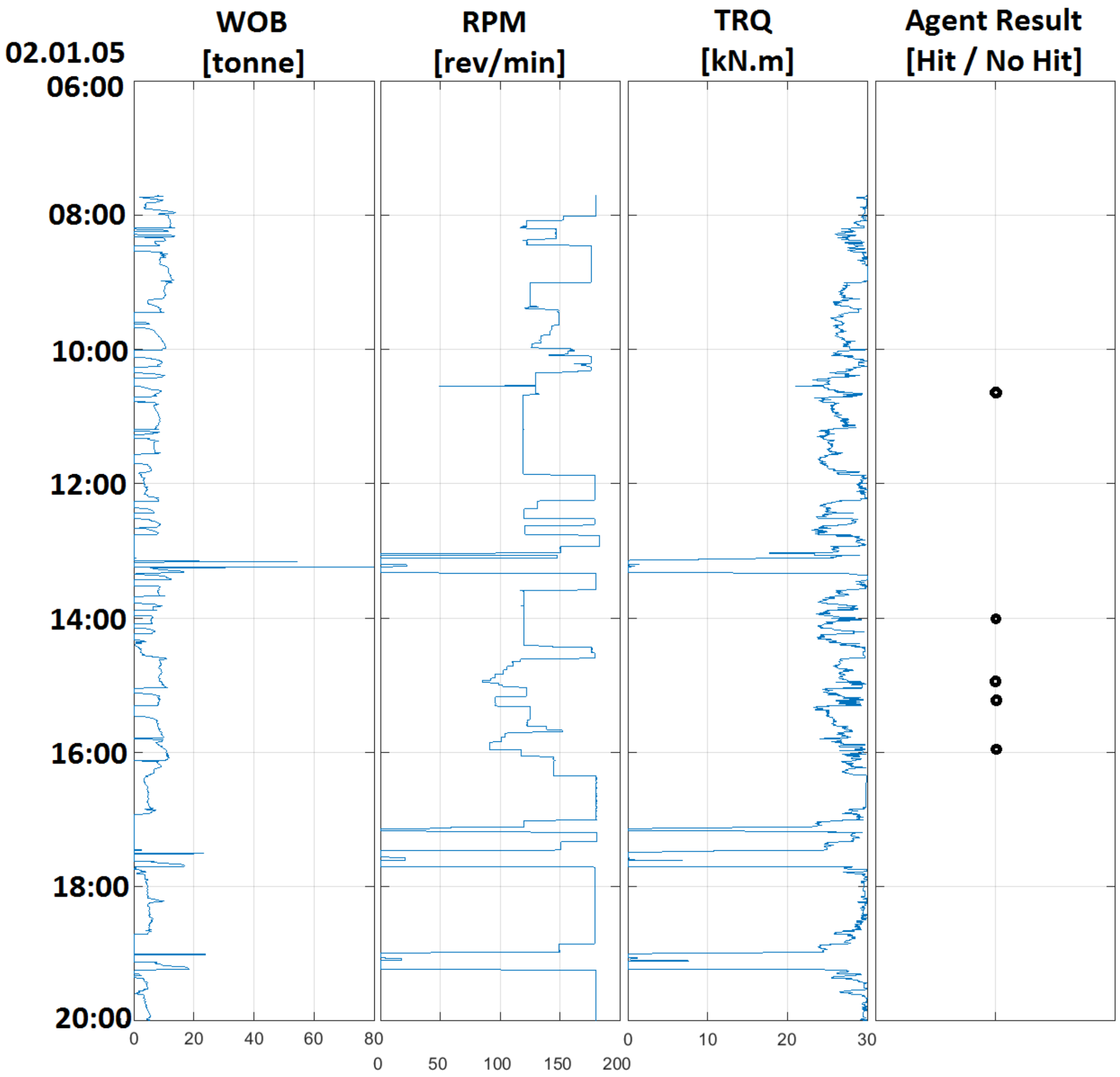


Figure 7-20: Raw output from Erratic Torque agent on the RTDD from case 2. The agent registered multiple hits at 10:45, 14:00, 14:45, 15:00 and 16:00.

The registered hits at 14:45 and 15:00 matches the manual interpretation in Figure 7-17. Hits detected by the agent in Figure 7-20 and the manual detection of symptoms from Figure 7-17 are summarized in Table 7-7.

Table 7-7: Symptoms (s) for well A-148. EoW report and well survey supported five symptoms, agent one symptom and RTDD nine symptoms. 14 symptoms were activated for Case 2.

Symptoms (s)	**Date**	**Time**	**TRUE**	**Supp.**
Activity of Directional Drilling (s)	02.jan	-	1	EoW
Activity Of Drilling (s)	02.jan	08:00	1	RTDD
Activity Of Reaming (s)	02.jan	16:30	1	RTDD
Activity of Tripping In (s)	-	-	0	RTDD
Activity of Tripping Out (s)	-	-	0	RTDD
Bit MD Long (s)	02.jan	-	1	RTDD
Cavings On Shaker (s)	-	-	0	Estimated
Cuttings Initial Concentration High (s)	-	-	0	Estimated
Cuttings Initial Concentration Low (s)	-	-	0	Estimated
DLS High (s)	02.jan	08:00	1	Figure 7-19
ECD - Collapse D Low (s)	-	-	0	Estimated
ECD - Frac D Low (s)	-	-	0	Estimated
ECD - Pore D High (s)	-	-	0	Estimated
ECD - Pore D Low (s)	-	-	0	Estimated
ECD High (s)	-	-	0	RTDD
ECD Low (s)	-	-	0	RTDD
Fm Hard (s)	02.jan	13:30	1	RTDD
Fm Hard Stringer (s)	02.jan	-	1	EoW
Fm Laminated (s)	02.jan	12:00	1	RTDD
Fm Soft (s)	02.jan	11:30	1	RTDD
HKL Erratic (s)	-	-	0	RTDD
HKL Signature Wellbore Restricted (s)	-	-	0	Estimated
HKL Signature Wellbore Wall Restricted (s)	-	-	0	Estimated
Losses Seepage (s)	-	-	0	RTDD
Losses Serious (s)	-	-	0	RTDD
Motor Stall Signature (s)	-	-	0	Estimated
MSE Cumulative High (s)	-	-	0	Estimated
MSE High (s)	-	-	0	Estimated
Mud Motor On (s)	02.jan	08:00	1	EoW
Overpull (s)	-	-	0	RTDD
Pressure Spike (s)	02.jan	16:45	1	RTDD
ROP Low (s)	02.jan	08:00	1	RTDD
RPM String On (s)	-	-	0	Estimated
Side Force High (s)	-	-	0	Estimated
Sliding Mode (s)	-	-	0	Estimated
SPP High (s)	-	-	0	Estimated
Time Long (s)	02.jan	19:30	1	EoW
Took Weight (s)	-	-	0	RTDD
Torque Cumulative High (s)	-	-	0	RTDD
Torque Erratic (s)	02.jan	14:45	1	Real Agent/ RTDD
Torque High (s)	-	-	0	Estimated
Tripping Speed High (s)	-	-	0	Estimated
WOB High (s)	-	-	0	Estimated
Csg Ann P High (s)	-	-	0	Estimated
Mud LGSC High (s)	-	-	0	Estimated
Pore P Increasing (s)	-	-	0	Estimated

The EoW report described problems with multiple hard stringers during drilling of the section. Fm Hard Stringer (s) were therefore assumed true even though it could not be identified in the RTDD. Appendix A-3 presents definitions of all symptoms (s). The program output with the symptoms from Table 7-6 and Table 7-7 entered are shown in chapter 8.2.2.

7.5 Case 3: Motor Stall (2)

Sheet #1: Well Description

Well C-147 was drilled in 2005/2006. The well entered the reservoir horizontally. It was drilled and completed in MPD mode.

General Information (Operator, EoW Report, 2006)

Well Name:	C-147
Failure Type:	Motor Stall (Type 2)
Failure No:	Motor Stall #2
Section:	17 1/2"
Depth of Occurrence:	2070 m MD / 1582 m TVD
Time of Occurrence:	25.12.2005 15:00
NPT	54 hours (approximately)

Summary Prior to Failure

Summary of events prior to the failure:	The 17 ½" section was drilled with Power Drive X5 RSS and 17 ½" milled tooth bit. The section was drilled using Ultradrill WBM. 17 ½" hole was drilled from 1515 m MD. Several hard stringers were hit from 1556 m MD to 1587 m MD. The Power Drive "hold inclination" mode and the near bit inclination/azimuth failed from 1593 m MD. The communication to the tool were poor but improved such that drilling could proceed.
Summary of events during the failure:	From 1900 m MD, torque and ECD readings increased and circulation and reaming was necessary to stop the string from stalling. At 2070 m MD, the Power Drive failed to turn left. A Bias Unit hinge pin broke after stalling, so that side forces was lost. It was POOH to replace the tool.
Summary of events after the failure:	The hole was circulated four times bottoms up prior to POOH with 5000 lpm and 180 RPM when the pump pressure suddenly increased and the hole partially packed off. Ten hours were spent to establish circulation in steps to 3800 lpm. The ECD varied between 1.692 – 1.714 SG EMW. After a stable flow check, it was pumped out of hole from 2025 m MD with 200 lpm. 96 hours were used to get out of hole. The BHA came out encapsulated in sticky cuttings. The Ultradrill WBM had never been used before. The inexperience combined with mixing the wrong mud additives caused the hole problems when POOH.

Figures Figure 7-21 and Figure 7-22 show well schematics and pressure plot for well A-148 respectively.

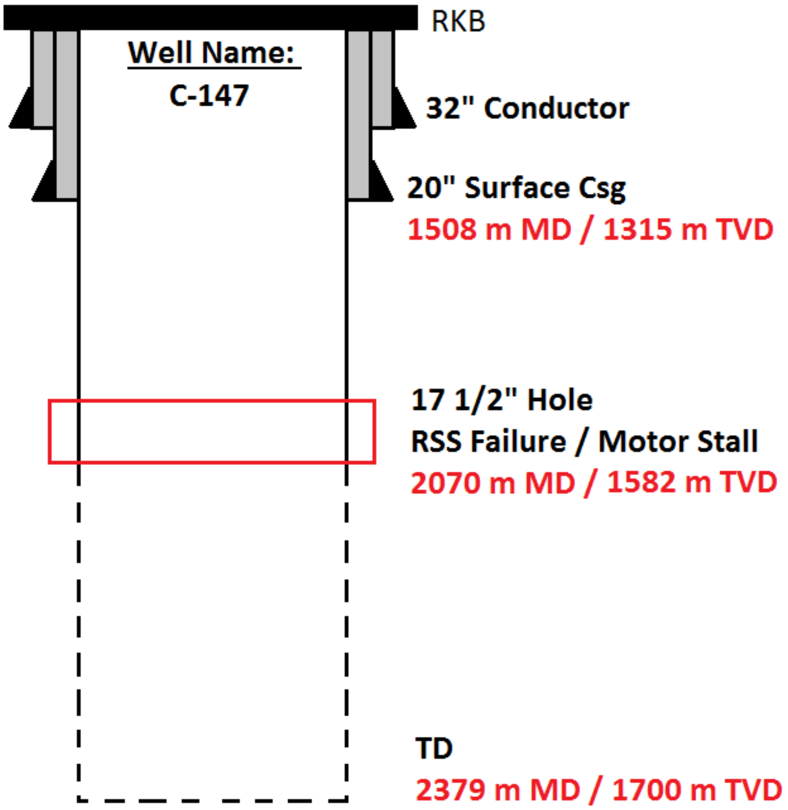


Figure 7-21: Well Schematics. Drawing was based on information from EoW report. TD (Target Depth). Free after (Operator, EoW Report, 2006).

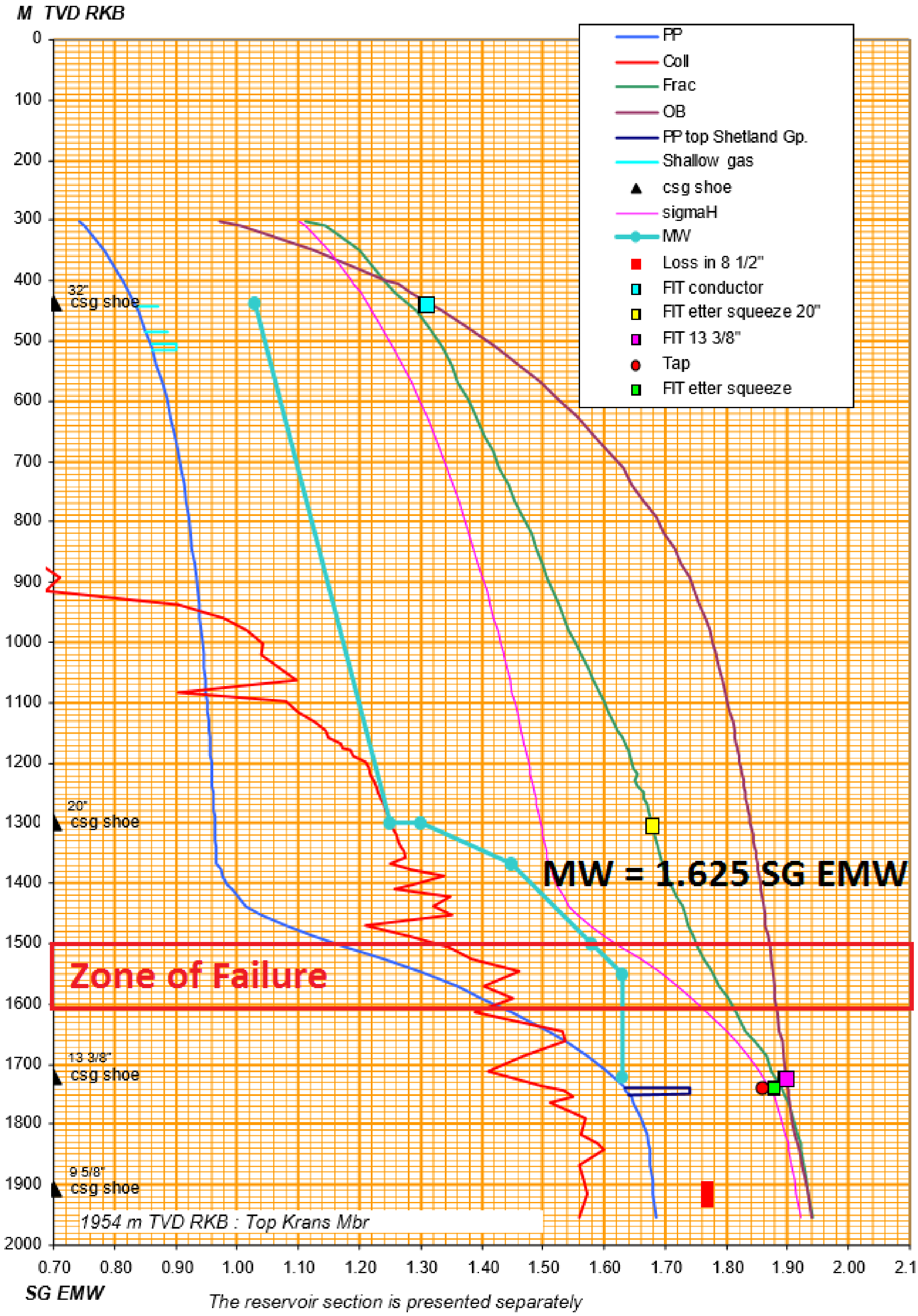


Figure 7-22: Pressure (S.G MW) vs. TVD (m) for well C-147. Boundaries for the entire formation and planned MW are included. Drawings were added in red and black. Free after (Operator, EoW Report, 2006).

Area of interest was from 1500 m TVD to 1582 m TVD. MW used in this window was 1.58 S.G and 1.625 S.G Ultradrill WBM

Sheet #2: RTDD

RTDD is presented in the following order:

- Interpretation of last 12 hour prior to failure.
- Manual symptom detecting from the last 12 hours of RTDD.

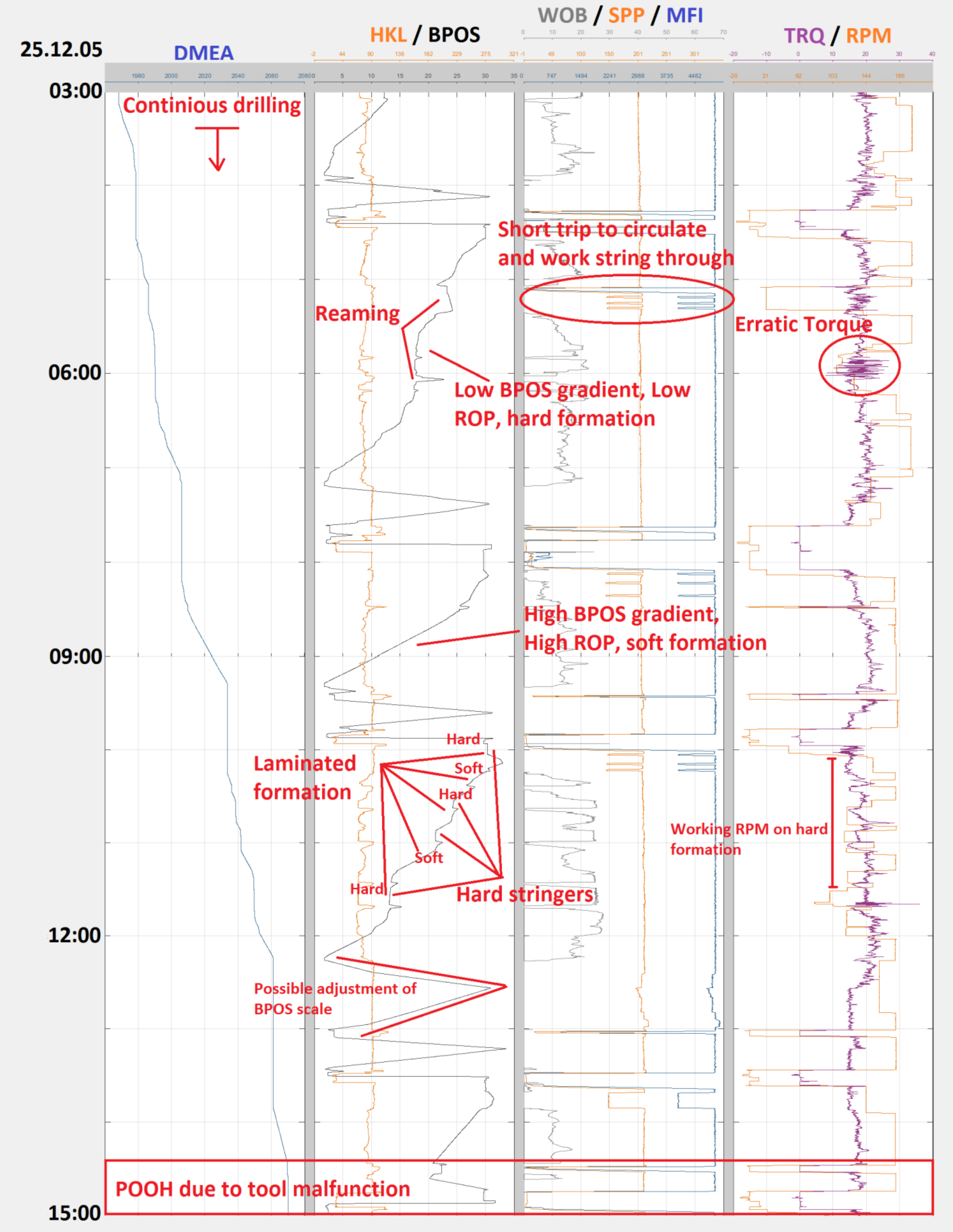


Figure 7-23: Interpretation of 12 hours of RTDD. Comments were added in red. (Raknes, 2014), free after (Operator, RTDD, 2006).

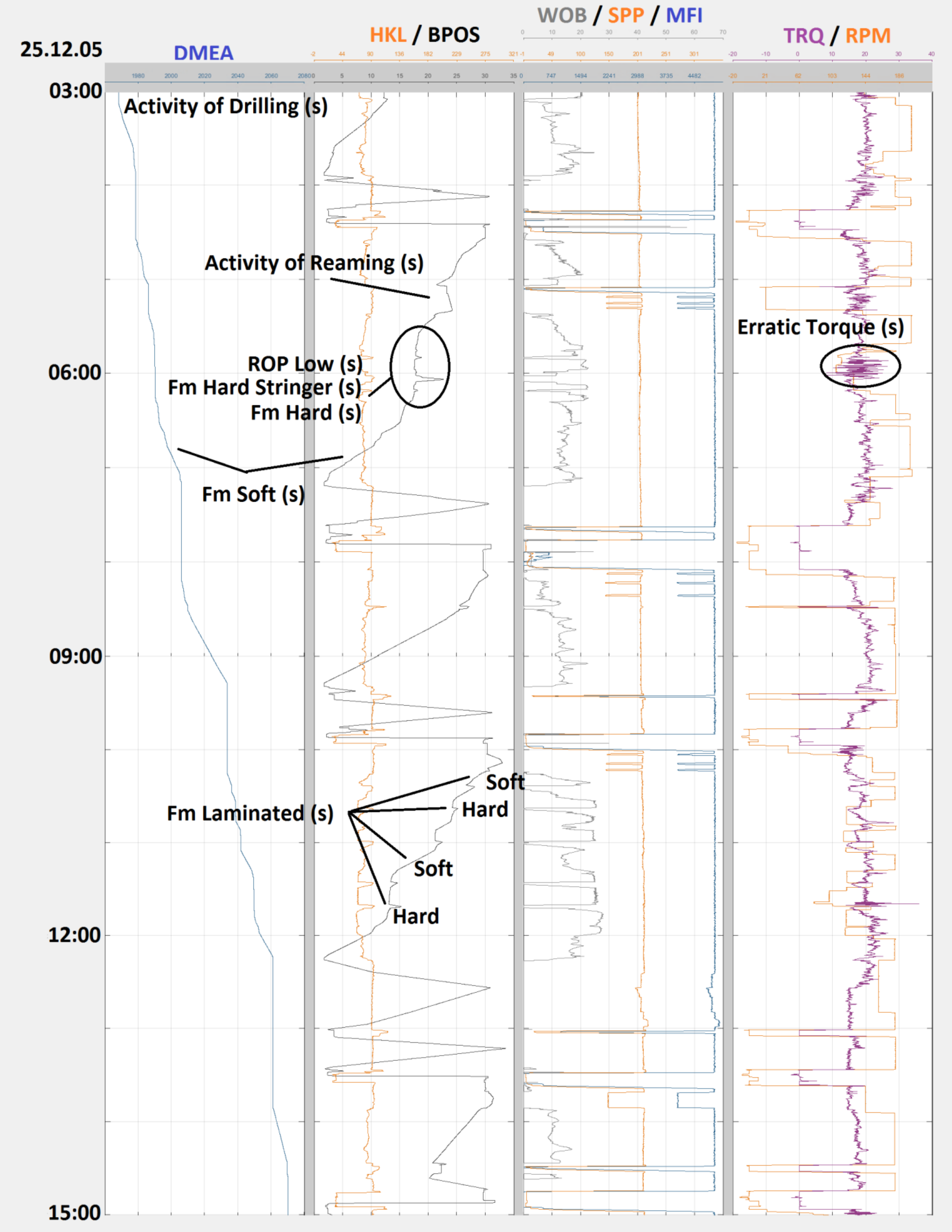


Figure 7-24: Symptom (s) detecting in the RTDD. 12 hours prior to failure. Only the earliest occurrence of each symptom is included. 8 symptoms was detected in the RTDD, these are added in black. (Raknes, 2014), free after (Operator, RTDD, 2006).

Sheet #3: Well Survey

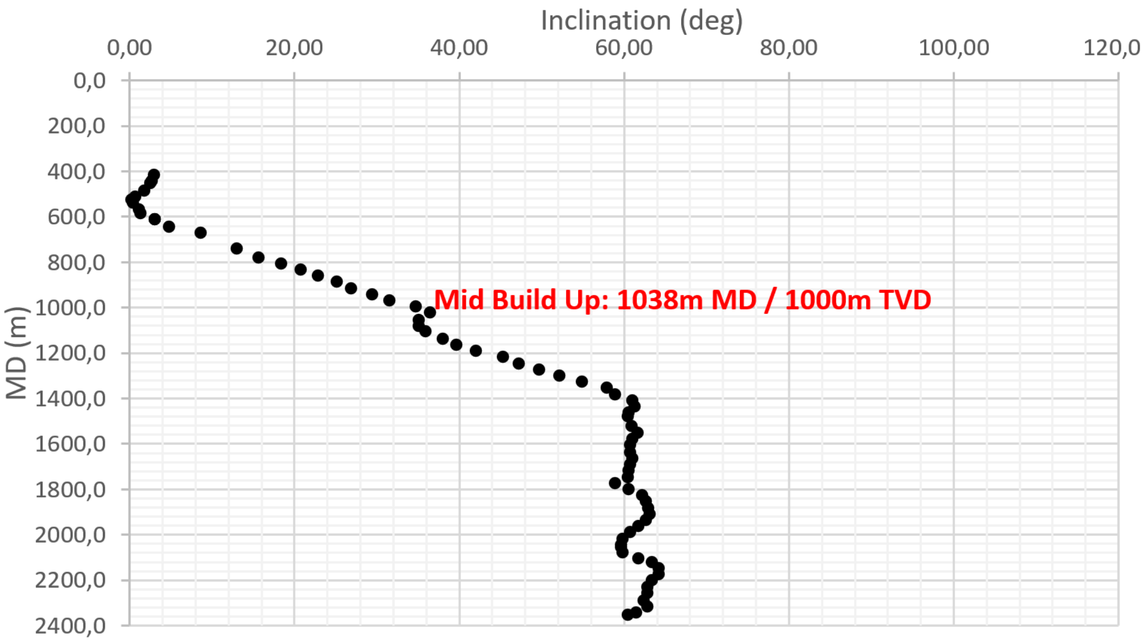


Figure 7-25: Well Survey of well C-147. Measured Depth (m) vs. Inclination (deg). Mid build-up was estimated as the halfway point of increasing data (Operator, EoW Report, 2006).

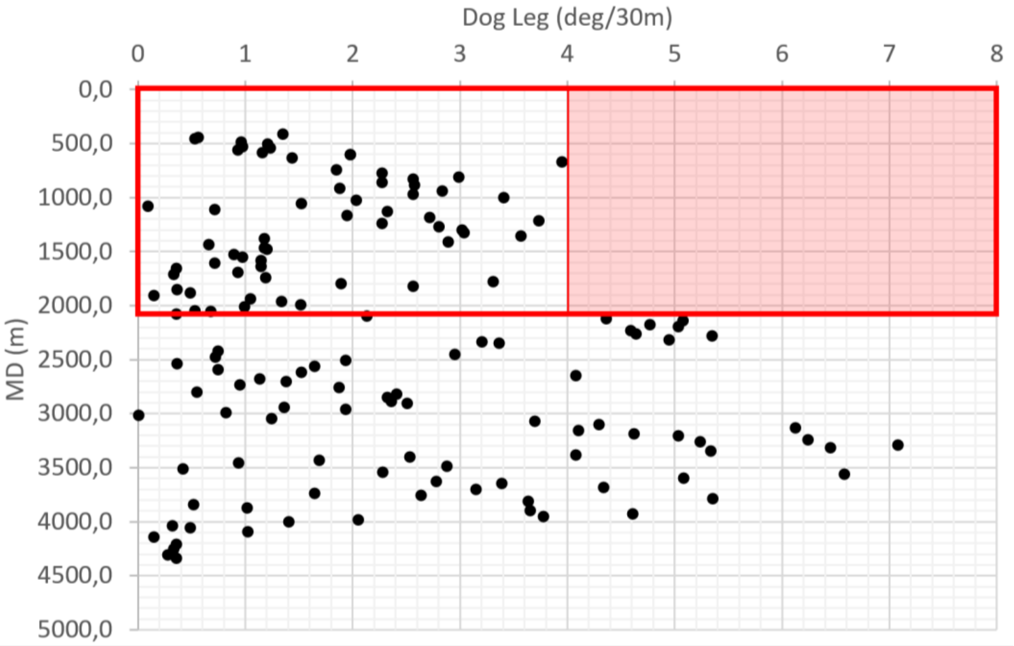


Figure 7-26: Measured Depth (m) vs. Dog Leg (deg/30m). Large red box indicates area of interest for Case 3. Transparent box indicates values with DLS (Operator, EoW Report, 2006).

The transparent box in Figure 7-26 shows that DLS never occurred during this section.

Sheet #4: The Input File

The input file includes:

- Drilling Parameters
  - Static Symptoms (ss)
- Agent Symptoms (s)

Drilling Parameters and Static Symptoms (ss)

Table 7-8 shows drilling parameters from the EoW report for well C-147.

Table 7-8: Drilling parameters as used in the input file for calculation of Static Symptoms (ss). Red values are raw inputs. Oil Field Unit (OFU). Supp (Supported by).

Drilling Parameters	OFU Value	Unit	SI Value	Supp.
Bit Type	Shear Bit	-	Shear Bit	EoW
Bit Size (Previous)	24	in	0,61	Figure 7-21
Bit Size (Present)	17,5	in	0,445	Figure 7-21
Bit Teeth Length	2	in	0,051	Assumed
Fm Above Csg Shoe is Charged	No	-	No	Assumed
Fm Special Expected	No	-	No	Assumed
Fm Boundary Expected	No	-	No	EoW
Fm Fault Expected	No	-	No	EoW
Fm Permeable Expected	No	-	No	EoW
Erosion Wellbore Factor	1,1	-	1,1	Assumed
ID Csg	18,73	in	0,476	Figure 7-21
Losses Expected	No	-	No	EoW
MD Build/Drop Upper	3405	ft	1037,844	Figure 7-25
MD Build/Drop Lowest	3405	ft	1037,844	Figure 7-25
MD Csg Shoe	4947,5	ft	1507,998	Figure 7-21
MD Water Depth	708	ft	215,798	EoW
MD Well	6791	ft	2069,897	Figure 7-21
Mud Type	WBM	-	WBM	EoW
Mud Water Activity	0,91	-	0,91	Assumed
Mud Weight	13,35	ppg	1,6	EoW
Mud YP	18	lb/100 ft^2	8,528	Assumed
OD Csg (Previous)	20	in	0,508	Figure 7-21
OD Stab	0	in	0	Assumed
OD DC	8	in	0,203	EoW
OD DP	5	in	0,127	EoW
Shallow Gas Expected	No	-	No	EoW
TVD Well	5190,3	ft	1582,003	Figure 7-21
Volume Cement	1580	bbl	188,02	EoW
Volume Cement Theoretical	1146,86	bbl	136,477	EoW + Calculations
Volume Csg	922,04	bbl	109,723	EoW + Calculations
Weighting Material	Other	-	Other	Assumed
Well Inclination	62	^{0}	62	Figure 7-25

Static symptoms (ss) were calculated automatically from the drilling parameters in Table 7-8. Table 7-9 show the resulting static symptoms (ss).

Table 7-9: Static Symptoms (ss) calculated from drilling parameters. 11 static symptoms were registered.

Static Symptoms (ss)	**Definition**	**True**
Bit Aggressive (ss)	Bit Teeth Length > 15 mm	1
Bit Type Shear Bit (ss)	When Bit Type = Shear Bit	1
Build/Drop Section Inside Csg (ss)	(MD Csg Shoe - MD Build/Drop Upper) > 0	1
Build/Drop Section Inside Open Hole (ss)	(MD Csg Shoe - MD Build/Drop Lower) < 0	0
Cement V/Theoretical V Low (ss)	(Volume Cement) / (Volume Cement Theoretical) < 1.5 - 1.25 - 1.0	1
Csg Ann Slot Narrow (ss)	(Bit Size (Previous) - OD Csg) < 4 - 3 - 2	0
Fm Above Charged (ss)	Yes = 1; Increasing res pressure due to natural fractures in the formation	0
Fm Boundary Expected (ss)	Yes = 1; Formation boundaries expected based on geology reports	0
Fm Fault Expected (ss)	Yes = 1; Fault/s expected based on geology reports	0
Fm Permeable Expected (ss)	Yes = 1; Drilling in the reservoir or a small permeable zone with length > 10 m	0
Fm Special Expected (ss)	Yes = 1; Special formation expected	0
Losses Expected (ss)	Yes = 1; Losses expected based on geology reports	0
Mud Water Activity High (ss)	Aw > 0.8 - 0.85 - 0.9	1
Mud Water Activity Low (ss)	Aw < 0.8 - 0.7 - 0.6	0
Mud Weight High (ss)	MW > 1.5 - 1,65 - 1,8 kg/l	1
Mud Weighting Material Is Barite (ss)	Weighting Material = Barite	0
Mud YP High (ss)	Mud YP > 15 - 25 - 35 Pa	1
OBM (ss)	Mud Type = OBM	0
Shallow Gas Expected (ss)	SGE = Yes; Challenging to drill through. Avoid by moving the rig	0
Stabilizer Undergauge (ss)	(Bit Size (Current) - Near Bit Stab Size) < 0.02 m	0
Water Depth High (ss)	Water Depth > 300 - 500 - 700 m	0
WBM (ss)	Mud Type = WBM	1
Well Depth High (ss)	Well TVD > 2000 - 3000 - 4000 m	0
Well Depth Shallow (ss)	Well TVD < 2000 - 1500 - 1000 m	1
Well Inclination High (ss)	Well Inclination > 60 deg	1
Well Inclination Low (ss)	Well Inclination < 30 deg	0
Well Inclination Medium (ss)	30 < Well Inclination < 60 deg	0
Well Length High (ss)	MD Well > 3000 - 4000 - 5000 m MD	0
Well Openhole Long (ss)	(MD Well - MD Csg Shoe) > 400 - 750 - 1 000 m MD	1
Wellbore - DC Dia Small (ss)	(Bit Size (Current) - OD DC) < 4 - 3 - 2 in	0
Wellbore - DP Dia Small (ss)	(Bit Size (Current) - OD DP) < 3 - 2 - 1 in	0

Symptoms (s)

The two already developed agents were used to detect symptoms (s). The raw output from running the ECD agent is not presented as the agent returned no hits. Figure 7-22 confirms that the MW is 0.175 s.g above the pore pressure and 0.175 s.g below the fracture pressure boundaries. Raw output from running the Erratic Torque agent is shown in Figure 7-27. Remaining symptoms were detected by manual inspection of the RTDD in Figure 7-24.

Erratic Torque Agent

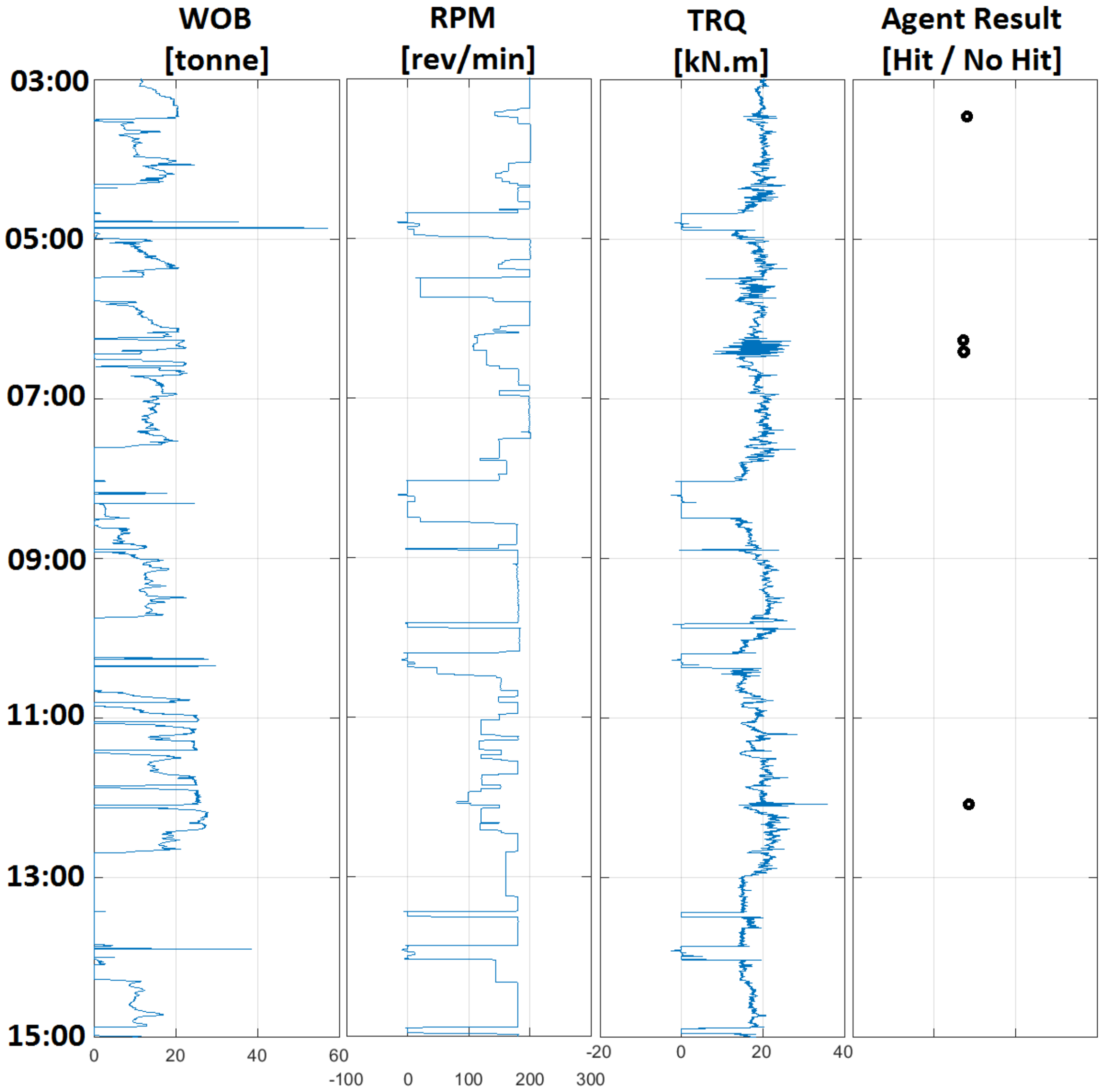


Figure 7-27: Raw result from running Erratic Torque agent on the 12 hour RTDD for case 3.

Column four in Figure 7-27 shows symptom hits at 03:30, 06:15 and 12:00. A true value (a one) was given the Erratic Torque (s) symptom in Table 7-10. This correlates with a manual interpretation of the torque in Figure 7-23. Table 7-10 shows the status of all symptoms.

Table 7-10: Summary of all symptoms (s). EoW report and well survey supported three symptoms. A real agent supported one symptom. RTDD supported eight symptoms. 11 symptoms were activated for Case 3.

Agent Symptoms (s)	Date	Time	TRUE	Supp.
Activity of Directional Drilling (s)	25.des	14:30	1	EoW
Activity Of Drilling (s)	25.des	14:30	1	RTDD
Activity Of Reaming (s)	25.des	05:15	1	RTDD
Activity of Tripping In (s)	-	-	0	RTDD
Activity of Tripping Out (s)	-	-	0	RTDD
Bit MD Long (s)	-	-	0	RTDD
Cavings On Shaker (s)	-	-	0	Assumed
Cuttings Initial Concentration High (s)	-	-	0	Assumed
Cuttings Initial Concentration Low (s)	-	-	0	Assumed
DLS High (s)	-	-	0	Figure 7-26
ECD - Collapse D Low (s)	-	-	0	Real Agent
ECD - Frac D Low (s)	-	-	0	Real Agent
ECD - Pore D High (s)	-	-	0	Real Agent
ECD - Pore D Low (s)	-	-	0	Real Agent
ECD High (s)	25.des	03:00	1	EoW
ECD Low (s)	-	-	0	RTDD
Fm Hard (s)	25.des	06:00	1	RTDD
Fm Hard Stringer (s)	25.des	06:00	1	RTDD
Fm Laminated (s)	25.des	11:00	1	RTDD
Fm Soft (s)	25.des	07:00	1	RTDD
HKL Erratic (s)	-	-	0	RTDD
HKL Signature Wellbore Restricted (s)	-	-	0	Assumed
HKL Signature Wellbore Wall Restricted (s)	-	-	0	Assumed
Losses Seepage (s)	-	-	0	RTDD
Losses Serious (s)	-	-	0	RTDD
Motor Stall Signature (s)	-	-	0	Assumed
MSE Cumulative High (s)	-	-	0	Assumed
MSE High (s)	-	-	0	Assumed
Mud Motor On (s)	25.des	-	1	EoW
Overpull (s)	-	-	0	RTDD
Pressure Spike (s)	-	-	0	RTDD
ROP Low (s)	25.des	06:00	1	RTDD
RPM String On (s)	-	-	0	RTDD
Side Force High (s)	-	-	0	Assumed
Sliding Mode (s)	-	-	0	RTDD
SPP High (s)	-	-	0	Assumed
Time Long (s)	-	-	0	EoW
Took Weight (s)	-	-	0	RTDD
Torque Cumulative High (s)	-	-	0	RTDD
Torque Erratic (s)	25.des	06:00	1	Real Agent/RTDD
Torque High (s)	-	-	0	RTDD
Tripping Speed High (s)	-	-	0	RTDD
WOB High (s)	-	-	0	RTDD
Csg Ann P High (s)	-	-	0	Assumed
Mud LGSC High (s)	-	-	0	Assumed
Pore P Increasing (s)	-	-	0	Assumed

Appendix A-3 presents definitions of the symptoms (s). The program output with the symptoms from Table 7-9 and Table 7-10 entered are shown in chapter 8.2.3.

8 Results

The program produce results when symptoms are entered. The symptoms that are entered in the input file determine the type of result, referred to as output. Four types of output were produced:

- Historical Data vs. Failure Distribution: Output from activating the program with all symptoms entered and PP enabled.
- Failure Distributions from Cases: Output from activating the program with specific case-symptoms activated and PP disabled. The output was then compared to what failure actually occurred.
    - A timeline of the events prior to failure is presented for Case 2.
- Adjustments to the Ontology: Adjustments of program and case output.

8.1 Historical Data vs. Failure Distribution

The program's failure distribution was compared to historical data to understand how well the program resembles reality. The goal was for the failure distribution to match the historical data. The history matching is presented as:

- Historical Data: Failure distribution based on historical data
- Program Output: Failure distribution provided by the program

Figure 8-1 shows historical data on common failures and their likelihood. The historical data was assumed to resemble reality.

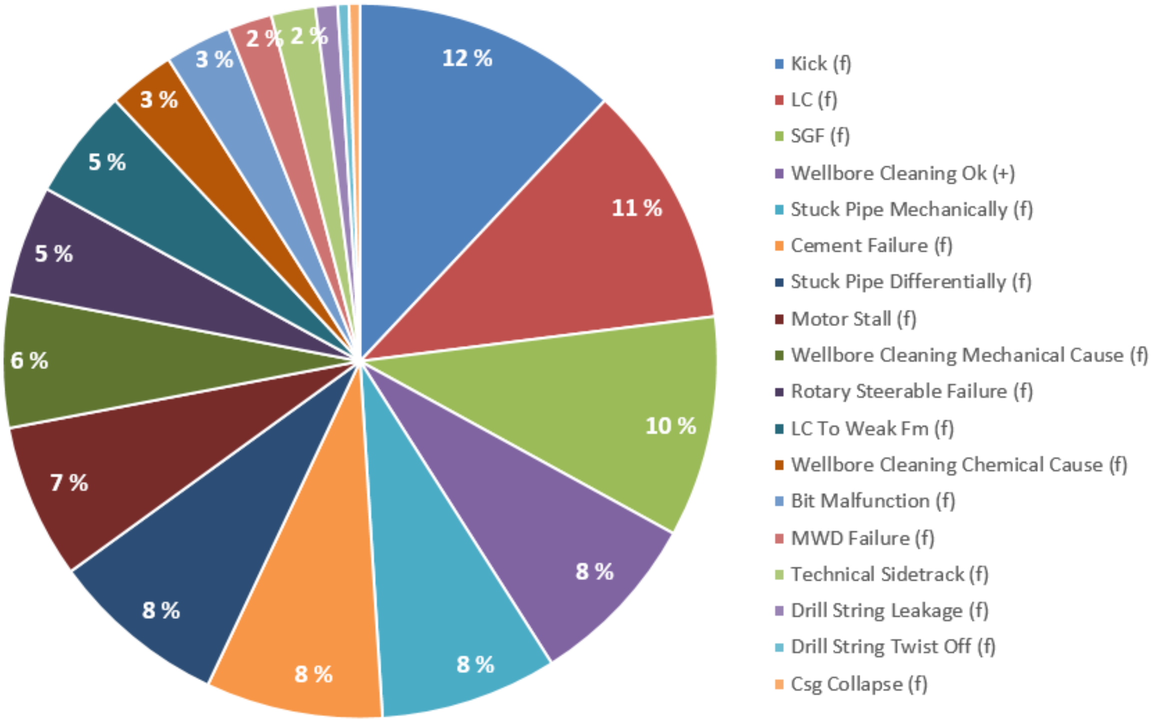


Figure 8-1: Historical failure distribution. (Pritchard, Roye, & Espinoza-Gala, 2012)

Figure 8-2 shows the result from activating the program with all symptoms entered and PPs enabled. The result represents how well the program resembles reality.

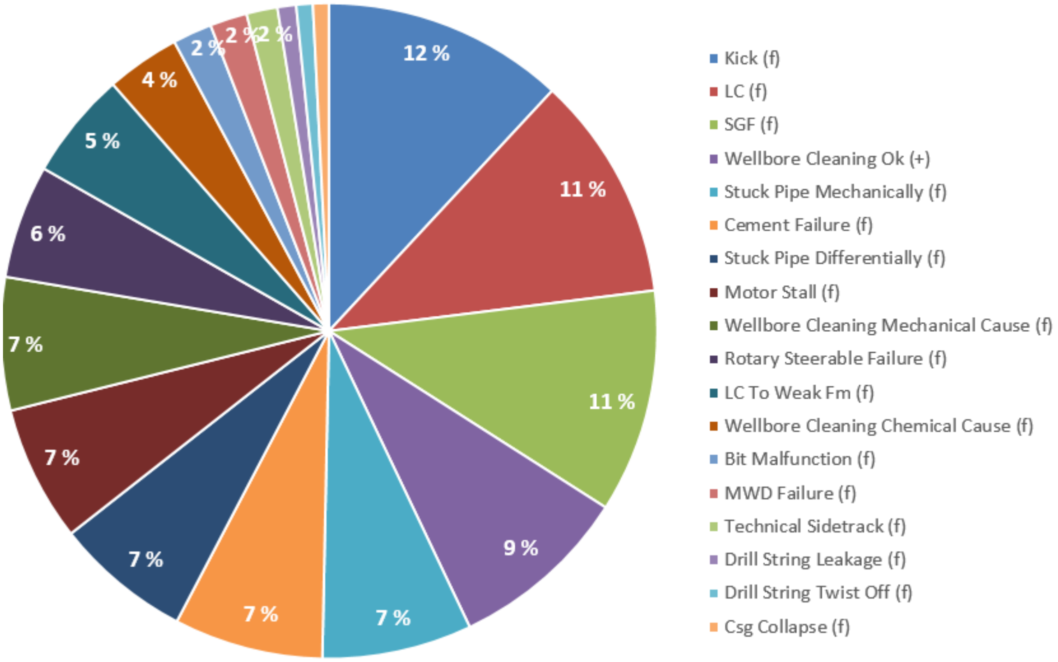


Figure 8-2: Program output. Failure distribution from activating the program with all symptoms entered and PPs enabled (Skalle, Discussion on modification of historical data, 2016).

The failure distribution in Figure 8-2 matches the historical data in Figure 8-1. This is an indication that the program is logical and resembles reality. The match was expected because the program was tuned to match historical data. The failure distribution shows that the three most likely failures when drilling are kick, lost circulation and shallow gas formation.

8.2 Failure Distributions from Cases

Failure distributions from cases were obtained when activating the program with case-symptoms enabled. All cases were created with assumptions. Some assumptions were:

- Values were assumed when information about the failure were missing.
- Symptoms that could not be detected in the RTDD were assumed false.
- The ontology and the program were assumed precise after tuning.

Because of assumptions, the case-result might not resemble reality but anything close is acceptable.

Backtracking is a process that was performed to understand the reasons behind deviations in the result. The process starts by looking at a specific failure. All contributions toward that failure is then localized. The paths are read backwards until reaching a symptom. Figure 8-4 shows how backtracking is performed. Relation-strengths and the number of paths are investigated.

Failure distributions from the following cases are presented:

- Case 1: Lost Circulation
- Case 2: Motor Stall (1)
- Case 3: Motor Stall (2)

8.2.1 Case 1: Lost Circulation

Figure 8-3 shows the result from Case 1 just a few minutes before time of occurrence. Table 8-1 shows the symptoms that were entered into the program.

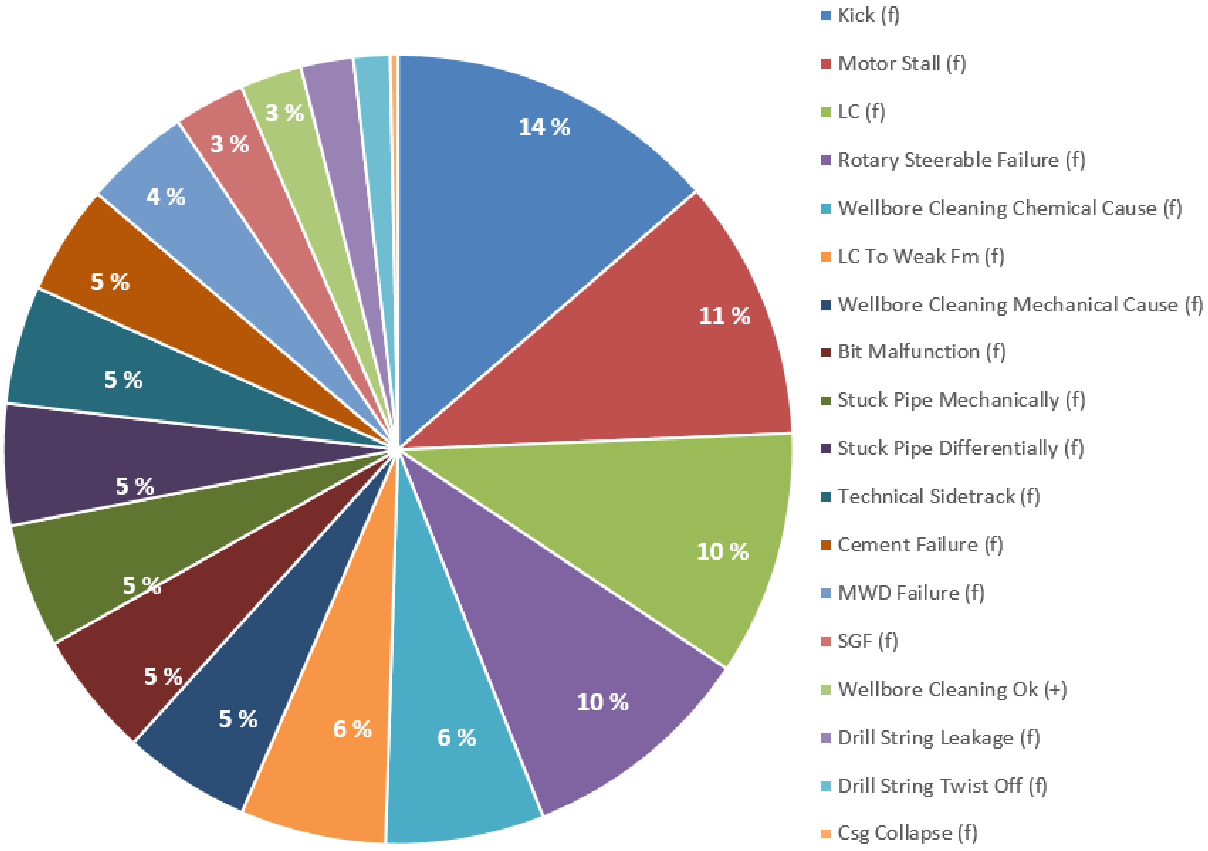


Figure 8-3: Case 1 failure distribution. Failure distribution was based on information from a 12 hour prior to failure window.

Table 8-1: Symptoms that were entered into the program when running Case 1. Column two and four refers to the occurrence of the symptom.

Symptoms	Occurrence	Symptoms	Occurrence
Bit Aggressive (ss)	Static	Bit MD Long (s)	Present from start
Bit Type Shear Bit (ss)	Static	DLS High (s)	Present from start
Build/Drop Section Inside Csg (ss)	Static	ECD - Pore D High (s)	Present from start
Cement V/Theoretical V Low (ss)	Static	Mud Motor On (s)	Present from start
Mud Water Activity High (ss)	Static	ROP Low (s)	15:30
Mud Weight High (ss)	Static	Losses Seepage (s)	14:30
Mud Weighting Material Is Barite (ss)	Static	Fm Hard (s)	15:30
Mud YP High (ss)	Static	HKL Erratic (s)	16:30
OBM (ss)	Static	Activity Of Reaming (s)	17:45
Well Depth Shallow (ss)	Static	Fm Laminated (s)	18:30
Well Inclination High (ss)	Static	Fm Soft (s)	18:50
Activity of Directional Drilling (s)	Present from start	Losses Serious (s)	19:45
Activity Of Drilling (s)	Present from start	ECD - Pore D Low (s)	19:50

Figure 8-3 shows that Kick (f) was most likely to occur next (14 %). Motor Stall (f) was second (11 %) and LC (f) was third (10 %). The distribution was not as extreme as expected, as the most likely failure should exceed 50 % at least. The low distribution indicates something wrong in the model. Possible causes are discussed further in section 9.1.

Backtracking was performed to understand why LC (f) was third and not the most likely failure according to Figure 8-3. Backtracking showed that Losses Seepage (s) was the reason why kick was more likely than LC. Figure 8-4 shows how Losses Seepage (s) is related to Kick (f) and LC (f).

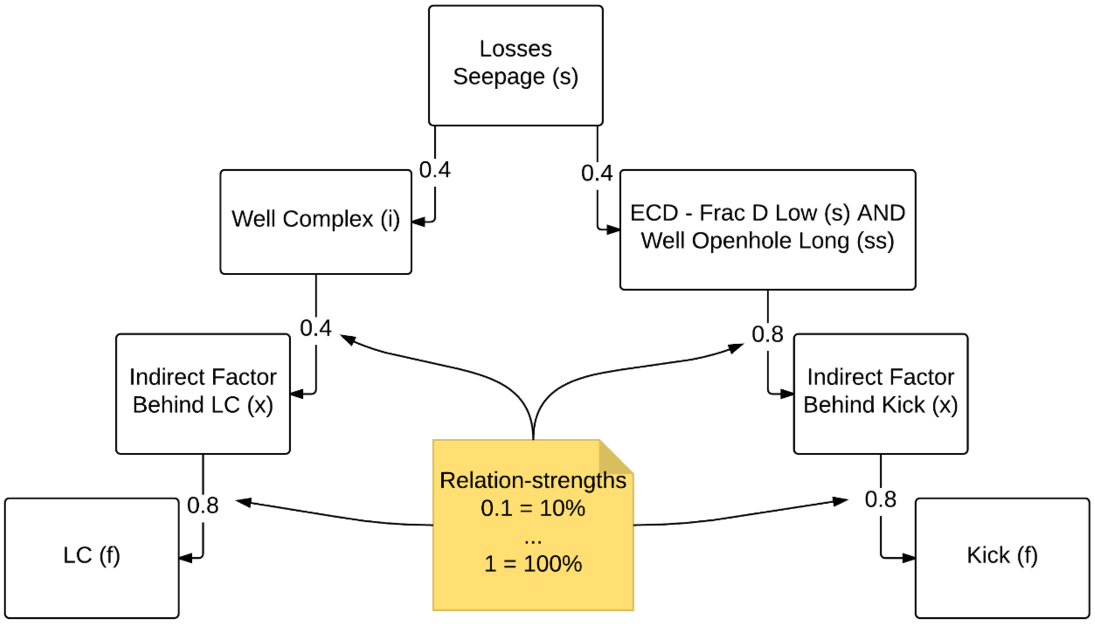


Figure 8-4: Backtracking of two paths for LC (f) and Kick (f). Two paths leading from Losses Seepage (s) to LC (f) (left) and Kick (f) (right). Numbers indicate percent in fraction of one.

Findings related to why Kick (f) was more probable than LC (f) are summarized as:

- Kick (f) is more probable than LC (f) if the well experienced only Losses Seepage (s).
- LC (f) had a 0.128 probability of occurring next based on one single path.
- Kick (f) had a 0.256 probability of occurring next based on one single path.
- The difference was caused by a relation-strength of 0.4 between Well Complex (i) and Indirect Factor Behind LC (x) compared to 0.8 for the opposite path.

The backtracking analysis was also performed to understand why Motor Stall (f) was more likely than LC (f) according to Figure 8-3. Figure 8-5 shows how Bit Vibration (err) effect Motor Stall (f) through multiple paths.

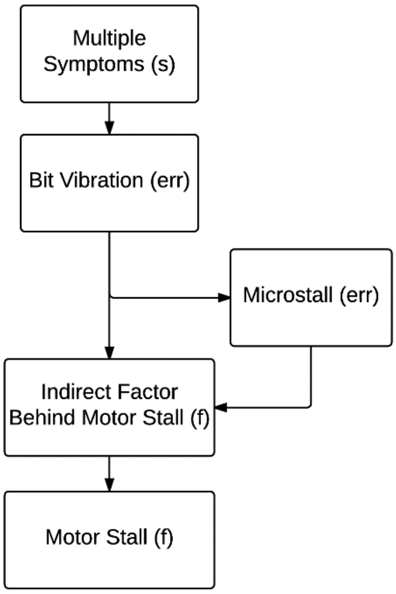


Figure 8-5: Backtracking of one path for Motor Stall (f) and Bit Vibration (err). Bit Vibration (err) causes Indirect Factor Behind Motor Stall (x) and Microstall (err). Both of these causes are related to Motor Stall (f).

Findings related to why Motor Stall (f) was more probable than LC (f) are summarized as:

- Motor Stall (f) is closely related to Bit Vibration (err).
- Bit Vibration (err) had a total of nine contributions from different paths (Indicated as “Multiple Symptoms (s)” in Figure 8-5). These paths existed due to the occurrence of:
    - HKL Erratic (s)
    - Torque Erratic (s)
    - Fm Hard (s)
    - Fm Hard Stringer (s)
- Motor Stall (f) is indirectly related to Microstall (err).
    - Microstall (err) is directly related to Bit Vibration (err).
- The contribution from Bit Vibration (err) effects Motor Stall (f) directly, and indirectly through Microstall (err).

HKL Erratic (s), Torque Erratic (s), Fm Hard (s) and Fm Hard Stringer (s) are symptoms that relates to bit vibration. The symptoms are also related to each other; if one occurs, the others often do to. In practice, this means that multiple symptoms causing Bit Vibration (err) might trigger when drilling in hard formation. Many symptom-hits causes multiple contributions that increase the likelihood of Motor Stall (f).

8.2.2 Case 2: Motor Stall (1)

Figure 8-6 shows the result from Case 2 just a few minutes before time of occurrence. Figure 8-7 shows a timeline of the events that were entered into the program.

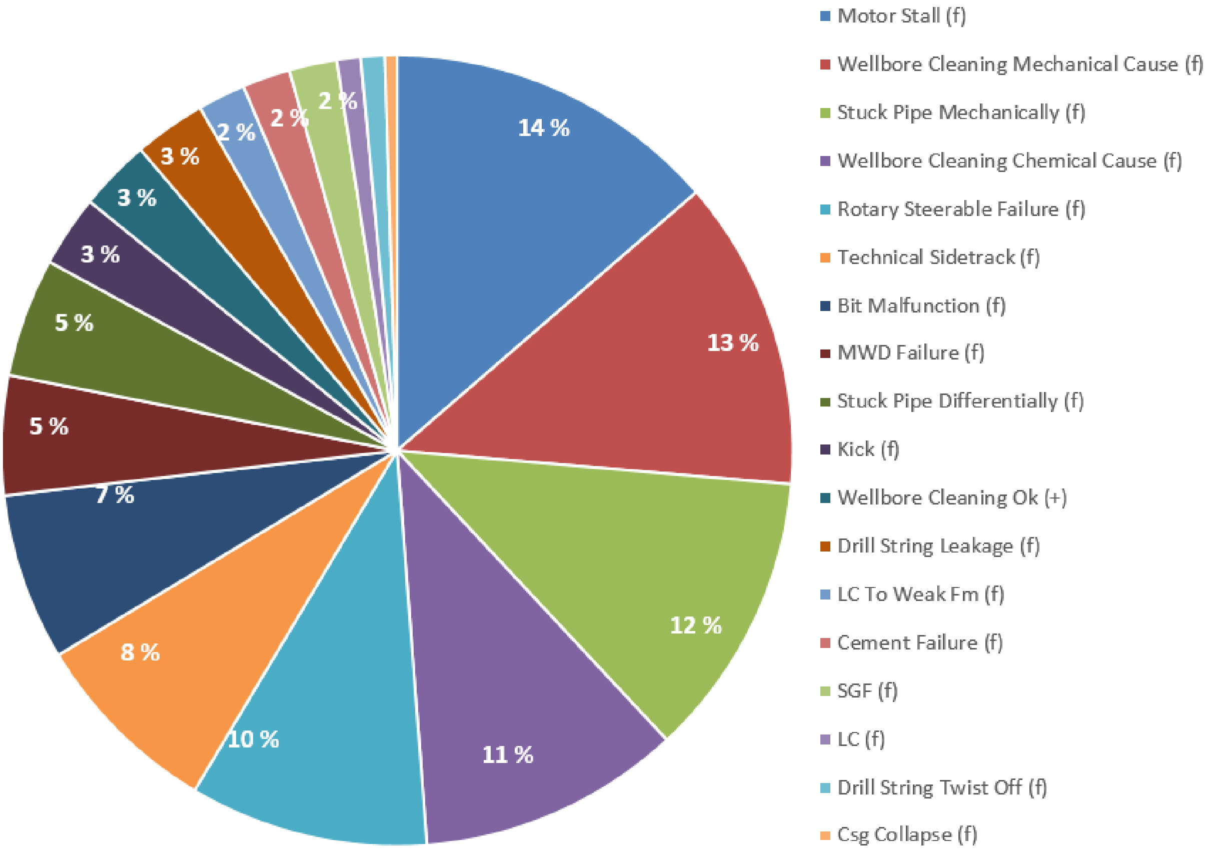


Figure 8-6: Case 2 failure distribution. Failure distribution was based on information from a 12-hour window prior to failure.

Figure 8-6 shows that the most likely failure to occur next is motor stall. This was expected as the actual failure was assumed to be Motor Stall (f). Backtracking was not needed as the result matched the expectations.

Events that occurred in Case 2 was presented as a timeline to investigate how early the program was able to predict the Motor Stall (f). Static symptoms (ss) were entered from the beginning of the case and remains active until the failure occurred. Symptoms are entered at the time of occurrence according to the timeline in Figure 8-7.

Figure 8-7 shows how Case 2 was divided into three periods and placed on a timeline.

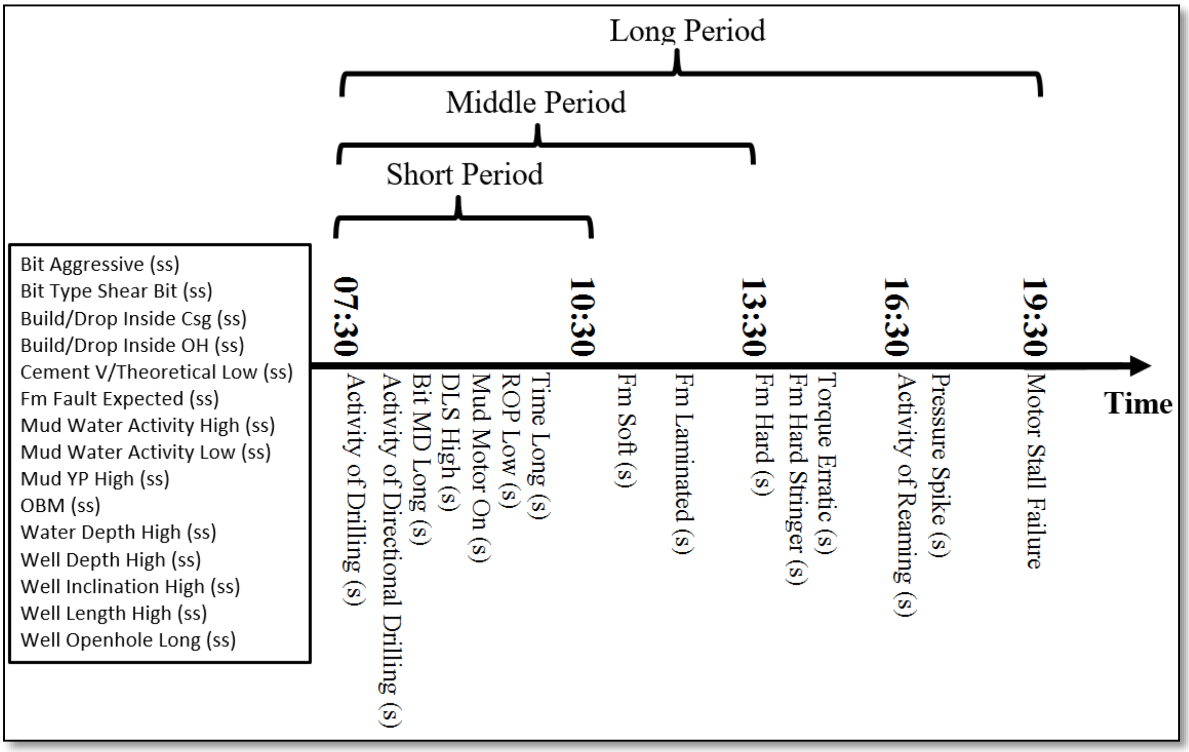


Figure 8-7: Timeline of the events leading up the motor stall failure in Case 2. The box indicates static symptoms (ss) that were present from the start. Symptoms are placed on the timeline when they occurred. The Motor Stall (f) occurred at 19:30.

Figure 8-8 shows the evolution of the probability of Motor Stall (f) based on the three time periods on the timeline.

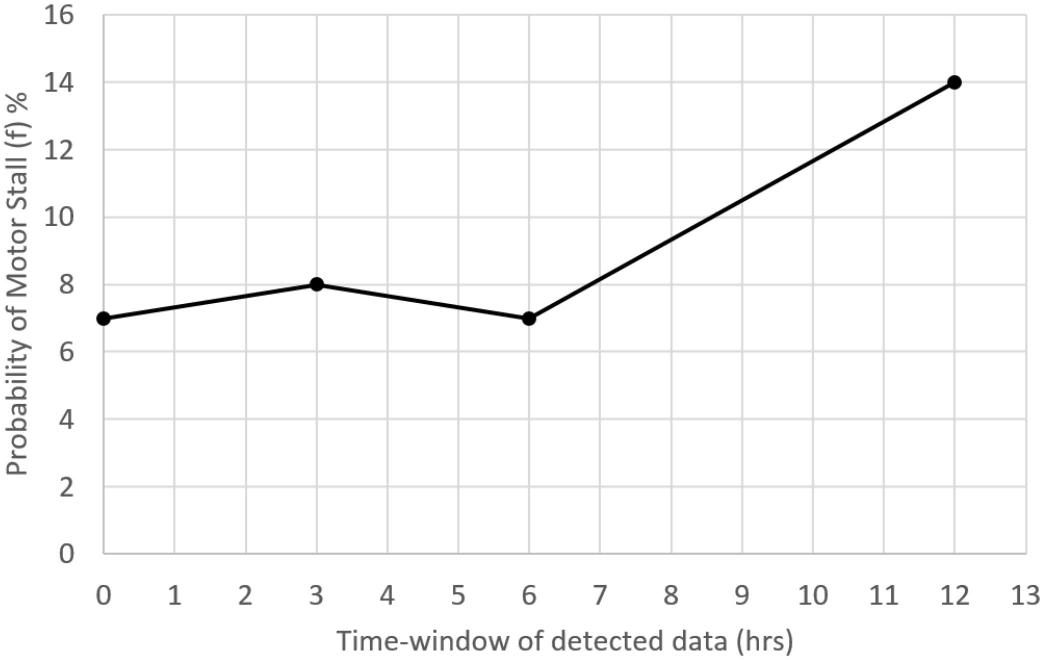


Figure 8-8: Evolution of the probability of a Motor Stall (f) for Case 2. At X = 0 the probability equalled the historical failure distribution of 7 %. When collecting data for 3 hours (X = 3) the probability increased to 8 %. After collecting data for 12 hours (X = 12) the probability reached its maximum of 14 %.

Detailed interpretation of Figure 8-7 and Figure 8-8 showed that the program returns the maximum value of 14 % when Fm Hard (s) and Fm Hard Stringer (s) were entered. This information is not clear in Figure 8-8. The result is therefore: Motor Stall (f) was predicted the most likely failure six hours prior to occurrence. A probability of 14 % is not extreme enough as a probability of at least 50 % is preferred.

8.2.3 Case 3: Motor Stall (2)

Figure 8-9 shows the result from Case 3 just a few minutes before time of occurrence. Table 8-2 shows symptoms that were entered into the program.

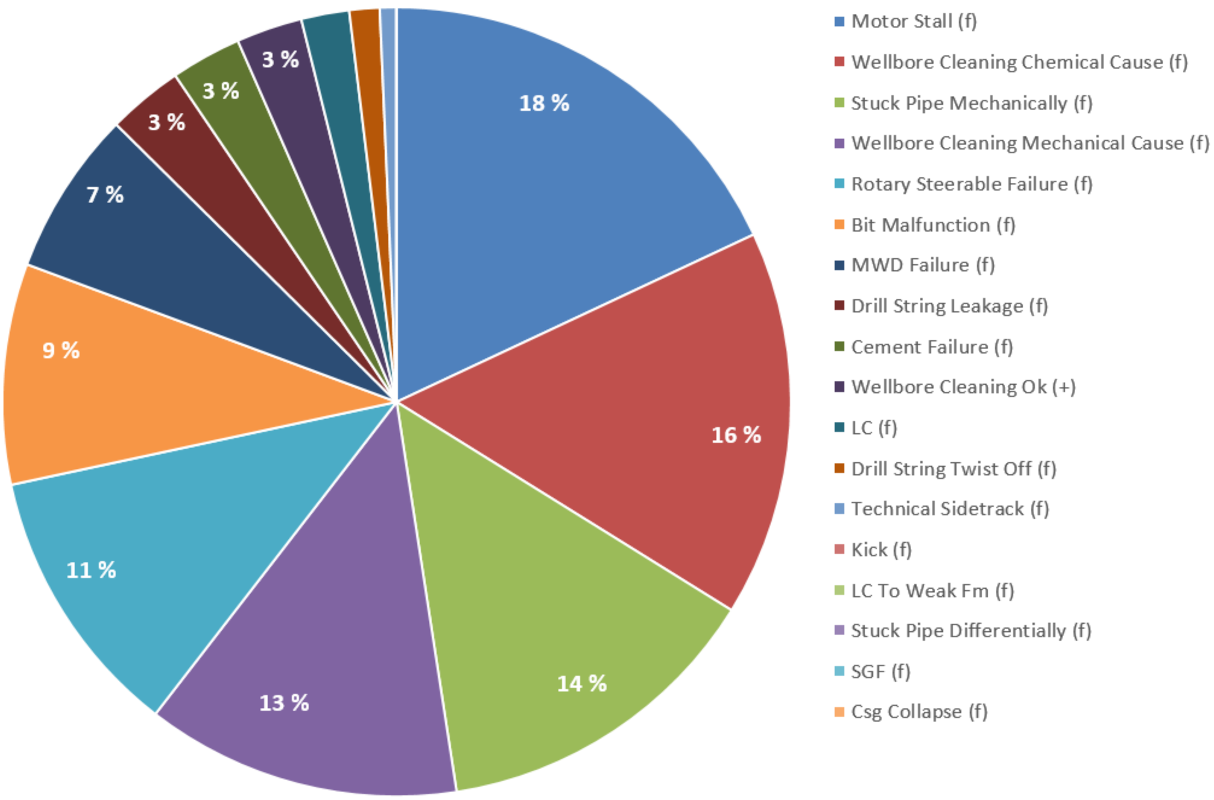


Figure 8-9: Case 3 failure distribution. Failure distribution was based on information from a 12-hour window prior to failure.

Table 8-2: Symptoms that were entered into the program when running Case 3. Column two and four refers to the time of occurrence for each symptom.

Symptoms	Occurrence	Symptoms	Occurrence
Bit Aggressive (ss)	Static	Mud Motor On (s)	Present from start
Bit Type Shear Bit (ss)	Static	ECD High (s)	03:00
Build/Drop Section Inside Csg (ss)	Static	Activity Of Reaming (s)	05:15
Cement V/Theoretical V Low (ss)	Static	ROP Low (s)	06:00
Mud Water Activity High (ss)	Static	Torque Erratic (s)	06:00
Mud Weight High (ss)	Static	Fm Hard (s)	06:00
Mud YP High (ss)	Static	Fm Hard Stringer (s)	06:00
WBM (ss)	Static	Fm Soft (s)	07:00
Well Depth Shallow (ss)	Static	Fm Laminated (s)	11:00
Well Inclination High (ss)	Static	Activity of Directional Drilling (s)	14:30
Well Openhole Long (ss)	Static	Activity Of Drilling (s)	14:30

Figure 8-9 shows that the most likely failure to occur next is motor stall. This was expected as the actual failure was assumed Motor Stall (f). Backtracking was not needed as the result matched the expectations.

8.3 Adjustments to the Ontology

Analysis of the program and the case-results revealed concepts that should be added, removed or changed. Inconsistencies that were discovered and possible solutions are presented below:

- Mud Gas Content High (i) points to no concept.
- Direct Factor Behind Fm Boundary (x) points to no concept.
- There is no clear difference in the definition between Motor Stall (f) and Rotary Steerable Failure (f).
- Motor Erosion (i) points to Microstall (err) twice. Once alone and once to an AND statement. Figure 8-10 shows both relationships. Including both relationships will cause the probability of Microstall (err) to become too high.

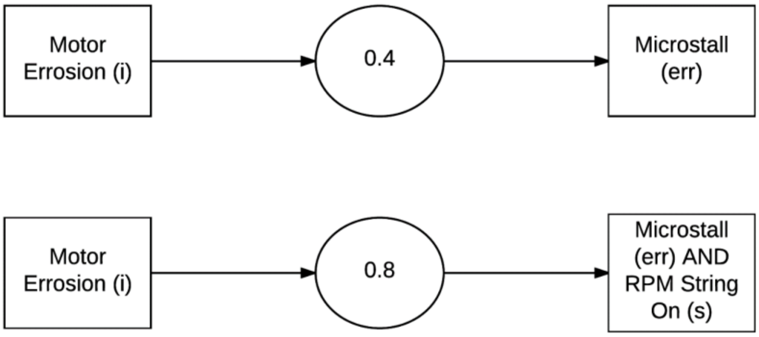


Figure 8-10: Two relationships including Microstall (err). Motor Erosion (i) is related to Microstall (err) through a single relationship (upper) and through an AND statement including RPM String On (s) (lower).

Section 9.4, Ontology, discusses possible solutions to the findings above.

9 Self-Assessment

The program developed in chapter 6 and the data used to create cases in chapter 7 include uncertainties. The quality, the shortcomings, the theory and the information applied to the program, depend on these uncertainties. Intelligent guessing are referred to as estimations. The chapter is structured like:

- Model Uncertainty
- Data Uncertainty
- Applicability
- Future Improvements

9.1 Model Uncertainty

The model has some uncertainties, mainly because estimations were used when developing the ontology and tuning the program. Uncertainties were present in:

- Prior Probability
- Ontology
- Program Output
- Program Inputs
- Development Method

Prior Probability

PP was introduced to make the program result comparable to historical failure distributions. PP refers to the likelihood of occurring given no other information. PP uncertainties are related to:

- Deciding how to add PP to the model.
- Using PP to tune the program.

Two approaches were available when adding PP to the model:

1. Adding PP to all concepts.
2. Adding PP to symptoms (s) and (ss) only.

Approach 1 was used (see; section 6.5). Initially it was assumed that PP would contribute to all concepts. The program was tuned based on approach 1. The following example is presented to show the difference in path-strengths when applying the incorrect PP approach.

Two concepts:

- Finding Gold
- Becoming Rich

You rarely find gold and you rarely become rich so the PP of these concepts are very low (say 0.001). If you have already found gold the likelihood of becoming rich is high, i.e. the relation-strength is high (say 0.5). Figure 9-1 illustrates the example.

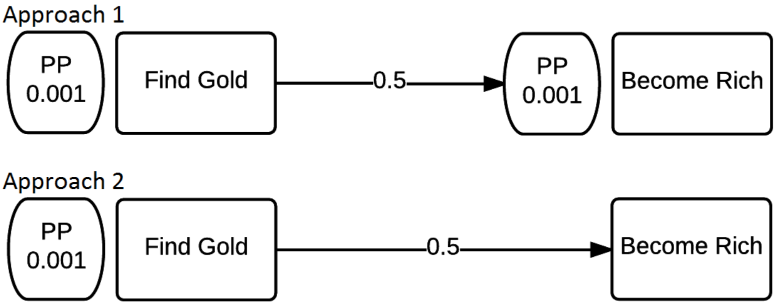


Figure 9-1: Relationships between Find Gold and Become Rich. The relation-strength is 0.5. Approach 1 (Top): The PP are added to both concepts in the relationship. Approach 2 (Lower): PP added only to the initiating (left side) concept.

Only the PP of finding gold should be included as we are interested in the probability of becoming rich given you already found gold. When adding PP to both concepts the affect becomes over-represented.

The probability of becoming rich after finding gold according to approach 1 is:

$$P(Become\ Rich)_{Find\ Gold} = 0.001\ x\ 0.5\ x\ 0.001 = 0.0000005$$

According to approach 2 the probability of becoming rich after finding gold is:

$$P(Become\ Rich)_{Find\ Gold} = 0.001\ x\ 0.5 = 0.0005$$

There is a clear difference in approach 1 and approach 2. Further testing is required to prove which approach is correct.

Figure 9-2 shows how the result in Figure 8-1 would look if approach 2 was applied.

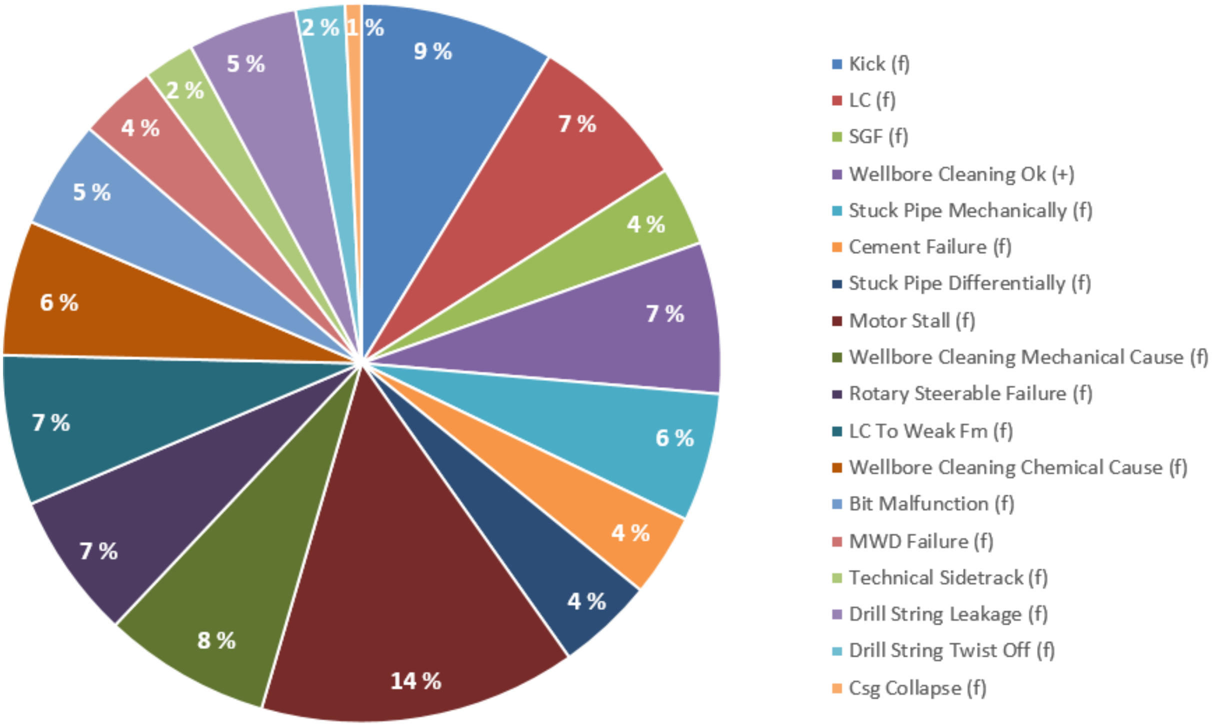


Figure 9-2: Program output if approach 2 was used instead of approach 1.

Figure 9-2 clearly shows a different result than approach 1 in Figure 8-1. The tuning process would also be different if applying approach 2. Uncertainties in the case-results and in the model are consequences from choosing approach 1.

Ontology

The ontology was developed prior to project start and had to be changed multiple times in order for program output to match the historical failure distribution.

- There were three main reasons to change the ontology:

    1. Gaining new knowledge about drilling related failures. This may cause adding, removing or changing of a concept.
    2. Deciding to try a new development approach. This may cause ontology rules to be added, removed or changed.
    3. Tuning the program. This may cause relation-strengths to change or the PP to change.

- How can relation-strengths be determined precisely?
  Relation-strengths caused model uncertainties because most of them were based on estimations that were necessary because little data on dependent probability existed. For some relationships, it can be difficult to not include information about general occurrence in the relation-strength. Relation-strengths were changed during tuning. It is difficult to verify that already existing relation-strengths are correct, when they were changed during tuning.
- What is the optimal number of paths?
  During development and tuning of the program, it was discovered that the number of paths towards a failure dominated the result too much. A new entity, referred to as DFBF/IFBF (x) (see; section 4.1.2) was added to make the number of paths equal. Rule 7 in section 4.1.2 states that all paths must go through a DFBF/IFBF concept. Figure 9-3 shows how the number of paths leading to a specific failure can be manipulated by scaling the relation-strength between this new entity and the failure.

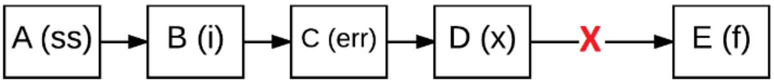


Figure 9-3: A path containing the concepts: A, B, C, D and E. The red "X" indicate the relation-strength between DFBF/IFBF (x) and the Failure (f).

> The red “X” was increased/decreased if the number of paths were under/over-represented. The entity (x) was applied to handle the number of paths while additional relationships were added or removed. Relation-strengths are verified when the ontology requires no further tuning after development. It is difficult to verify the relation-strengths if the scaling explained above is necessary to produce a correct failure distribution.

Applying the changes above requires cooperation between the program- and ontology-developers to update the ontology and implement the changes. The current state of the ontology does not have to be in the best state, it has to be in a sufficient state. A sufficient state was determined based on the history matching. Throughout development, the ontology was changed until a sufficient state was finally achieved.

Program Output

The program output is a failure probability distribution of the next failure. The output provides information on what is the most likely failure to occur next. However, the program produces a failure distribution even though no failure is going to occur. This weakness exists because the program output is presented as a percentage. The result provides no information on the number of paths leading to the failures. The program will produce a result even if only a few symptoms are active.

Figure 9-4 shows how the failure distribution would look if only static symptoms (ss) were active and drilling have not even started.

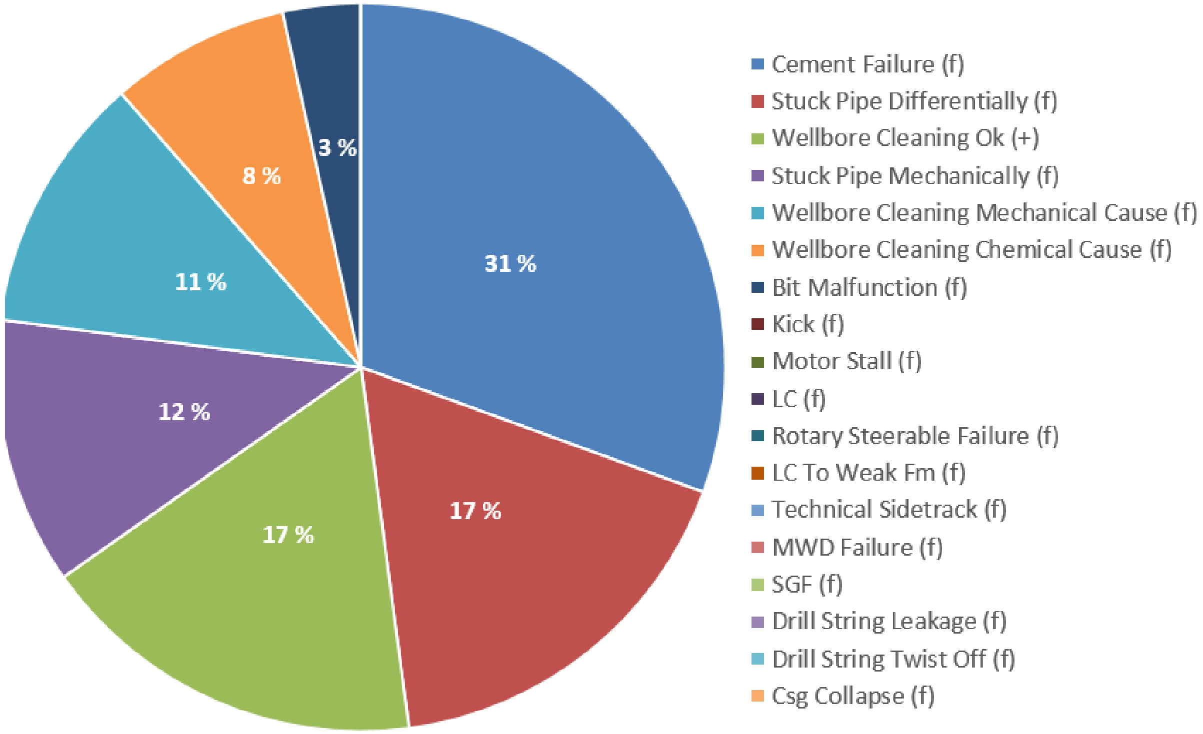


Figure 9-4: Program output where some static symptoms (ss) and no symptoms (s) are included. Drilling have not started.

The result produced in Figure 9-4 should be read as: There is a 31 % probability that the next failure that occurs will be Cement Failure (f)". The program is unable to predict the probability of this failure actually occurring.

Program Inputs

Drilling parameters and agents detect static symptom and symptom hits. The static symptoms are valid during the complete drilling operation (or until a change is reported). There are currently no rules for expiry of symptoms (s). A hit remains active until manually removed. The symptoms in a test case (see; Figure 8-7) remains active until the failure occurs or other is reported. That symptoms never deactivates are a problem for short-time concepts like Torque Erratic (s) and for depth-based symptoms like Fm Hard Stringer (s). Ideally, symptoms like Torque Erratic (s) would decay over time. Some symptoms should have a long decay time while others should decay almost instantaneously.

Development Method

A hierarchal structure was chosen as part of the development method. UnixSpace (2016) presents other possible structures, such as:

- Network Model
- Relational Model
- Object/Rational Model
- Context Model

Only the hierarchal structure was used and tested due to limited resources and time. The hierarchal structure cannot be verified as optimal when only testing one model. Concepts were allowed to provide information forward and backward in early stages of development. In later stages, the concepts could only provide information forward. The structure in early stages resembled the Network Model where information can flow across all levels.

9.2 Data Uncertainty

Collection and interpretation of data is important when creating cases. The quality of a case depends on the quality and the quantity of the data. Data used to create cases were:

- EoW Reports
- RTDD
- Surrounding Wells

This section discusses the uncertainties found in the data.

EoW Report

Two EoW reports were available. One for well C-147 and one for well A-148. The reports included most of the necessary drilling parameters but some values had to be estimated. There were two reasons for estimating a value:

1. The value was not listed in the EoW report.
2. The value was listed but did not correlate with other available data. This data could be from other parts of the EoW report or from the RTDD. In this case, a value was estimated based on the available information.

The EoW reports included information from drilling the conductors until the wells were stimulated for production. Unfortunately, an EoW report only focuses on the final well path if one or multiple side-tracks are performed. Because of this, Case 2 on well A-148 had little information about A-148 (A-148 was later side-tracked into A-148T). Most drilling parameters were assumed equal to those reported in A-148T. This was justified as A-148T was drilled parallel to A-148 in the same layers.

Drilling parameters from EoW reports are used to calculate static symptoms. Some of these formulas have estimated thresholds for true or false. An example is:

The static symptom Well Openhole Long (ss) is true when the well is exposed to the formation for a “long period of time”. A” long period of time” is defined as the time spent drilling 750 m MD since last casing shoe.

Drilling 750 m MD might require a day in one situation and a week in another situation. Clearly, some uncertainties are attached to such definitions and estimations.

RTDD

RTDD was available for all three cases. A total of 78 different logs were available and most of them included valuable data. Appendix C presents the complete list of logs. The quantity of the RTDD was more than sufficient for detecting symptoms. The quality of the RTDD was related to:

- **Sampling Frequency**

  The sampling frequency varied in all sections for both the wells. Sampling was calculated by dividing the measuring time by the amount of data points. Table 9-1 shows the sampling frequencies.

Table 9-1: Sampling frequencies for cases 1, 2 and 3 in seconds per sample.

Case	Well	Section	Sampling	Unit
1	C-147	12 1/4"	4,4	s/sample
2	A-148	8 1/2"	5,6	s/sample
3	C-147	17 1/2"	4,6	s/sample

  A sampling frequency above 4 seconds per sample is insufficient to determine some symptoms like HKL Erratic (s) and Torque Erratic (s).

- **Consistency**

  Some RTDD will always be lost during drilling. Some data is corrupted due to tool interference, contamination or other interruptions. Because of this, some logs included no or only small amounts of data. A human interpreting the RTDD can read between the lines when data is missing, but an agent will struggle. Because of this, all logs required quality control (QC) before use. QC involved changing invalid numbers equal to zero and ignoring scale adjustments.

Inaccurate sampling speeds and loss of consistency in the data were the two main uncertainties found in the RTDD.

Surrounding Wells

Information and data from surrounding wells were used when missing vital data. Well A-148 was correlated with well A-148T in Case 2. Correlation with surrounding wells is good practice in most drilling situations and allows estimation of parameters that are normally not available. It is important to be aware of the risk and the uncertainty with such correlation.

9.3 Applicability

The developed model has applicability even though no optimal state was reached. This section explains some practical and the theoretical applications of the model.

Practical Applicability

Practical applicability is related to the physical program within the model. The program in its current state is able to transform input into output through calculation. Drilling parameters are automatically transformed into pre-defined static symptoms. Symptoms in the RTDD are found manually by the exception of a few already created agents. A failure distribution is produced automatically when new inputs are added.

The program can be used as a platform for future development. The hierarchal structure connecting all the relationships from the ontology is already developed. The program is integrated to an input file and a result file. The results are logical and resemble reality. In its current state, the program carry too many uncertainties for live use and the output is not extreme enough. The applicability is therefore related to testing, tuning and further development rather than actual use.

Theoretical Applicability

Theoretical applicability is related to the entire probability model. The results obtained from real cases confirmed that the current model state is not accurate but that it resembles reality. The applicability is what theory works and what does not. This is information about:

- How to use an ontology as the foundation for a probability model.
- Strengths and weaknesses with a hierarchal development structure:
    - The structure is logical and intuitive. Information can be changed with only minor changes to the program.
    - The structure is time consuming to develop and require manual work. Paths are created manually and connected automatically.

- How a program can handle multiple inputs and produce dynamic output (results that changes with every changed input).
- How MS Excel can be used to develop this type of program.
- The results in section 8.3 show what concepts should be added, removed or changed in the ontology.

These findings are useful when further developing this probability model or when applying theory to a new model.

9.4 Future Improvements

The probability model is not in an optimal nor sufficient state. The shortcomings mentioned in sections 9.1 and 9.2 need to be resolved to obtain a sufficient quality level. This section explains how to handle the shortcomings through future improvements.

Prior Probability

Approach 2 (see; section 9.1) is believed to be the correct approach. Approach 2 can be applied by removing PP for all concepts except symptoms. Further testing is required to prove what approach is correct. The program will still require tuning. It is believed that the case output will match historical data better after tuning approach 2.

Ontology

Figure 9-3 shows how the DFBF/IFBF (x) entity was added to all paths. Adding the entity was a short term fix, but allowed efficient and easy adjustment of the number of paths leading to a failure. In long term, the ontology can be improved by removing the DFBF/IFBF (x) entity and instead creating additional paths. Ideally, the number of paths should be equal for all failures to avoid imbalance. Adding paths are preferred as it increases the overall information in the ontology. Changes should only be applied to the ontology if they can be supported by theory.

Section 8.3 presents what concepts should be changed based on analysis of the program and case results.

- Mud Gas Content High (i)
    - Add: Relationship to Well P Too Low (err)
- Direct Factor Behind Fm Boundary (x)

  The concept was originally added to the ontology for testing purposes. It was used to test if the (x) entity also could point to positive information.
    - Change: The concept was kept in the ontology by a mistake after testing. The concept should be removed.
- Motor Stall (f) vs. Rotary Steerable Failure (f)
    - Change: Motor Stall (f) should be defined as the motor being unable to transform mud energy into mechanical energy for drilling, steering and other applications.
    - Change: Rotary Steerable Failure (f) should be defined as when a RSS tool is unable to maintain a specific inclination/azimuth due to formation properties when still mechanically and electronically functional.
    - Add: BHA Broken/Failure (f) should be added and defined as when a vital part of the BHA (excluding motor) is damaged to the point that drilling cannot proceed.
- Motor Erosion (i) points to Microstall (err) twice.
    - The double relation was found to be an example of expanding AND series (see; rule 8 section 4.1.3)
    - It is clear that including both the relationships in Figure 8-10 over-represents the probability of Microstall (err).
    - Remove: The relationships in Figure 8-10 should be changed to an expanding AND series (see; rule 8 section 4.1.3)

Program Output

One shortcoming of the program is that it provides a distribution even though only a few symptoms are active. A possible solution is to include the total path-strength in the visual presentation of the result. A low path-strength indicates few active symptoms while a high path-strength indicates many active symptoms. The higher path-strength the more trustworthy the distribution is. Figure 9-5 shows an example of how the result would look if including the total path-strength.

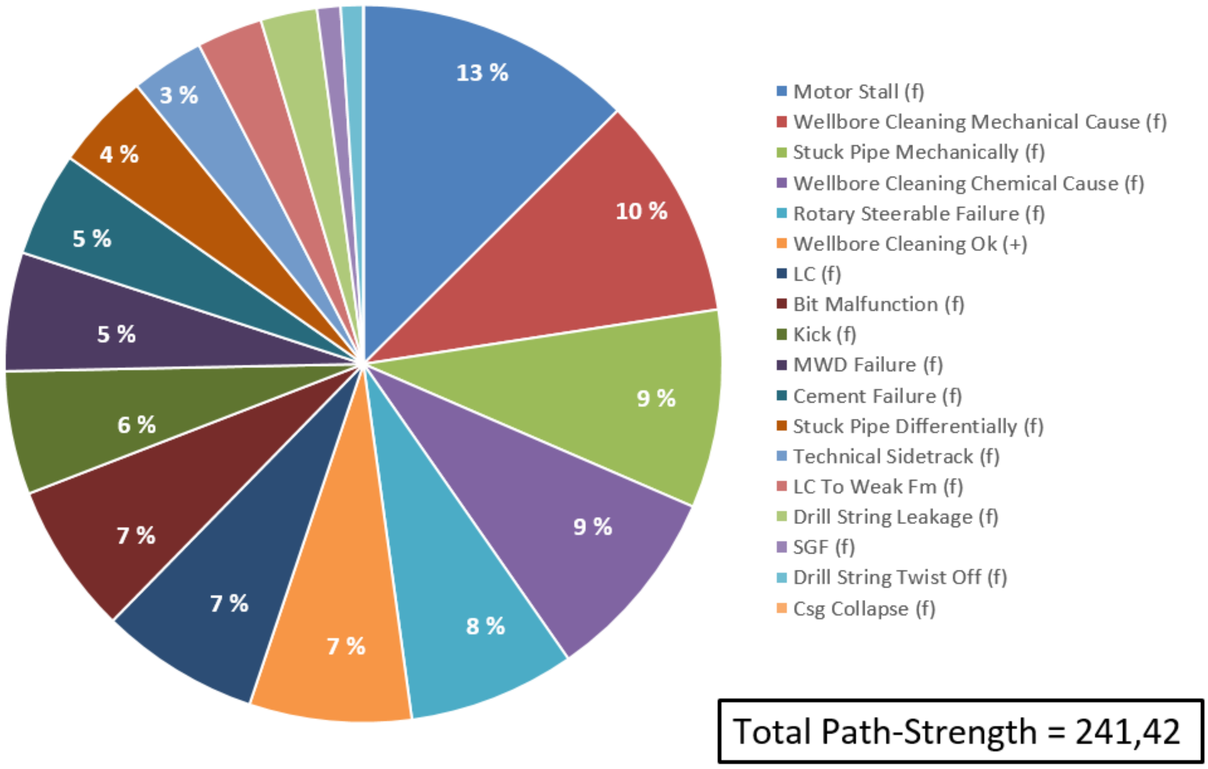


Figure 9-5: Program output including a measure of total path-strength.

Total path-strength is calculated automatically and easy to extract from the program. Active symptoms should also be presented to show the background of the failure distribution. To put values in perspective: A full 12-hour-investigation of Cases 1, 2 and 3 had a total path-strength ranging from 146.00 – 241.42. The example in Figure 9-4 had a total path-strength of 13. The total path-strength and the number of active symptoms would serve as an indication of output certainty.

The failure distribution can be overwhelming to read and understand if the probability of all 18 failures are presented. Presenting only failures with probabilities above a set threshold or top three failures would make the distribution easier to read and understand.

Inputs

Future improvement of the input file includes adding decay functions to all symptoms. A decay function should follow all symptoms (s) in the ontology. Possible functions are:

- **Linear decay functions**
  Symptoms like Losses Seepage (s) that affects the operation in some time after occurrence.
- **Exponential decay functions**
  Symptoms like Torque Erratic (s) that affects the operation only short after occurrence.
- **Depth functions**
  Depth-based symptoms like Fm Hard (s) should only be true for a defined number of meters after occurrence.

Some symptoms may require different functions. Static symptoms that remain active the entire section should have no decay function. Applying decay functions will make the cases more realistic as symptoms that no longer affect the operation is removed.

Development method

Only the hierarchal development structure was used and tested. Other development structures should be tested to determine the optimal structure. The Network Model should be tested as it allows information to float in all directions.

The Network Model is much like a hierarchal model but allows the “children” to communicate with other “children” and “parents”. In practice this means that concepts would be allowed to provide information forwards, backwards and sideways. Figure 9-6 shows an example of this:

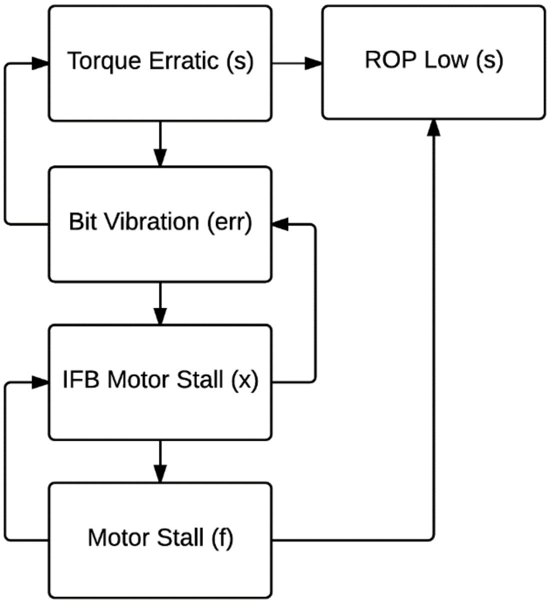


Figure 9-6: Possible paths according to the Network Model (UnixSpace, 2016). Torque Erratic (s) leads the main path to Motor Stall (f). Information can flow everywhere between children and parents.

Figure 9-6 is an example to show how information could flow between different or equal levels in the network structure. Some information is lost when using the one-directional approach. Applying this model would require a set of rules to avoid occurrence of loops.

Available Data

The model require more cases for testing. The cases require available data. High quality EoW reports and RTDD with better sampling should be acquired to make good cases. Type 1 cases (see; chapter 7) represent the amount of data available in a live case and should be prioritized. AGR (2016) is a large database that provides high quality EoW reports and RTDD. It is also possible to request data from operating companies.

Automate symptom detecting

Agents should do the process of detecting symptoms in the RTDD. In the current model state, this process is manual. Some agents have already been developed and are capable of detecting symptoms in the RTDD. The process of providing the input file with agent result is still not in place. A possible solution would be to use Matlab as an agent platform and develop a script that communicates directly with the MS Excel input file.

10 Conclusions

Based on all the information presented in this thesis, the following conclusions were made. Conclusions were sub-divided into four categories.

Ontology

- Ontology and program require continuous tuning based on output.
- The number of paths pointing toward a failure affects the result and should be equal for all failures.
- PP enables efficient comparison of program output and historical failure distributions.

Development and programming method

- A hierarchal structure can be used when developing a failure predicting program.
- The occurrence of loops are avoided in a one directional approach.
- Ontology information is lost when applying the one directional approach.
- MS Excel is a good tool for developing failure predicting programs.
    - Easy to create large structures.
    - Easy visualization and editing of large amounts of data.
    - The approach is logical and easy to understand in MS Excel.

Cases

- The program was able to predict the correct failures in 2 of 3 cases.
- NPT could potentially be decreased by 192 hours and 54 hours for Cases 2 and 3 if the program was running prior to failure.
- A motor stall failure can be predicted six hours prior to occurrence.
- Existing agents can detect symptoms in the RTDD.

Future work

- PP should only be added to symptoms. The contribution of PP is over-represented if added to all concepts.
- The program must be adjusted, as the failure distribution is too weak.
    - Most probable failure should exceed 50 % at least.
- Agents cannot provide inputs directly to the input file. The user provides inputs manually at this stage.
- Quantity and quality of EoW reports and RTDD affects the quality of cases and hence the program output.
    - Unfortunately, little data was available.
    - Operating companies, external databases like AGR (2016) and other resources should be used to obtain more high quality data.
- Using Matlab can enable cooperation between agents and program.

11 Nomenclature

Abbreviations

Activity of Water	Aw
Alternating Current	AC
Annulus	Ann
Bottom Hole Assembly	BHA
Bottom Hole Pressure	BHP
Case Based Reasoning	CBR
Casing	Csg
Chemical Cause	CC
Collapse Pressure	Coll.
Degrees	deg
Derrick Drilling Machine	DDM
Diameter	DIA
Direct Factor Behind Failure	DFBF
Dog Leg Severity	DLS
Drill Collar	DC
Drill Pipe	DP
East/West	E/W
End of Well	EoW
Equivalent Circulating Density	ECD
Equivalent Mud Weight	EMW
Formation	Fm
Formation Integrity Test	FIT
Fracture Pressure	Frac.
High Pressure	HP
Indirect Factor Behind Failure	IFBF
Inner Diameter	ID
Kick Off Point	KOP
Liquid Gravity Solids Content	LGSC
Liter Per Minute	lpm
Lost Circulation	LC
Make Up	M/U
Manage Pressure Drilling	MPD
Mean Sea Level	MSL
Measured Depth	MD
Mechanical Cause	MC
Microsoft	MS
Mud Weight	MW
Non Productive Time	NPT
North/South	N/S
Oil Based Mud	OBM
Oil Field Unit	OFU
Outer Diameter	OD
Overburden	OB
Polycrystalline Diamond Cutters	PDC
Pore Pressure	Pore P.
Prior Probability	PP
Pulling Out Of Hole	POOH
Quality Control	QC
Real Time Drilling Data	RTDD
Revolutions	Rev.
Rotary Kelly Bushing	RKB
Rotary Steerable System	RSS
Run In Hole	RIH
Shallow Gas Expected	SGE
Shallow Gas Formation	SGF
Specific Gravity	SG
Supported	Supp.
Target Depth	TD
True Vertical Depth	TVD
Volume	V
Water Based Mud	WBM
Yield Point	Yp

Symbols

Δ	Change
z	Depth
g	Gravity
L	Length
p	Pressure
P	Probability

Units

ft	Feet
"	Inches
kg	Kilo
N	Newton
lpm	Liter per Minute
m	Meter
mm	Millimeter
Min	Minutes
lbs	Pounds
ppg	Pounds Per Gallon
RPM	Revolutions per Minute
Rev	Revolutions
bbl	US barrels

Logs	Definition	Unit
ACTC	Rig Mode	
BDIA	Bit diameter	inches
BDTI	Bit Drill Time	h
BITAZ	Well azimuth calculated at bit depth	deg
BITINC	Well inclination calculated at bit depth	deg
BITRUN	Bit run number	
BONB	Bit on Bottom	
BPOS	Block Position	m
BROT	Bit rotation Time - Time Based Data	h
BVEL	Block Velocity	m/s
CCVL	Cement Volume Pumped - Time Based	m3
CDI	Cement Density In - Time Based	g/cm3
CDO	Cement Density Out - Time Based	g/cm3
CEPP	Cement Pump Pressure - Time Based	bar
CFI	Cement Flow In - Time Based	l/min
CFO	Cement Flow Out - Time Based	l/min
CHP	Choke Pressure - Time Based	bar
COPP	Completion Pump Pressure	bar
CTVL	Cementing Total Volume Pumped - Time Based	m3
DBTM	Bit Depth (MD)	m
DBTV	Bit Depth (TVD)	m
DBTV	Bit Vertical Depth - Time Based	m
DEPT	Bit Depth	m
DMEA	Hole depth (MD)	m
DRTM	Lag Depth(MD)	m
DRTV	Lag Depth (TVD)	m
DVER	Hole depth (TVD)	m
DWOB_RT	MWD Downhole WOB	1000 kg f
ECDB	Effective Circulating Density at Bit - Time Based	g/cm3
ECDC	Effective Circulating Density as Casing Shoe - Time Based	g/cm3
ECDM	Measured Effective Circulating Density at bit	g/cm3
ECDT	Effective Circulating Density at TD	g/cm3
ECDW	Effective Circulating Density at Weakest Point - Time Based	g/cm3
EPEN	Neo-Pentane	ppm
ESD	PWD Equivalent Static Density	g/cm3
ETH	Ethane gas in mud - Time Based	ppm
ETPT	Expected Trip Pit Volume Totalizer - Time Based	m3
FVOC	Fill/gain volume obs. (cum)	m3
GAS	Total gas in mud - Time Based	%
GRM1	MWD Gamma Ray (API BH corrected)	G API
HKL	Hook Load - Time Based	tonne
HVMX	Heave peak to peak max - Time Based	m
IBUT	Iso Butane gas in mud - Time Based	ppm
IPEN	Iso Pentane gas in mud - Time Based	ppm

KLP	Kill Line Pressure - Time Based	bar
MDI	Mud Density in average - Time Based	g/cm3
MDO	Mud Density out average - Time Based	g/cm3
METH	Methane gas in mud - Time Based	ppm
MFI	Mud Flow in average - Time Based	l/min
MFO	Mud Flow out average - Time Based	l/min
MTI	Mud Temperature in - Time Based	Deg C
MTO	Mud Temperature Out - Time Based	Deg C
MWDAP	MWD annulus pressure	bar
MWDPP	MWD delta pressure	bar
MWDT	MWD temperature	Deg C
NBUT	Nor Butane gas in mud - Time Based	ppm
NPEN	Nor Pentane gas in mud - Time Based	ppm
PESD	PWD Static Pressure	kPa
PRP	Propane gas in mud - Time Based	ppm
ROP	Rate of Penetration	m/h
RPM	Average Rotary Speed	rev/min
RPMA	String RPM average	rpm
RPMB	Bit RPM average	rpm
RSD	Running speed - Time Based	m/sec
RSDX	Running speed-down (max)	m/s
RSU	Pulling speed - Time Based	m/sec
SPP	Stand Pipe Pressure average - Time Based	bar
SPPA	Average Standpipe Pressure	kPa
SURG	Surge pressure gradient - Time Based	g/cm3
SWAB	Swab pressure gradient - Time Based	g/cm3
SWOB	Weight on Bit	1000 kg f
TBR	Total Bit Cumulative Revolutions - Time Based	unitless
TPVT	Trip pit volume totalizer - Time Based	m3
TRQ	Torque - Time Based	kN.m
TVA	Active Tank Volume	m3
WAC	WITS activity code - Time Based data	un
WHP	Well Head Pressure - Time Based	bar
WOB	Weight on bit - Time Based	tonne

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13 Figures

Appendix A The Ontology

This appendix includes the entire ontology. Ontology elements include:

- Relationships
- Concept Definitions
- Static Symptoms
- Symptoms

Appendix A-1 Relationships

Table A- 1: The complete ontology. All relations have been moved so that they are read from left to right (Skalle, Ontology, 2016).

Concept A causes B		**Concept B causes A**
Accumulated Barite (i)	4	Barite Sag (err)
Accumulated Barite (i)	2	Cuttings Bed Compact (i)
Accumulated Barite (i) AND Time Long (i) AND Mud YP High (ss)	6	Cuttings Bed Compact (i)
Accumulated Barite (i) AND Wellbore Inclination Medium (s) AND Time Long (i)	6	Barite Sag (err)
Accumulated Blocks (err)	6	HKL Erratic (s)
Accumulated Blocks (err)	8	Torque Erratic (s)
Wellbore Wall Restricted (i)	4	Direct Factor Behind Wellbore Cleaning Mechanical Cause (x)
Accumulated Blocks (err)	6	Indirect Factor Behind Wellbore Cleaning Mechanical Cause (x)
Accumulated Cavings (err)	6	Overpull (s)
Accumulated Cavings (err)	6	Took Weight (s)
Accumulated Cavings (err)	8	Wellbore Restricted (i)
Accumulated Cavings (err)	6	Took Weight (s)
Accumulated Cavings (err)	8	Direct Factor Behind Wellbore Cleaning Mechanical Cause (x)
Accumulated Cuttings (err)	8	Overpull (s)

Accumulated Cuttings (err)	8	Wellbore Restricted (i)
Activity Of Drilling (s)	4	Cuttings Bed Erosions High (i)
Activity Of Reaming (s)	6	Cuttings Bed Erosions High (i)
Barite Sag (err)	6	Indirect Factor Behind Wellbore Cleaning Mechanical Cause (x)
Barite Sag (err) AND Activity Of Tripping In (s)	6	Took Weight (s)
Barite Sag (err) AND Activity Of Tripping Out (s)	6	Overpull (s)
Bending Of BHA (i)	4	Direct Factor Behind Technical Sidetrack (x)
Stabilizer Undergauge (ss) AND WOB High (s)	6	DLS High (s)
Bit Aggressive (ss)	6	Torque High (s)
Bit Balled (err)	2	SPP High (s)
Bit Balled (err)	4	ROP Low (s) AND Torque Erratic (s)
Bit Balled (err)	2	Indirect Factor Behind Wellbore Cleaning Chemical Cause (x)
Bit Vibration (err)	2	Indirect Factor Behind Drill String Leakage (x)
Bit Vibration (err)	2	Indirect Factor Behind MWD Failed (x)
Bit Vibration (err)	4	Indirect Factor Behind Bit Malfunction (x)
Bit Vibration (err)	6	HKL Erratic (s)
Bit Vibration (err)	6	Torque Erratic (s)
Bit Vibration (err)	6	HKL Erratic (s) AND ROP Low (s)
Bit Vibration (err)	6	Torque Erratic (s) AND ROP Low (s)
Bit Vibration (err)	6	Torque High (s) AND ROP Low (s)
Bit Vibration (err)	6	Microstall (err)
Bit Vibration (err)	2	Direct Factor Behind Rotary Steerable Failure (x)
Build/Drop Section Inside Csg (ss)	6	Cement Sheath Quality Low (i)
Cavings Blocky (i)	6	Accumulated Blocks (err)
Cavings Blocky (i)	4	Fm Special Expected (ss)
Cavings Produced (i)	8	Accumulated Cavings (err)
Cavings Produced (i)	6	Cavings On Shaker (s)
Cement Insufficiently Displaced (i)	6	Cement Sheath Quality Low (i)

Cement Sheath Quality Low (i)	6	Direct Factor Behind Cement Failure (x)
Csg Erosion High (err) AND Cement Sheath Quality Low (i)	6	External Factor Behind Csg Collapse (x)
Cement Sheath Quality Low (i) AND ECD - Pore D High (s)	6	Cement Failure (f)
Cement V/ Annulus V Low (ss)	4	Cement Insufficiently Displaced (i)
Csg Ann Slot Narrow (ss)	6	Cement Sheath Quality Low (i)
Csg Erosion (err)	4	Indirect Factor Behind Csg Collapse (x)
Cuttings Bed Compact (i)	6	Cuttings Bed Erosion Low (i)
Cuttings Bed Compact (i)	6	Indirect Factor Behind Wellbore Cleaning Ok (x)
Cuttings Bed Erosion High (i)	8	Cuttings Concentration High (i)
Cuttings Bed Erosion Low (i)	8	Cuttings Concentration Low (i)
Cuttings Concentration High (i)	4	Cuttings On Shaker (i)
Cuttings Concentration High (i)	2	Accumulated Cuttings (err)
Cuttings Concentration High (i) AND Cuttings Bed Erosion Low (i)	6	Accumulated Cuttings (err)
Cuttings Concentration High (i) AND Cuttings Bed Erosion Low (s) AND Enlarged Wellbore (i)	8	Accumulated Cuttings (err)
Cuttings Concentration Low (i)	6	Indirect Factor Behind Wellbore Cleaning Ok (x)
Cuttings Initial Concentration High (s)	8	Cuttings Concentration High (i)
Cuttings Initial Concentration Low (s)	8	Cuttings Concentration Low (i)
DLS High (s)	2	Indirect Factor Behind Technical Sidetrack (x)
Drill String Cyclic Load High (i)	4	Direct Factor Behind Drill String Leakage (x)
Drill String Cyclic Load High (i) AND Bit Vibration (err)	6	Direct Factor Behind Drill String Leakage (x)
Drill String Cyclic Load High (i) AND Torque Cumulative High (s)	8	Direct Factor Behind Drill String Leakage (x)
Drill String Leakage (f)	4	Drill String Twist off (f)
ECD - Collapse D Low (s)	2	Cavings Blocky (i)
ECD - Collapse D Low (s)	2	Cavings Produced (i)

ECD - Collapse D Low (s) AND Fm Special Expected (ss)	4	Cavings Blocky (i)
ECD - Collapse D Low (s) AND Shale Brittle (i)	6	Cavings Blocky (i)
ECD - Collapse D Low (s) And Time Long (i)	6	Cavings Produced (i)
ECD - Collapse D Low (s) And Time Long (i) AND Shale Brittle (i)	8	Cavings Produced (i)
ECD - Frac D Low (s)	2	Well P Too High (err)
ECD - Frac D Low (s)	2	Well P Too High (err)
ECD - Frac D Low (s) AND Mud Weight High (s) And Well Depth High (ss)	6	Wellbore Wall Ballooning (err)
ECD - Frac D Low (s) AND Well Openhole Long (ss)	4	Losses Seepage (s)
ECD - Frac D Low (s) AND Well Openhole Long (ss)	6	Well P Too High (err)
ECD - Pore D High (s)	4	Filter Cake Thick (i)
ECD - Pore D High (s) AND Filter Cake Thick (i)	4	Direct Factor Behind Stuck Pipe Differentially (x)
ECD - Pore D High (s) AND Filter Cake Thick (i) AND Time Long (s)	6	Direct Factor Behind Stuck Pipe Differentially (x)
ECD - Pore D Low (s)	4	Well P Too Low (err)
ECD - Pore D Low (s) AND Well Openhole Long (ss) AND Time Long (ss)	4	Wellbore Wall Creeping (err)
ECD High (s)	6	Well P Too High (err)
ECD Low (s)	6	Well P Too Low (err)
Indirect Factor Behind Bit Malfunction (x)	4	Bit Malfunction (f)
Indirect Factor Behind Bit Malfunction (x)	4	ROP Low (s)
Indirect Factor Behind Bit Malfunction (x)	2	Torque High (s)
Indirect Factor Behind Bit Malfunction (x)	2	Torque Erratic (s)
Indirect Factor Behind Cement Failure (x)	8	Csg Ann P High (i)
Indirect Factor Behind Cement Failure (x)	6	Cement Failure (f)
Indirect Factor Behind Csg Collapse (x)	2	Cement Failure (f)
Indirect Factor Behind Csg Collapse (x)	4	Csg Collapse (f)
Indirect Factor Behind DS Twist Off (x)	4	Drill String Twist Off (f)
Indirect Factor Behind DS Leakage (x)	4	Drill String Leakage (f)
Indirect Factor Behind Kick (x)	8	Kick (f)
Indirect Factor Behind LC (x)	8	LC (f)
Indirect Factor Behind LC To Weak Fm (x)	6	LC To Weak Fm (f)

Indirect Factor Behind Motor Stall (x)	6	Motor Stall (f)
Indirect Factor Behind Motor Stall (x)	4	ROP Low (s)
Indirect Factor Behind Motor Stall (x)	8	Motor Stall Signature (s)
Indirect Factor Behind MWD Failure (x)	4	MWD Failure (f)
Indirect Factor Behind Rotary Steerable Failure (x)	6	Rotary Steerable Failure (f)
Indirect Factor Behind SGF (x)	8	SGF (f)
Indirect Factor Behind Stuck Pipe Differentially (x)	6	Stuck Pipe Differentially (f)
Indirect Factor Behind Stuck Pipe Mechanically (x)	8	Stuck Pipe Mechanically (f)
Indirect Factor Behind Technical Sidetrack (x)	4	Technical Sidetrack (f)
Indirect Factor Behind Wellbore Cleaning Chemical Cause (x)	6	Wellbore Cleaning Chemical Cause (f)
Indirect Factor Behind Wellbore Cleaning Mechanical Cause (x)	6	Wellbore Cleaning Mechanical Cause (f)
Indirect Factor Behind Wellbore Cleaning Ok (x)	6	Wellbore Cleaning Ok (+)
Fm Above Charged (ss)	2	Indirect Factor Behind Cement Failure (x)
Fm Fault Expected (ss)	4	Cavings Blocky (i)
Fm Fault Expected (ss)	8	Wellbore Ledge/Shoulder (i)
Fm Hard (s)	8	WOB High (s)
Fm Hard Stringer (s)	4	Direct Factor Behind Fm Boundary (x)
Fm Hard Stringer (s)	8	WOB High (s)
Fm Hard Stringer (s)	6	Wellbore Ledge/Shoulder (i)
Fm Hard Stringer (s) AND Fm Boundary Expected (ss)	6	Direct Factor Behind Fm Boundary (x)
Fm Laminated (s)	4	DLS High (s)
Fm Laminated (s)	6	WOB High (s)
Fm Laminated (s)	6	Wellbore Ledge/Shoulder (i)
Well Length High (ss) AND Fm Laminated (s) AND MSE High (ss)	4	Indirect Factor Behind Technical Sidetrack (x)
Well Length High (ss) AND Fm Laminated (s)	2	Indirect Factor Behind Technical Sidetrack (x)
Fm Permeable Expected (ss)	8	Mud Gas Content High (i)
Fm Soft (s)	2	Wellbore Enlarged (i)
Fm Soft (s) AND Mud Water Activity High (ss)	6	Shale Swelling Invisible (i)
Fm Soft (s) AND Mud Water Activity High (ss)	4	Wellbore Enlarged (i)

Well Length High (ss) AND Fm Soft (s)	2	Indirect Factor Behind Technical Sidetrack (x)
Well Length High (ss) AND Fm Soft (s) AND MSE High (s) AND Stabilizer Undergauge (ss)	6	Indirect Factor Behind Technical Sidetrack (x)
Direct Factor Behind Bit Malfunction (x)	4	Bit Malfunction (f)
Direct Factor Behind Cement Failure (x)	6	Cement Failure (f)
Direct Factor Behind Csg Collapse (x)	4	Csg Collapse (f)
Direct Factor Behind DS Twist Off (x)	4	Drill String Twist Off (f)
Direct Factor Behind DS Leakage (x)	4	Drill String Leakage (f)
Direct Factor Behind Kick (x)	8	Kick (f)
Direct Factor Behind LC (x)	8	LC (f)
Direct Factor Behind LC To Weak Fm (x)	6	LC To Weak Fm (f)
Direct Factor Behind Motor Stall (x)	6	Motor Stall (f)
Direct Factor Behind MWD Failure (x)	4	MWD Failure (f)
Direct Factor Behind Rotary Steerable Failure (x)	6	Rotary Steerable Failure (f)
Direct Factor Behind SGF (x)	8	SGF (f)
Direct Factor Behind Stuck Pipe Differentially (x)	6	Stuck Pipe Differentially (f)
Direct Factor Behind Stuck Pipe Mechanically (x)	8	Stuck Pipe Mechanically (f)
Direct Factor Behind Technical Sidetrack (x)	4	Technical Sidetrack (f)
Direct Factor Behind Wellbore Cleaning Chemical Cause (x)	6	Wellbore Cleaning Chemical Cause (f)
Direct Factor Behind Wellbore Cleaning Mechanical Cause (x)	6	Wellbore Cleaning Mechanical Cause (f)
Direct Factor Behind Wellbore Cleaning Ok (x)	6	Wellbore Cleaning Ok (+)
Losses Seepage (s)	4	Indirect Factor Behind LC (x)
Losses Serious (s)	8	Direct Factor Behind LC (x)
Losses Serious (s) AND Well Depth Shallow (ss)	2	Indirect Factor Behind LC To Naturally Fractured Fm (x)
Microstall (err)	4	Indirect Factor Behind Motor Stall (x)
Microstall (err)	6	Pressure Spike (s)
Microstall (err)	4	Motor Erosion (i)
Microstall (err) AND MSE High (s) AND Mud Motor On (s)	6	Indirect Factor Behind Motor Stall (x)
Microstall (err) AND RPM String On (s)	8	Motor Erosion (i)
Motor Erosion (i)	6	Direct Factor Behind Motor Stall (x)

MSE Cumulative High (s)	4	Direct Factor Behind Bit Malfunction (x)
MSE High (s)	4	Microstall (err)
MSE High (s) AND Bit Type Shear Bit (ss)	4	Bit Vibration (err)
MSE High (s) AND Bit Type Shear Bit (ss) AND Well Inclination Low (ss) AND Mechanical Restriction (i)	6	Bit Vibration (err)
MSE High (s) AND Fm Hard (s)	2	Bit Vibration (err)
MSE High (s) AND ROP Low (s)	6	Bit Vibration (err)
MSE High (s) AND ROP Low (s)	8	Indirect Factor Behind Motor Stall (x)
ROP Low (s) AND MSE High (s)	8	Direct Factor Behind Bit Malfunction (x)
MSE High (s) AND ROP Low (s)	8	Fm Hard (s)
Pore P Increasing (i)	2	Indirect Factor Behind Kick (x)
Mud Motor On (s) AND Activity Of Directional Drilling (s)	8	Sliding Mode (i)
Mud Water Activity High (ss)	4	Shale Swelling Invisible (i)
Mud Water Activity Low (ss)	6	Shale Brittle (i)
Mud Weighting Material Is Barite (ss) AND Mud Weight High (ss) AND Well Openhole Long (ss)	4	Accumulated Barite (i)
OBM (ss)	4	Indirect Factor Behind Wellbore Cleaning Ok (x)
Shale Swelling (err)	8	Direct Factor Behind Wellbore Cleaning Chemical Cause (x)
Shale Swelling (err)	6	Wellbore Wall Restricted (i)
Shale Swelling (err)	6	Mud LGSC High (i)
Shale Swelling (err)	4	Fm Special Expected (ss)
Shale Swelling Invisible (i) AND Time Long (i)	6	Shale Swelling (err)
Shallow Gas Expected (ss)	6	Mud Gas Content High (i)
Side Force High (s)	4	Csg Erosion (err)
Side Force High (s) AND Build/Drop Section Inside Openhole (ss)	6	Wellbore Wall Erosion (i)
Side Force High (s) AND Build/Drop Section Inside Csg (ss)	6	Csg Erosion (err)
Side Force High (s) AND Well Length High (ss)	6	Drill String Cyclic Load High (i)
Sliding Mode (s)	6	Cuttings Bed Erosion Low (i)
SPP High (s)	4	Wellbore Wall Restricted (i)

Tripping Speed High (s) AND Bit MD Long (s) AND Activity Of Tripping In (s)	6	ECD High (i)
Tripping Speed High (s) AND Bit MD Long (s) AND Activity Of Tripping Out (s)	6	ECD Low (i)
Water Depth High (ss)	4	Well Complex (i)
WBM (ss) AND MSE High (s)	4	Bit Balled (err)
WBM (ss) AND MSE High (s) AND ROP Low (s)	6	Bit Balled (err)
WBM (ss) AND MSE High (s) AND ROP Low (s) AND Shale Swelling (i)	8	Bit Balled (err)
Well Complex (i)	2	Factor Behind Kick (x)
Well Complex (i)	4	Losses Seepage (s)
Well Complex (i)	2	Indirect Factor Behind Kick (x)
Well Depth High (ss)	2	Indirect Factor Behind Csg Collapse (x)
Well Depth Shallow (ss) AND (ECD - Frac D Low (s)	6	Direct Factor Behind LC To Naturally Fractured Fm (x)
Well Length High (ss) AND Well Depth High (ss) AND (ECD - Frac D Low (ss))	6	Well Complex (i)
Well Length High (ss) AND Well Depth High (ss) AND (ECD - Pore D Low (ss))	6	Well Complex (i)
Well Openhole Long (ss)	8	Time Long (i)
Well P Too High (err)	6	Direct Factor Behind LC (x)
Well P Too Low (err)	6	Direct Factor Behind Kick (x)
Wellbore Cleaning Chemical Cause (f)	2	Stuck Pipe Mechanically (f)
Wellbore Cleaning Mechanical Cause (f)	4	Stuck Pipe Mechanically (f)
Wellbore Enlarged (i)	6	Accumulated Cuttings (err)
Wellbore Enlarged (i)	6	Wellbore Ledge/Shoulder (i)
Wellbore Ledge/Shoulder (i)	2	Wellbore Wall Restricted (i)
Well Length High (ss)	2	Indirect Factor Behind Drill String Twist Off (x)
Torque Cumulative High (s)	4	Direct Factor Behind Drill String Twist Off (x)
Wellbore Restricted (i)	6	HKL Signature Wellbore Restricted (s)
Wellbore Restricted (i)	4	Torque Erratic (s)
Wellbore Restricted (i)	2	Torque High (s)

Wellbore Restricted (i)	4	Direct Factor Behind Stuck Pipe Mechanically (x)
Wellbore Restricted (i)	6	Direct Factor Behind Wellbore Cleaning Mechanical Cause (x)
Wellbore Wall Ballooning (err)	2	Indirect Factor Behind Kick (x)
Wellbore Wall Creeping (err)	4	Indirect Factor Behind Wellbore Cleaning Mechanical Cause (x)
Wellbore Wall Restricted (i)	6	Direct Factor Behind Wellbore Cleaning Mechanical Cause (x)
Wellbore Wall Creeping (err)	6	Wellbore Wall Restricted (i)
Wellbore Wall Erosion (i)	6	Wellbore Enlarged (err)
Wellbore Wall Restricted (i)	6	HKL Signature Wellbore Wall Restricted (s)
Wellbore Wall Restricted (i)	6	Torque Erratic (s)
Wellbore Wall Restricted (i)	2	Torque High (s)
Wellbore Wall Restricted (i)	4	Direct Factor Behind Stuck Pipe Mechanically (x)
Wellbore Wall Restricted (i)	6	Indirect Factor Behind Wellbore Cleaning Chemical Cause (x)
WOB High (s) AND Stabilizer Undergauge (ss)	6	Bending Of BHA (i)

Appendix A-2 Concept Definitions

Table A- 2: Concepts and their PPs and definitions (Skalle, Ontology, 2016).

PP	Concepts	Definition
0,10	Accumulated Barite (i)	Barite dropping slowly out of the mud during laminar flow in highly inclined wells
0,05	Accumulated Blocks (err)	Blocky fragments in the accumulated cuttings bed
0,05	Accumulated Cavings (err)	Caving from the wall dominate in the accumulated cuttings bed, and increases gradually
1,00	Accumulated Cuttings (err)	Cuttings slip to the bottom and accumulate and form a solids bed
0,50	Activity Of Reaming (s)	Pumping and rotating the drill string while tripping slowly

0,10	Activity Of Directional Drilling (s)	Ok
1,00	Activity Of Drilling (s)	Ok
0,50	Activity Of Tripping In (s)	Ok
0,50	Activity Of Tripping Out (s)	Ok
0,05	Barite Sag (err)	Barite accumulates in the wellbore inclination-transition, between high and low inclination
0,10	Bending Of BHA (i)	High bending is caused by compressive stress combined with undergauge stabilizers
0,05	Bit Aggressive (ss)	Long body and rel. long teeth
0,10	Bit Balled (err)	The fouling of a rock bit in sticky, gumbo-like shale. Could also be the BHA
	Bit Malfunction (f)	The bit fails to function normally i.e. stops making progress due to mechanical failure
0,50	Bit MD Long (s)	When > 2 000 - 3 000 - 4 000 mMD (+)
0,10	Bit Type Shear Bit (ss)	Ok
0,10	Bit Vibration (err)	Includes Whirl, Stick-Slip, Bounce. They are all more or less related
0,10	Build/Drop Section Inside Csg (ss)	Ok
0,05	Build/Drop Section Inside Open Hole (ss)	Ok
0,05	Cavings Blocky (i)	Pre-existing weakness; fault, interbedded fm, coal beds, conglomerate, loose sand etc
0,05	Cavings On Shaker (s)	Large amounts of cavings are coming out on the shaker (nobody is reporting it to us so far)
0,05	Cavings Produced (i)	Occurs as the collapse pressure is underpassed
	Cement Failure (f)	HC are erupting in the sand around the rig
0,10	Cement Insufficiently Displaced (i)	Casing not sufficiently cemented
0,10	Cement Sheath Quality Low (i)	Small leaks behind the casing

0,10	Cement V/Theoretical V Low (ss)	When < 1.5 - 1.25 - 1.0 (+)
1,00	Cnx Time (s)	An interesting statistical info for the oil company
0,01	Csg Ann P High (s)	Not always measured. Therefore marked as (i)
0,10	Csg Ann Slot Narrow (ss)	When < 2 - 1.5 - 1.0 in (+)
	Csg Collapse (f)	The casing have insufficient strength to resist the combination of large external pressure and low internal pressure
0,10	Csg Erosion (err)	The cased hole is internally eroded. Reduced thickness reduces the casing strength
0,10	Cuttings Bed Compact (i)	The resulting solid bed, is slowly solidifying due to long time and high amount of fine, sticky particles like Bentonite, Barite and LGSC
0,10	Cuttings Bed Erosion High (i)	High (RPM & MFI/A) AND/OR Reaming
0,10	Cuttings Bed Erosion Low (i)	Low (RPM & MFI/A)
0,50	Cuttings Concentration High (i)	Defined by: ROP * A-bit / MFI. Until steady state. Will normally stay until at well heel. More dispersed through vertical well
0,50	Cuttings Concentration Low (i)	Defined by initial c and Hydraulic Erosion Low (i)
0,10	Cuttings Dunes (i)	Formed during high hydraulic energy level in long wells.
0,50	Cuttings Initial Concentration High (s)	Estimated based on ROP, MFI and Bit Size. High when > 0.02
0,50	Cuttings Initial Concentration Low (s)	Estimated based on ROP, MFI and Bit Size. Low when < 0.01
0,10	Cuttings On Shaker (s)	Meaning much more than normal
0,05	DLS High (s)	A sudden change in wellbore direction; > 4 degrees pr. 30 m
0,10	Drill Sting Cyclic Load High (i)	High Side Force & High RPM String
	Drill String Twist Off (f)	Drill string part due to high forces and abrasion
	Drill String Leakage (f)	A crack and a leak develop in the drill pipe

0,05	ECD - Collapse D Low (s)	When < 2 - 1.0 - 0 kg/l (+)
0,05	ECD - Frac D Low (s)	Frac P - ECD < 2 - 1.0 - 0 kg/l. This is the average values. Peaks are worse but short lasting (+)
0,10	ECD - Pore D High (s)	ECD - Pore P < 5 - 7.5 - 10 kg/l (+)
0,05	ECD - Pore D Low (s)	ECD - Pore P < 2 - 1 - 0 kg/l (+)
0,10	ECD High (s)	Increases in well pressure caused by downward movement of the drill string
0,10	ECD Low (s)	Reduction in well pressure caused by upward movement of wellbore equipment
0,10	Indirect Factor Behind Bit Malfunction (x)	We let everything go through two factors, one intrinsic and one external, to streamline the model
0,50	Indirect Factor Behind Cement Failure (x)	
0,10	Indirect Factor Behind Csg Collapse (x)	These 2 factors will even out short cuts and will also make it easier to adjust sought failure frequency distribution
0,10	Indirect Factor Behind DS Twist Off (x)	
0,10	Indirect Factor Behind DS Leakage (x)	
0,50	Indirect Factor Behind Kick ()	Indirect Factor must point at the target concept through an indirect, third factor
0,50	Indirect Factor Behind LC To Weak Fm (x)	
0,50	Indirect Factor Behind Motor Stall (x)	All concepts are routed through two factors, one intrinsic, representing the main cause, and one external-supportive. In this manner the path strengths will become dampened and evened out. And we can control the model better.

0,50	Indirect Factor Behind MWD Failure (x)	
0,50	Indirect Factor Behind Rotary Steerable Failure (x)	
0,50	Indirect Factor Behind SGF (x)	Published failure frequency are split into 3 causal levels; c4, c6 and c8
1,00	Indirect Factor Behind Stuck Pipe Differentially (x)	when f < 4 then = c4, f = 4-8 then = c6, f > 8 then = c8
1,00	Indirect Factor Behind Stuck Pipe Mechanically (x)	
0,10	Indirect Factor Behind Technical Sidetrack (x)	
1,00	Indirect Factor Behind Wellbore Cleaning Chemical Cause (x)	
1,00	Indirect Factor Behind Wellbore Cleaning Mechanical Cause (x)	
0,05	Filter Cake Thick (i)	Filter Cake Thickness is driven by high differential pressure and high solids and LGSC. Even in the ovb you may find fractures and fissures
0,01	Fm Above Charged (ss)	Increasing reservoir pressure due to natural frature in the formation or drilling fluid entering the reservoir through later induced fractures
	Fm Boundary (+)	A Hard Stringer points it out
0,10	Fm Boundary Expected (ss)	This is known from experience
0,05	Fm Fault Expected (ss)	Fault intersect may add to the complexity of the well
0,50	Fm Hard (s)	The Fm is 20 % harder than the average so far in this wellbore section
0,10	Fm Hard Stringer (s)	The Fm is 30 % harder than the average so far in this wellbore section within a drilled distance of 5 m or less

0,10	Fm Laminated (s)	The Fm hardness fluctuates +/- 30 % more frequent than every 5 m. Otherwise this is just Hard Fm or Hard Stringers
0,05	Fm Permeable Expected (ss)	While drilling in a gas reservoir or crossing a gas zone. Length of > 0 > 10 > 100 m (+)
0,50	Fm Soft (s)	The Fm is 20 % less hard than the average so far in this wellbore section
0,05	Fm Special Expected (ss)	Here it will be specified what is Special I
0,50	HKL Erratic (s)	As a result of BHA Vibration
0,50	HKL High (s)	When > 20 % of expected average
0,05	HKL Signature Wellbore Restricted (s)	Isak
0,05	HKL Signature Wellbore Wall Restricted (s)	Isak
0,10	Direct Factor Behind Bit Malfunction (x)	
1,00	Direct Factor Behind Cement Failure (x)	
0,10	Direct Factor Behind Csg Collapse (x)	We let everything go through two factors, one intrinsic and one external, to streamline the model
0,10	Direct Factor Behind DS Twist Off (x)	
0,10	Direct Factor Behind DS Leakage (x)	Direct factor is the most direct obvious factor pointing at the target concept
0,50	Direct Factor Behind Kick (x)	
0,50	Direct Factor Behind LC To Weak Fm (x)	
0,50	Direct Factor Behind Motor Stall (x)	We let everything go through two factors, one intrinsic and one external, to streamline the model
0,50	Direct Factor Behind MWD Failure (x)	
0,50	Direct Factor Behind Rotary Steerable Failure (x)	

1,00	Direct Factor Behind SGF (x)	
0,50	Direct Factor Behind Stuck Pipe Differentially (x)	
1,00	Direct Factor Behind Stuck Pipe Mechanically (x)	
0,10	Direct Factor Behind Technical Sidetrac (x)	
1,00	Direct Factor Behind Wellbore Cleaning Chemical Cause (x)	
1,00	Direct Factor Behind Wellbore Cleaning Mechanical Cause (x)	
1,00	Direct Factor Behind Wellbore Cleaning Ok (x)	
	Kick (f)	A flow of formation fluids into the wellbore during drilling operations due to pressure in the wellbore is lesser than the formation fluids
	LC (f)	LC is mostly induced. As opposed to natural fractures these are induced by high pressure
	LC To Naturally Fractured Fm (f)	Rock matrix surrounded by irregular vuggs + natural fractures. Loss to highly permeable zones, cavernous formations, and natural fractures
0,05	Losses Expected (ss)	Known before drilling
0,10	Losses Seepage (s)	Loss < 5 - 3.5 - 2 % of pump rate (+)
0,05	Losses Serious (s)	Loss > 5 - 10 - 15 % of pump rate (+)
0,05	Microstall (err)	When Pressure Spikes occur during drilling. # 1 - 2 - > 3 (+)
0,05	Motor Erosion (i)	Due to erosion it starts to leak
	Motor Stall (f)	The failure when the downhole motor is destroyed (the stator is eroded)
0,10	Motor Stall Signature (s)	Agent by Isak

0,50	MSE High (s)	Mechanic Specific Energy, normalized: WOB/WOBnorm * RPM/RPMnorm * Trq/Trqnorm /(Abit*ROP/ROPnorm) When > 0 > 15 > 25 % higher than normal (+)
0,50	MSE Cumulative High (s)	When > 0 > 15 > 25 % higher than normal (+)
0,10	Mud CEC High (i)	CEC is measured through the MBT
0,05	Mud Gas Content High (i)	Mud Gas Content > 10 %
0,05	Mud LGSC High (i)	LGSC > 5 %
0,10	Mud Motor On (s)	Mud Motor is in use (for changing well path)
0,10	Mud Water Activity High (ss)	When > 0.8 - 0.85 - 0.9 (+)
0,10	Mud Water Activity Low (ss)	When > 0.8 - 0.7 - 0.6 (+)
0,10	Mud Weight High (ss)	When > 1.5 kg/l
0,05	Mud Weighting Material Is Barite (ss)	ok
3,00	Mud YP High (ss)	When > 15 Pa
	MWD Failed (f)	No data transmission from bottom hole to surface when MWD tools running. May lead to a trip
0,05	OBM (ss)	Need to know type of mud in use (OBM or not)
0,10	Overpull (s)	Hook weight increases suddenly although tripping velocity is more or less constant: 1 - 2 - 3 (+)
0,05	Pore P Increasing (i)	Keep on hold - find cases of it before developing into an (s)- concepts
0,10	Pressure Spike (s)	SPP increases suddenly although mud pump is running at constant speed while reaming. While drilling it depends on mud motor or not. Detected through Hydraulic Friction Normalized. 1 - 2 - 3 (+)

0,10	ROP High (s)	Cuttings will eventually build up in the horizontal section. When > 10 - 20 - 30 m/h. (+)
0,10	ROP Low (s)	Could indicate balled bit and motor stall. When < 3 - 2 - 1 (+)
	Rotary Steerable Failure (f)	This delicate drilling system enable directional drilling but have its limitations
1,00	RPM String On (s)	The string is rotated in addition to the bit
	SGF (f)	Shallow gas zones are penetrated before BOB / Riser is installed
0,05	Shale Brittle (i)	High mud salt content sucks the pore water out
0,10	Shale Swelling (err)	Wellbore wall expands and the drilling operation responds to this phenomena
0,05	Shale Swelling Invisible (i)	Clay or shale reacts with water. This can be seen through MBT
0,50	Shallow Gas Expected (ss)	Very challenging to drill through. Best avoided by moving the rig
0,05	Side Force High (s)	When > 30 - 40 - 50 kN (+)
0,05	Sliding Mode (s)	With downhole motor it is common to rotated the drill string very slowly or not at all
0,50	SPP High (s)	SPP/(K*MD*MFI**1.7). Normalized to ca 1.0. SPP signal delay f (MD**2. SPP). When > 1.05 - 1.1 - 1.15 (+)
0,50	SPP Low (s)	When SPP drops > 5 bars for no other reason (at same flow rate). When < 0.9 - 0.8 - 0.7 (+)
0,50	SPP Mud Motor Normalized (s)	SPP * Delay (f (MD**2)) / WOB
0,05	Stabilizer Undergauge (ss)	When Bit Size Minus Stab OD > 1 in. Or near bit stabilizer is missing!
	Stuck Pipe Differentially (f)	The drill string cannot be rotated or moved vertically
	Stuck Pipe Mechanically (f)	The drill string can be rotated but cannot be moved vertically

	Technical Sidetrack (f)	A seldom failure but costly
0,10	Time Long (s)	Well Openhole Long. Same increase as Well Openhole: > 0.4 - 0.75 - 1 (+)
0,10	Took Weight (s)	Hook weight decreases suddenly although tripping velocity is more or less constant. 1 - 2 - 3 (+)
0,05	Torque Cumulative High (s)	Includes High + Very High + Erratic Torque
0,05	Torque Erratic (s)	Frequency > 0.1 Hz and amplitude > average Torque
0,10	Torque High (s)	Torque 20 % > than expected level at that depth and RPM
0,05	Torque Low (s)	Torque 20 % < than expected level at that depth and RPM
0,50	Tripping Speed High (s)	When > 0.75 - 1 - 1.25 m/s (+)
0,05	Water Depth High (ss)	When > 300 - 500 - 700 m (+)
1,00	WBM (ss)	ok
0,01	Well Complex (i)	The well is deep, long and is in deep water with narrow pressure boundaries. Complicated geology, uncertainties. Errors are frequent
0,10	Well Depth High (ss)	Well TVD > 2 - 3 - 4 km (+)
0,10	Well Depth Shallow (ss)	When < 2 000 - 1 500 - 1 000 m (+)
0,50	Well Inclination High (ss)	Well Inclination > 60 degrees
0,50	Well Inclination Low (ss)	Well Inclination < 30 degrees
0,50	Well Inclination Medium (ss)	Well Inclination between 30 and 60 degrees (this is known through the Well Plan or EoW report
0,10	Well Length High (ss)	Measured well Length > 3 - 4 - 5 km MD (+)
0,10	Well Openhole Long (ss)	Openhole > 0.4 - 0.75 - 1 km MD (+)
1,00	Well P Too High (err)	Too high for many reasons

1,00	Well P Too Low (err)	Too low for many reasons
0,10	Wellbore - DC Dia Small (ss)	Hyd dia < 0 - 0.5 - 1 in (+)
0,10	Wellbore - DP Dia Small (ss)	Hyd dia < 4". It is the drill pipe annulus we are defining here, not BHA-ann. < 5 - 4 - 3 (+)
	Wellbore Cleaning Chemical Cause (f)	The wellbore makes too much resistance during tripping, for mechanical reasons (cuttings and cavings)
	Wellbore Cleaning Mechanical Cause (f)	The wellbore makes too much resistance during tripping, for mechanical reasons (swelling)
	Wellbore Cleaning Ok (f+)	A positive statement!
0,05	Wellbore Enlarged (i)	Rock wall material disintegrate in weak bedding planes. Hole OD is slowly becoming larger than the original wellbore.
0,05	Wellbore Ledge/Shoulder (i)	A Ledge or shoulder in the wellbore wall is making the position difficult to pass; tubulars can be hooked by the shoulder
0,05	Wellbore Restricted (i)	The wellbore area becomes smaller and thus restricted. Restricted geometry in the annulus between a string and the borehole wall
0,05	Wellbore Wall Ballooning (err)	Wellbore wall responds to wellbore pressure. Changed pressure makes drilling fluid flow out or into the well
0,01	Wellbore Wall Creeping (err)	The wall is creeping and reducing its diameter
0,10	Wellbore Wall Erosion (i)	Caused by Side Forces in the openhole section
0,10	Wellbore Wall Restricted (i)	This type of restriction is different from Wellbore Restricted
0,50	WOB High (s)	We cannot make data agents of all concepts. This concept is just a result of several Fm Hardness concepts

Appendix A-3 Static Symptoms

Table A- 3: Static Symptoms (ss) and their definitions (Skalle, Ontology, 2016).

Static Symptom (ss)	**Definition**
Bit Aggressive (ss)	Bit Teeth Length > 15 mm
Bit Type Shear Bit (ss)	When Bit Type = Shear Bit
Build/Drop Section Inside Csg (ss)	(MD Csg Shoe - MD Build/Drop Upper) > 0
Build/Drop Section Inside Open Hole (ss)	(MD Csg Shoe - MD Build/Drop Lower) < 0
Cement V/Theoretical V Low (ss)	(Volume Cement) / (Volume Cement Theoretical) < 1.5 - 1.25 - 1.0
Csg Ann Slot Narrow (ss)	(Bit Size (Previous) - OD Csg) < 4 - 3 - 2
Fm Above Charged (ss)	Yes = 1; Increasing res pressure due to natural fratures in the formation
Fm Boundary Expected (ss)	Yes = 1; Formation boundaries expected based on geology reports
Fm Fault Expected (ss)	Yes = 1; Fault/s expected based on geology reports
Fm Permeable Expected (ss)	Yes = 1; Drilling in the reservoir or a small permeable zone with length > 10 m
Fm Special Expected (ss)	Yes = 1; Special formation expected
Losses Expected (ss)	Yes = 1; Losses expected based on geology reports
Mud Water Activity High (ss)	Aw > 0.8 - 0.85 - 0.9
Mud Water Activity Low (ss)	Aw < 0.8 - 0.7 - 0.6
Mud Weight High (ss)	MW > 1.5 - 1,65 - 1,8 kg/l
Mud Weighting Material Is Barite (ss)	Weighting Material = Barite
Mud YP High (ss)	Mud YP > 15 - 25 - 35 Pa
OBM (ss)	Mud Type = OBM
Shallow Gas Expected (ss)	SGE = Yes; Challenging to drill through. Avoid by moving the rig
Stabilizer Undergauge (ss)	(Bit Size (Current) - Near Bit Stab Size) < 0.02 m
Water Depth High (ss)	Water Depth > 300 - 500 - 700 m
WBM (ss)	Mud Type = WBM
Well Depth High (ss)	Well TVD > 2000 - 3000 - 4000 m
Well Depth Shallow (ss)	Well TVD < 2000 - 1500 - 1000 m

Well Inclination High (ss)	Well Inclination > 60 deg
Well Inclination Low (ss)	Well Inclination < 30 deg
Well Inclination Medium (ss)	30 < Well Inclination < 60 deg
Well Length High (ss)	MD Well > 3000 - 4000 - 5000 m MD
Well Openhole Long (ss)	(MD Well - MD Csg Shoe) > 400 - 750 - 1 000 m MD
Wellbore - DC Dia Small (ss)	(Bit Size (Current) - OD DC) < 4 - 3 - 2 in
Wellbore - DP Dia Small (ss)	(Bit Size (Current) - OD DP) < 3 - 2 - 1 in

Appendix A-4 Symptoms

Table A- 4: Symptoms (s) and their definitions (Skalle, Ontology, 2016).

Symptoms (s)	**Definition**
Activity of Directional Drilling (s)	Drilling deviated with some kind of RSS
Activity Of Drilling (s)	Drilling
Activity Of Reaming (s)	Pumping and rotating the drill string while tripping slowly
Activity of Tripping In (s)	Tripping in
Activity of Tripping Out (s)	Tripping out
Bit MD Long (s)	Long well drilling; Well MD > 3000 m MD
Cavings On Shaker (s)	Large amounts of cavings are coming out of the shaker
Cuttings Initial Concentration High (s)	Estimated based on ROP, MFI and Bit Size; High > 0,02
Cuttings Initial Concentration Low (s)	Estimated based on ROP, MFI and Bit Size; Low < 0,01
DLS High (s)	A sudden change in wellbore direction; > 4 degrees pr. 30 m
ECD - Collapse D Low (s)	ECD minus collapse pressure
ECD - Frac D Low (s)	Frac P minus ECD
ECD - Pore D High (s)	ECD minus Pore P
ECD - Pore D Low (s)	ECD minus Pore P
ECD High (s)	Increases in well pressure caused by downward movement of the drill string
ECD Low (s)	Reduction in well pressure caused by upward movement of wellbore equipment
Fm Hard (s)	The Fm is 20 % harder than the average so far in this wellbore section

Fm Hard Stringer (s)	The Fm is 30 % harder than the average so far in this wellbore section within a drilled distance of 5 m or less
Fm Laminated (s)	The Fm hardness fluctuates +/- 30 % more frequent than every 5 m. Otherwise this is just Hard Fm or Hard Stringers
Fm Soft (s)	The Fm is 20 % less hard than the average so far in this wellbore section.
HKL Erratic (s)	Erratic HKL readings as a result of BHA Vibration
HKL Signature Wellbore Restricted (s)	
HKL Signature Wellbore Wall Restricted (s)	
Losses Seepage (s)	Recorded seepage; Losses < 3.5 % of pump rate
Losses Serious (s)	Serious losses; Loss >10 % of pump rate
Motor Stall Signature (s)	
MSE Cumulative High (s)	Mechanic Specific Energy is cumulative high; MSE > 15 % higher than normal
MSE High (s)	Normalized MSEn: WOB/WOBn * RPM/RPMn * TRQ/TRQn / (Abit*ROP/ROPn)
Mud Motor On (s)	Mud motor is being used
Overpull (s)	Hook weight increases suddenly although tripping velocity is more or less constant.
Pressure Spike (s)	SPP increases suddenly although mud pump is running at constant speed while reaming. While drilling it depends on mud motor or not.
ROP Low (s)	Could indicate balled bit and motor stall
RPM String On (s)	The string is rotated in addition to the bit
Side Force High (s)	When forces acting on casing/DP are high; Force > 40 kN
Sliding Mode (s)	Rotating DP slowly with motor
SPP High (s)	SPPn = SPP/(K x MD x MFI x 1.7); SPPn > 1.1
Time Long (s)	Well Openhole Long; (MD Well - MD Csg Shoe) > 750 m MD
Took Weight (s)	Hook weight decreases suddenly although tripping velocity is more or less constant
Torque Cumulative High (s)	If Torque is; High + Very High + Erratic
Torque Erratic (s)	See agent; Standard Deviation of last 100 measured points > Threshold
Torque High (s)	Torque > 20 % of expected level at that depth and RPM
Tripping Speed High (s)	Tripping out or in too fast; Speed > 1 m/s
WOB High (s)	A result of several Fm Hardness concepts being true.

Csg Ann P High (s)	Annular Pressure High (Related to formation pore pressure in open hole)
Mud LGSC High (s)	
Pore P Increasing (s)	

Appendix B Agents

The Matlab code for already developed agents are presented below.

Appendix B-1 ECD Agent

```
%% ECD Agent
% This agent aim to locate incidents where the ECD is close to or exceeds
% pore pressure or fracture pressure boundaries.
%
% Created by Daniel Rosland and Andreas Aarstad, 2015 NTNU
%
%% INPUTS (These Values Can Be Changed)
clear; clc;
runWell_noPlot;                     % To obtain RTDD
[Pp,Fp] = Pore_frac(X.DVER,X.Time); % Obtaining Pore/Fracture gradients
fm = 0.5;                           % User input. Set to 0.5 for now
OD = 12.25*0.0254;                  % Assumed 12.25" for this section
ID = 5*0.0254;                      % Assumed a constant 5" DP
dH = OD-ID;                         % Hydraulic diameter
BHA_fraction = 0.85;                % Assumed BHA OD is 85% of hole OD
LBHA = 90;                          % Assumed L BHA is 90m (3 stands)
K = 2;                              % Rheology constants assumed 2 & 0.5
n = 0.5;

%% QC Selected Data
X = QC_NaN(X);                      % Calls for X and QC's selected data

%% CALCULATIONS (Nothing Below This Point Should Be Changed)
APLSw=SurSwab(fm,OD,ID,BHA_fraction,LBHA,X.DMEA,X.RSD,X.MDI);
APLS=-SurSwab(fm,OD,ID,BHA_fraction,LBHA,X.DMEA,X.RSD,X.MDI);
APLd=laminar_pressure(K,n,OD,ID,X.DMEA,X.MFI,X.MDI,LBHA)+...
    BHAP(K,n,OD,BHA_fraction,LBHA,X.MFI,X.MDI,X.DMEA);

for i = 1:length(X.ACTC)
    if X.ACTC(i)==8 || X.ACTC(i)==33     % 8 = tripping in, 33 = short
        ECD(i) = X.MDI(i) + (APLSw(i)/(X.DVER(i)*9.81*1000)+...
            (APLd(i)/(X.DVER(i)*9.81*1000)));
    elseif X.ACTC(i)==9 || X.ACTC(i)==34 % 9 = tripping out, 34 = short
        ECD(i) = X.MDI(i) + (APLS(i)/(X.DVER(i)*9.81*1000)+...
            (APLd(i)/(X.DVER(i)*9.81*1000)));
    else                                 % no tripping
        ECD(i) = X.MDI(i) + (APLd(i)/(X.DVER(i)*9.81*1000));
    end
end

%% TAGGING (Compares Calculated ECD to Pore/Frac Boundaries)
% Change the tagging boundaries by changing the Tagging.m file
Tagg = Tagging(ECD,Fp,Pp);

%% PLOTTING (ECD, MDI, Pore/Frac Pressure vs Time)
% (360000:end) represents the last 18-30 days of the raw RTDD
hold on;
plot(ECD(360000:end),'r');
plot(X.MDI(360000:end),'k','linewidth',3);
plot(Pp(360000:end),'g','linewidth',4);
```

```
plot(Fp(360000:end),'k','linewidth',4);
plot(Tagg(360000:end),'b','linewidth',3);

grid;
xlabel('Time (s)','fontsize',20);
ylabel('Density (g/cc)','fontsize',20);
title('ECD and Mud Density In','fontsize',20);
h=legend('ECD','Mud Density In','Pore Pressure','Fracture Pressure');
set(h,'FontSize',14)
hold off;
```

```
function dP_circ = laminar_pressure(K,n,OD,ID,DMEA,MFI,MDI,LBHA)

dH = OD-ID;
v=(MFI/(60*1000))/((OD^2-ID^2)*pi/4);
Ka=K*(2*n+1/3*n)^n;
a=(log(n)+3.93)/50;
b=(1.75-log(n))/7;

for i = 1 : length(DMEA)
Nre(i)=(dH^n)*v(i).^(2-n)*MDI(i)/((Ka*(12^(n-1))))*1000;
   if Nre(i)<3000
   dP_circ(i)=4*K*((12*v(i)/dH)*(2*n+1/(3*n)))^n*((DMEA(i)-LBHA)/dH);
   else
   dP_circ(i)=a*(Nre(i)^-b)*(4*(DMEA(i)-LBHA)/dH)*(0.5*MDI(i)*(v(i).^2));
   end

end
```

```
function[Pp,Fp] = Pore_frac(TVD,Time)
%% QC of data points where the TVD decreases
% The out put is two vectors, one for Pp and one for Fp
i = 1;

while TVD(i)<0
    i = i+1;
end

TVD(1)=TVD(i);
for i = 2 : length(TVD)
    if TVD(i)+10<TVD(i-1);
        TVD(i)=TVD(i-1);
    end
end
```

```
%% Creating The Pore Pressure Gradient
% Equations are based on EXCEL trend line regression
% This creates a Pp gradient based on 3 equations (1)(2) and (3)
for i = 1:length(Time)
    if TVD(i)<1400
        Pp(i)=-2*10^-7*TVD(i)^2+0.0004*TVD(i)+0.6519;    % (1)
    elseif TVD(i)>=1400 && TVD(i)<1700
        Pp(i)=0.0021*TVD(i)-2.013;                      % (2)
    elseif TVD(i)>=1700
        Pp(i)=0.0003*TVD(i)+1.1184;                     % (3)
    end
end

%% Creating The Fracture Pressure Gradient
```

```
% Equations are based on EXCEL trend line regression
% This creates a Fp gradient based on 1 equation
for i = 1:length(Time)
    Fp(i) = -4.67914E-13*TVD(i)^4 + 2.69478E-09*TVD(i)^3 -...
        5.71208E-06*TVD(i)^2 + 5.45858E-03*TVD(i) - 1.87948E-01;
end

end
```

```
%% Importing and QC data
% Function sets NaN values equal to zero
function data = QC_NaN(data)
QC_NAN = -999.25;
bad_incides = (data == QC_NAN);
good_incides = 1 - bad_incides;
data = data.*good_incides;
end
```

Appendix B-2 Erratic Torque Agent

```
runWell_noPlot;
% Obtains RTDD as vectors

depth_start=2359;
% Measured depth start

depth_end=2407;
% Measured depth end

[time_start,time_end] = time_period(X.DMEA,depth_start,depth_end);
% Locates the time period of based on the measured depth period above

timevec = time(time_start,time_end,X.Time);
% Creates a time vector based on the time period above

[WOB,RPMB,TRQ,Agent] = agent(time_start,time_end,X.TRQ,X.WOB,X.RPMB);
% Creates WOB, ROP and TRQ vectors based on the RTDD above.
% agent.m locates periods with erratic torque

Agent_result = results(agent);
% Creates the result vector based on the result from agent.m

subplot(1,4,3)
plot(TRQ,timevec)
subplot(1,4,4)
plot(Agent_result,timevec)
subplot(1,4,2)
plot(RPMB,timevec)
subplot(1,4,1)
plot(WOB,timevec)
```

```
function [time_start,time_end] = time_period(dmea,depth_start,depth_end)

time_start=1;

while dmea(time_start)<depth_start
    time_start=time_start+1;
```

```
end

time_end=1;

while dmea(time_end)<depth_end
    time_end=time_end+1;
end

end
```

```
function timevec = time(time_start,time_end,time_full)

c=1;

for p=time_start:time_end
    timevec(c)=(time_full(time_end)-time_full(p))*24;
    c=c+1;
end

end
```

```
function [WOB,RPMB,TRQ,Agent] = agent(time_start,time_end,trq,wob,rpm)

 b=1;

for i=time_start:time_end

    if wob(i)> 7 && rpm(i)>0
        if trq(i-1)>8 && trq(i)>8
              Agent(b)=abs(trq(i)-trq(i-1));
        else
            Agent(b)=0;
        end
    else
        Agent(b)=0;
    end

    WOB(b)=wob(i);
    RPMB(b)=rpm(i);
    TRQ(b)=trq(i);
    b=b+1;

end
```

```
function Agent_result = results(Agent)

d=1;

for j=1: length(Agent)
    if Agent(j)>4
        Agent_result(d)=1;
    else
        Agent_result(d)=0;
    End

    d=d+1;

end
```

runWell_noPlot.m was provided by Raknes (2014).

Appendix C RTDD

Table C- 1 presents logs available in the RTDD for wells C-147 and A-148.

Table C- 1: RTDD logs available for Cases 1, 2 and 3. All logs are collected using MWD tools.

Mnemonic	**Description**	**Unit**
ACTC	Rig Mode	
BDIA	Bit diameter	inches
BDTI	Bit Drill Time	h
BITAZ	Well azimuth calculated at bit depth	deg
BITINC	Well inclination calculated at bit depth	deg
BITRUN	Bit run number	
BONB	Bit on Bottom	
BPOS	Block Position	m
BROT	Bit rotation Time - Time Based Data	h
BVEL	Block Velocity	m/s
CCVL	Cement Volume Pumped - Time Based	m3
CDI	Cement Density In - Time Based	g/cm3
CDO	Cement Density Out - Time Based	g/cm3
CEPP	Cement Pump Pressure - Time Based	bar
CFI	Cement Flow In - Time Based	l/min
CFO	Cement Flow Out - Time Based	l/min
CHP	Choke Pressure - Time Based	bar
COPP	Completion Pump Pressure	bar
CTVL	Cementing Total Volume Pumped - Time Based	m3
DBTM	Bit Depth (MD)	m
DBTV	Bit Depth (TVD)	m
DBTV	Bit Vertical Depth - Time Based	m
DEPT	Bit Depth	m
DMEA	Hole depth (MD)	m
DRTM	Lag Depth(MD)	m
DRTV	Lag Depth (TVD)	m
DVER	Hole depth (TVD)	m
DWOB_RT	MWD Downhole WOB	1000 kgf
ECDB	Effective Circulating Density at Bit - Time Based	g/cm3

ECDC	Effective Circulating Density as Casing Shoe - Time Based	g/cm3
ECDM	Measured Effective Circulating Density at bit	g/cm3
ECDT	Effective Circulating Density at TD	g/cm3
ECDW	Effective Circulating Density at Weakest Point - Time Based	g/cm3
EPEN	Neo-Pentane	ppm
ESD	PWD Equivalent Static Density	g/cm3
ETH	Ethane gas in mud - Time Based	ppm
ETPT	Expected Trip Pit Volume Totaliser - Time Based	m3
FVOC	Fill/gain volume obs. (cum)	m3
GAS	Total gas in mud - Time Based	%
GRM1	MWD Gamma Ray (API BH corrected)	gAPI
HKL	Hook Load - Time Based	tonne
HVMX	Heave peak to peak max - Time Based	m
IBUT	Iso Butane gas in mud - Time Based	ppm
IPEN	Iso Pentane gas in mud - Time Based	ppm
KLP	Kill Line Pressure - Time Based	bar
MDI	Mud Density in average - Time Based	g/cm3
MDO	Mud Density out average - Time Based	g/cm3
METH	Methane gas in mud - Time Based	ppm
MFI	Mud Flow in average - Time Based	l/min
MFO	Mud Flow out average - Time Based	l/min
MTI	Mud Temperature in - Time Based	Deg C
MTO	Mud Temperature Out - Time Based	Deg C
MWDAP	MWD annulus pressure	bar
MWDPP	MWD delta pressure	bar
MWDT	MWD temperature	Deg C
NBUT	Nor Butane gas in mud - Time Based	ppm
NPEN	Nor Pentane gas in mud - Time Based	ppm
PESD	PWD Static Pressure	kPa
PRP	Propane gas in mud - Time Based	ppm
ROP	Rate of Penetration	m/h
RPM	Average Rotary Speed	rev/min
RPMA	String RPM average	rpm
RPMB	Bit RPM average	rpm
RSD	Running speed - Time Based	m/sec
RSDX	Running speed-down (max)	m/s

RSU	Pulling speed - Time Based	m/sec
SPP	Stand Pipe Pressure average - Time Based	bar
SPPA	Average Standpipe Pressure	kPa
SURG	Surge pressure gradient - Time Based	g/cm3
SWAB	Swab pressure gradient - Time Based	g/cm3
SWOB	Weight on Bit	1000 kgf
TBR	Total Bit Cumulative Revolutions - Time Based	unitless
TPVT	Trip pit volume totalizer - Time Based	m3
TRQ	Torque - Time Based	kN.m
TVA	Active Tank Volume	m3
WAC	WITS activity code - Time Based data	un
WHP	Well Head Pressure - Time Based	bar
WOB	Weight on bit - Time Based	tonne

Appendix D The Program

The program is included as a separate zip file.