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Improving well delivery process in exploration and applying drilling and geological principles

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Improving well delivery process in exploration and applying drilling and geological principles

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I declare in lieu of oath, that I wrote this thesis and performed the associated research myself, using only literature cited in this volume

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Abstract

In order to be able to successfully drill an exploration well the geology and the implication it has on the drilling practices need to be known. The first part of the thesis is a practical part that tries to visualize the magnitude of the geological components such as layers of rock or faults and other features using an outcrop analysis. This outcrop analysis includes a detailed insight about the geological setting of the rock, presence of fault or tectonic activity, mineralogy of the rock and sedimentological background. Using this data a geological roadmap is created. In the field samples are taken in order to be analyzed in the petrophyisics laboratory. Taken all this data into consideration a hypothetical well is planned in onto the outcrops. The well plan for the hypothetical well is compared to a well in similar formations, in order to be able to illustrate the optimum well delivery process for this certain geological setting. This is critical for harmonization and de-risking projects and key efficiency improvements in operators.

The second part of this thesis is a theoretical part that focuses on well data and shows for different geological settings the best possible solutions. The data used in the analysis is log data, geological maps and others. It analyses the methods that were used to drill these wells under the certain geological circumstances and additionally proposes different well design solutions using other practices. It depicts how the geology influences the drilling methods that were used and compares different wells.

Furthermore a new workflow for the well design in exploration projects is presented. This new workflow includes the implementation of field studies in order to acquire further geological information to minimize the risks and increase the chances of success for exploration projects. The methodology of the field studies is similar to the ones carried out for this thesis. Additionally all the advantages and disadvantages of this new workflow are discussed in detail.

Kurzfassung

Um eine Explorationsbohrung erfolgreich durchführen zu können muss die Geologie und deren Implikationen auf die Bohrtechniken bekannt sein. Der erste Teil dieser Arbeit ist ein praktischer Teil, welcher die Größe und Dimensionen von verschiedenen geologischen Voraussetzungen wie Gesteinsschichtungen und Verschiebungen etc. mittels geologischer Feldstudien darstellt. Diese Aufschlussanalysen enthalten detaillierte Informationen über die geologischen Umstände, die Präsenz von Aufschiebungen oder tektonischer Aktivität, Mineralogie der Gesteine und sedimentologischem Hintergrund. Mit den hier gewonnen Daten wird eine geologische Karte der Aufschlüsse erstellt. Im Feld werden Proben genommen um danach im Petrophysik Labor untersucht zu werden. Nach der Analyse der Daten wird eine hypothetische Bohrung durch die Aufschlüsse geplant. Der Plan der hypothetischen Bohrung wird danach mit einer Bohrung verglichen die durch ähnliche Formationen führt. Dies dient dazu die optimalen Lösungen für diese bestimmten. Das ist essentiell für die Harmonisierung die Risiko Reduktion und die Effizienz Steigerung von Explorationsprojekten.

Der zweite Teil dieser Arbeit ist ein theoretischer Teil, welcher sich auf Bohrungsdatenanalyse bezieht um für verschieden geologische Voraussetzungen die optimalen und bestmöglichen Lösungen zu finden. Die in dieser Analyse verwendeten Daten sind Log Daten, geologische Karten etc. Es werden die Methoden analysiert die unter bestimmten Voraussetzungen verwendet wurden und es werden andere alternative Lösungen für den Bohrungsplan präsentiert. Es stellt dar wie die Geologie die verschiedenen verwendeten Methoden beeinflusst und vergleicht verschieden Bohrungspläne.

Des Weiteren wird ein neuer Workflow für die Erstellung eines Bohrungsplans im Explorationsbereich präsentiert. In diesen Workflow werden Feldstudien implementiert um weitere Informationen sammeln zu können im Hinblick auf Risikominimierung und Erhöhung der Erfolgschancen. Die Methodik der im Workflow verwendeten Feldstudien ist gleich zu denen die in dieser Arbeit ausgeführt wurden. Zusätzlich werden die Vor und Nachteile dieses neuen Workflows im Detail diskutiert.

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1. Introduction

One of the biggest challenges in drilling exploration wells is the uncertainty about the geological setting of the well path. It is of crucial importance for a safe well delivery process to be aware of the geological parameters of the formations one will encounter during drilling. These formations will have a grand influence on each part of the well design. A drilling engineer must be apprehensive about the geology of the wellbore since this governs vastly important aspects such as mineralogy, stress distribution and others. All these factors have a particular implication on different parts of the well design and need to be taken into consideration.

The first objective of this thesis is the execution of three separate field studies in Dorset, United Kingdom. The purpose of these investigations is to evaluate their individual geological and sedimentological background, in order to determine their implications on the drilling process. The focus is to assess the problems that these formations cause during drilling. For these problems, solutions are provided. Significant issues about key factors for the well design in the distinct layers are discussed. All the formations shown in this work are regularly being drilled in the North Sea and are therefore representative for assessing drilling problems. Furthermore, the methodology of the outcrop analysis is provided in detail and can be used as a standard for future investigations.

The second goal of this work is the presentation of an improved workflow for the well delivery process in exploration. This workflow includes the implementation of field studies in the planning process in order to acquire further information at a relatively low cost. The structure and the advantages/disadvantages of this new workflow are discussed in detail. The proposed field studies in the new workflow should follow the methodology of the outcrop analysis in the foregoing objective of this research.

For the third aim solutions for real wells are analyzed with the focus on the geological setting of the wells. This is done to show the implications the geological background has on the decisions in the well planning process. In this research multiple different sources of data are used, to be able to clearly depict the solutions for the wells. These data sources contain daily drilling reports, log data, seismic information and others. Connections between the solutions for these wells and the insight found at the outcrop analysis are drawn.

Furthermore, alternative solutions for the wells analyzed in the previous objective are presented. These alternative well plans are created with the software Landmark by Halliburton. They include information about the trajectory, casing schematic, bottom hole assembly (BHA) and hydraulic calculations. For the alternative solutions information acquired in the field is also used.

This thesis gives insight on the importance and value of geological information in the well delivery process. It shows the benefit of the implementation of field studies into the workflow of well planning. Moreover, it depicts typical downhole formations and shows the implications the geology of these formations has. It is critical for the success of exploration well operations to be able to understand the implications individual geological settings have on the drilling practices.

2. Geological Investigation and setting the Scene.

The first objective of this thesis is to gather geological field data. This is accomplished with three separate and independent outcrop analyses in different locations around the northern and southern coast of southwest England. The first two locations are set on the Jurassic Coast in Dorset, these are Bridport, West Bay and Lyme Regis. The third location is Watchet, which lies on the northern coast of Somerset. All these locations are chosen because of their extraordinary display of rock strata and their significance for the petroleum industry especially in the North Sea. The field data provided in this thesis was acquired during a field trip from the 24th of July 2015 to the 2nd of August 2015.

2.1 Jurassic Coast

The Jurassic Coast ranges from Orcombe Point in Devon close to Exmouth, to Swanage in Dorset. This coast provides rocks from the Triassic, Jurassic and the Cretaceous. Generally the rocks become older from east to west. **Figure 1,** below, from Underhill (1998), shows a map that depicts this age trend. The geology of this region is well preserved and variable, thus many international field studies are performed in this area and therefore it is one of the most documented areas in the world. At a length of around 150 km it provides numerous outcrops and cliffs with varying age and geology.

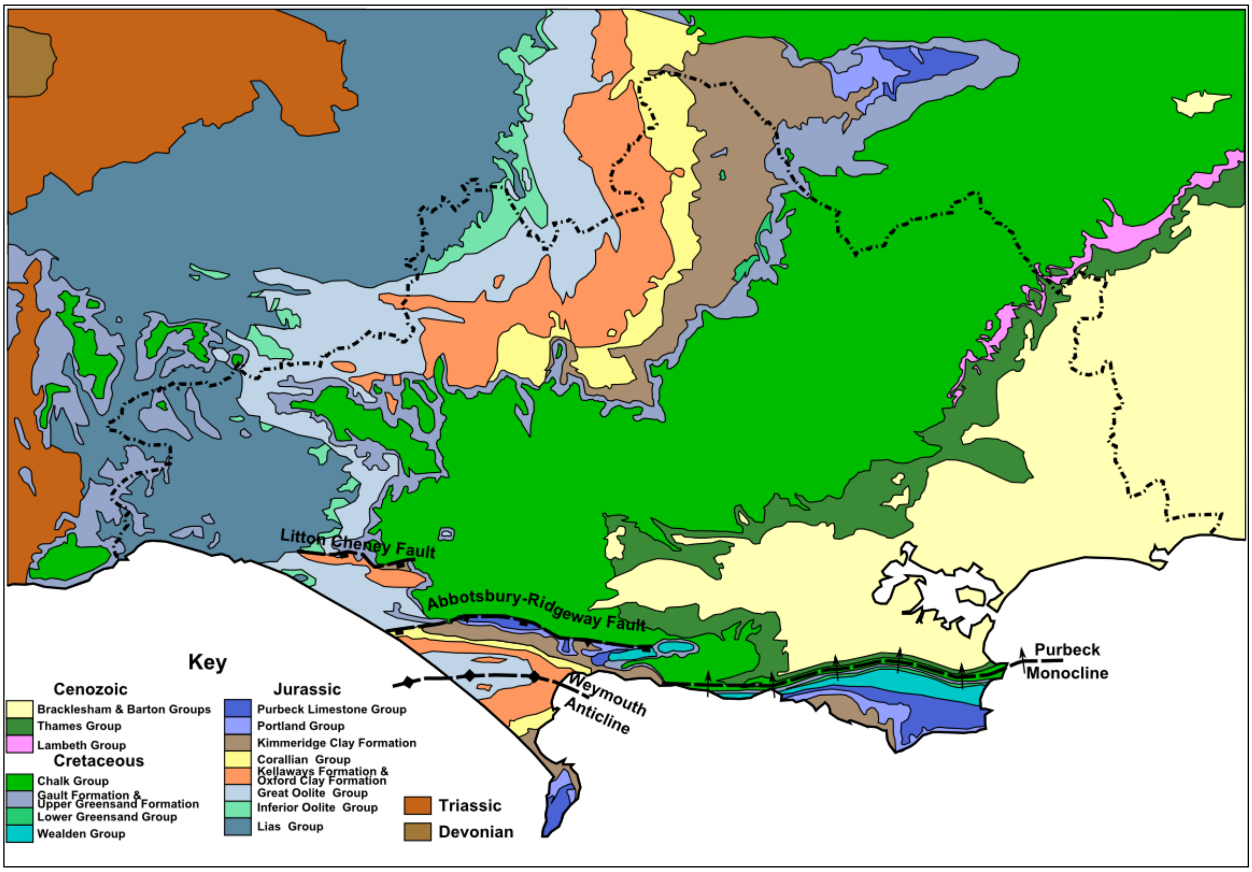


Figure 1: Geological Map of Dorset

An important formation of the Jurassic coast is the Kimmeridge Clay. Herbin (1995) states that it is a major source for the oil in the North Sea and even further in West Siberia, since it has up to 60 % TOC (Total Organic Carbon) and a petroleum potential of up to 400 kg HC/t rock. The Kimmeridge Clay reaches from northern Yorkshire all the way to northern France in the Boulonnais. The best outcrops of this particular formation can be found in East Dorset.

The parts of the Jurassic coast that are taken into consideration for this work are the lower Jurassic Blue Lias formation in Lyme Regis and the Bridport Sand formation, which is also lower Jurassic. In terms of a petroleum system point of view, the Blue Lias formation can be considered a source rock, while the Bridport Sand formation is a potential reservoir rock. It is necessary to investigate both types of rock, since they have different drilling considerations and are both crucial for petroleum exploration. The third outcrop investigated in this work is located on the northern coast of Somerset, which is not a part of the Jurassic Coast.

2.2 Outcrop Research Methodology

The following methodology is used for the investigation of outcrops located in Bridport, Lyme Regis and Watchet. The methodology consists of the following steps:

1. Look and decide for a meaningful location
2. Measure and mark the dimensions of the location
3. Sketch the outcrop
4. Take pictures
5. Measure Strike and Dip
6. Take Samples
7. Analyze samples on sight
8. Look for sedimentary structures
9. Bring samples to Austria for further investigation

The research is carried out using several tools including a hammer, a geological compass, a measuring tape (20 m), magnifying glasses, sample bags, a camera and a sketch board. In order to get consistent results from the different outcrops this methodology is executed precisely at every location.

3. Bridport, West Bay

3.1 General Information

The first location that is taken into consideration is West Bay, Bridport in Dorset (UK). It is chosen because of its significant cliffs at the coastal line, which are a major reservoir analogue. In West Bay there are very steep cliffs that provide an insight on their geology. All layers of rock are clearly visible and are not disturbed by any vegetation what so ever, therefore it is an ideal place to perform an outcrop analysis.

West Bay is located at the southern coast of England near Bournemouth **Fig.(2)**. It is of particular interest for geological research, since it is part of the Jurassic Coast. The geological facies that can observed are mainly lower Jurassic sandstones also known as the Bridport Sand formation.

Figure 2: Map of southern England with the location of Bridport, West Bay (Google Maps)

The investigation of the exposed formations is performed at the eastern part of West Bay **Fig.(3).** It is easily accessible via the beach. It is to state here that rock fall is a potential health threat in this region. The use of helmets is highly recommended.

Figure 3: View of the Bridport Sand Formation

3.2 Geology of Bridport, West Bay

The formation visible at West Bay is an Upper Lias fine grained sand formation. There are well compacted layers with a calcite cementation followed by less compacted friable sands without cementation. The cemented layers have a grey color and are harder than the other layers without cement. This varying hardness is quite a challenge for the bit selection. The hard parts require a different setup of the bit then the friable and soft ones. It is of utter importance to understand the impact of the varying calcite content on the rock hardness. Since the change of hardness occurs rapidly from meter to meter a very variable bit is recommended in order to overcome this challenge. This rapid change in rock hardness can´t be displayed on a seismic image since the changes are smaller than seismic resolution. Therefore it is crucial to understand the impact and effect of the calcite content. The uncemented layers have a yellow color. West (2013) states that this yellow color is often misinterpreted, since the formation is usually grey. The grey color can be found in cores from boreholes in this formation. It appears yellow, due to the exposure to oxygen, which changes the original reduced conditions and oxidizes the formation. **Figure 4** shows the magnitude of the succession between cemented and uncemented layers.

Figure 4: Shows the layering of the Bridport Sand Formation

The layers are laterally continuous and have a rather constant thickness. The total height of the whole formation is approximately 40 m. The thickness of the friable yellow sandstone layers decreases in the upper part, thus the carbonate content becomes higher and the cemented sandstone layers become thicker.

West (2013), states that this represents a time of limited detrital deposition. On the other hand calcium carbonate of shells and other living organisms accumulated. This becomes more and more prominent if we go up further in the succession until we reach the Inferior Oolite, which is a formation that consists almost entirely of calcium carbonate

Furthermore West (2013) states that the cemented sandstones have a carbonate content of around 20-30 %, while the friable sands only have a content of around 2 %.West (2013) assumes that the sedimentation rate was around 20.000 years/m. The carbonate cemented layers are usually parallel to the friable sands, but sometimes they are hard to make out due to erosion.

There are sedimentary structures that indicate that this formation has a shallow marine EOD (Environment of Deposition). Supporting this theory is wavy bedding that indicates wave action **Fig. (5)**. Furthermore the high carbonate content also implies the same EOD. West (2013) states that these depositions are marine barrier bar sediments.

Figure 5: The layering shows clear indications of wave action

The grain size is around 0.0064 mm and it is rather constant over the whole height, this also supports the marine barrier sediment theory. If we think about log patterns this formation yields a cylinder shape, thus representing a bar sediment. Additionally shells can be found in the cemented sandstones. **Figure 6** shows fragments of a shell in the sandstone.

Figure 6: Shell fragments

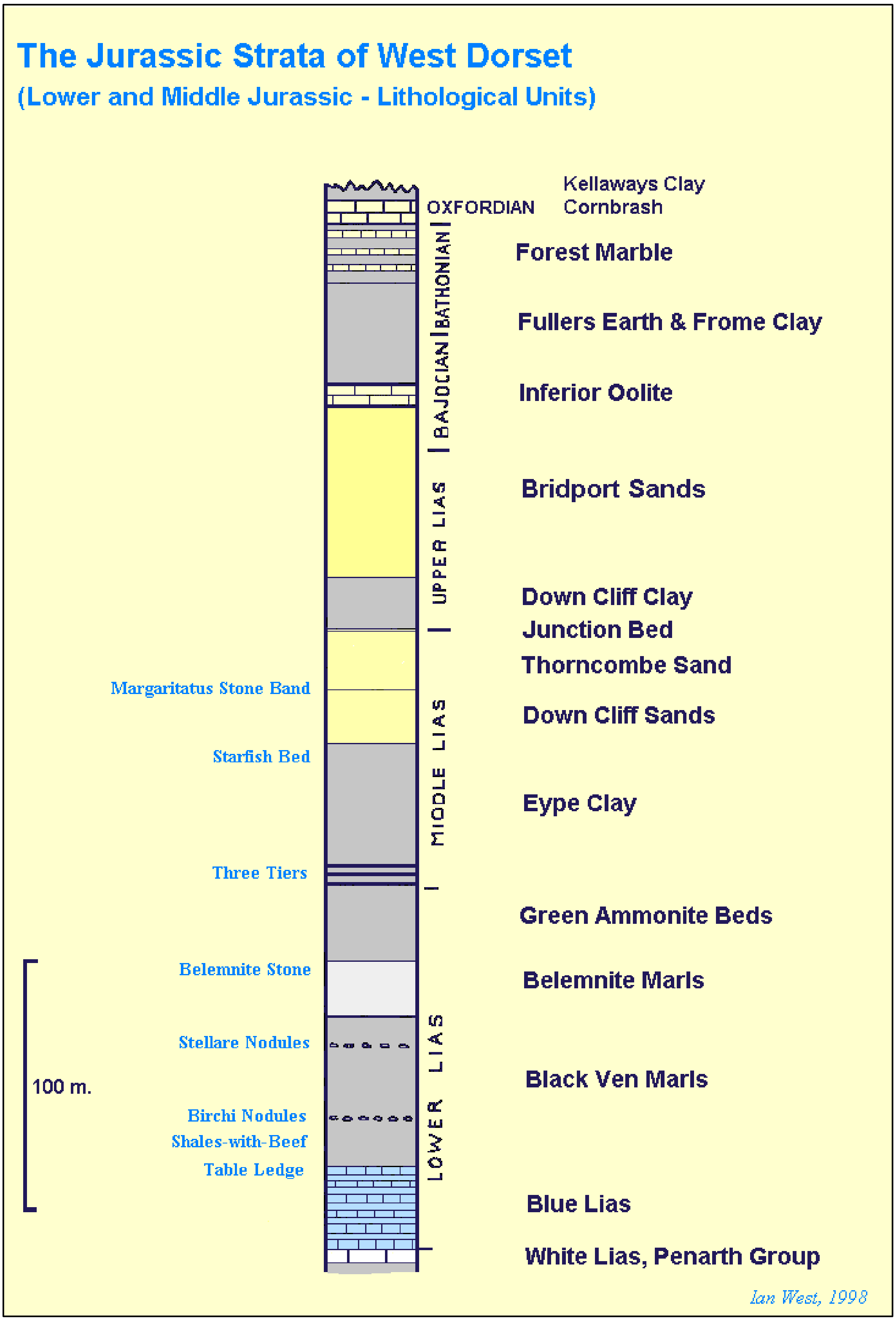


Figure 7: Strata of the West Dorset Jurassic

The strata of West Dorset as shown on **Figure 7** by West (2013), has a major significance for the petroleum industry, since the oldest and largest onshore oil field of the UK and is the largest in Western Europe.; Wytch Farm field is producing out of the Bridport Sands. This field also has some of the longest extended reach wells in the world. Wytch Farm was discovered by British Gas, a very long time before the creation of Centrica and BG Group. They sold the field to BP in 1984. For the rest of the field's operational life BP were the owners until divesting in 2011 to Perenco.

According to West (2013) porosity in these sands ranges from around 20-26% and permeability from 5-64 mD. This data is supported by core experiments that were carried out by the Petrophysics Laboratory in Leoben. For the samples that were tested, the porosity ranges between 28-32% and the permeability ranges between 48-52 mD. These excellent reservoir properties may cause severe problems with lost circulation and eventually could lead to well control difficulties. Therefore the mud needs to be designed properly with the right bridging particle size and distribution to form a proper filter cake and to prevent losses.

Figure 8 shows a cross section of the Wytch farm Oilfield from Thornton (2013).

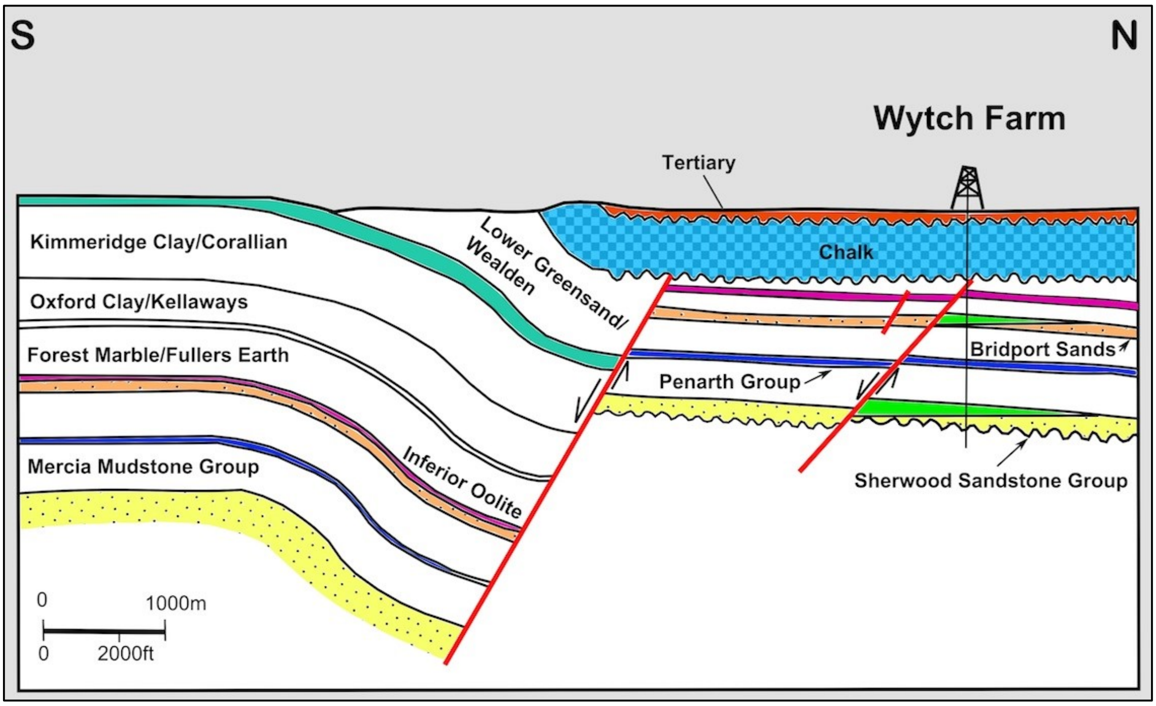


Figure 8: Cross section of the Wytch Farm oil field

An exceptional sedimentary structure is the so called honey comb weathering. This occurs due to the high carbonate content in the rocks. Parts of the rock are prone to carbon dioxide weathering and therefore eroded away, while others withstand this type of weathering and are not eroded. This causes a distinct honey comb like structure. These structures are very important for the local birds as nest places. **Figure 9** shows the honey comb weathering.

Figure 9: The orange arrow shows honey comb weathering

The clay content of this formation will be absolutely critical for any potential drilling operation in this type of formation. According to West (2013) the clay content consist of kaolinite and mixed layer types such as illite, chlorite and smectite combinations. Especially the illite-smectite type can swell when in contact with water, thus resulting in a volumetric increase. For the mud design the clay content is one of the key factors. In this particular formation the clay minerals that are present require an inhibitive mud system. It is recommended to use an Oil Based Mud (OBM) with a high concentration KCL brine in a ratio of 70% base oil and 30% KCL brine.

There are not a lot of fractures and no faults in this formation. The only fractures that occur are vertically continuous fractures. There is absolutely no displacement of the layers, i.e., evidence of tectonic influence is minimal.

The lateral continuity of the layers and the absence of major fractures and faults is beneficial for drilling operations in this formation. Especially faults could lead to a deflection of the well path or may even transmit overpressure into the formation if permeable.

3.3 Outcrop Analysis

The investigated outcrop is located on the eastern side of Bridport, West Bay. It is only a ten minute walk via the beach away from the center of the village. It is near the western edge of the cliffs. The formation that is examined in the outcrop is the Bridport Sand formation, which is upper Lias or lower Jurassic. The rocks are mainly fine sandstone either hard with carbonate cement or friable without carbonate cement. The outcrop has a lateral continuity of a few kilometers, so in order to be able to perform a field study only a small section was investigated, which was 40 meters in width and 40 m in height. **Figure 10** from West (2013) shows a geological map of Bridport, West Bay including the location of the analyzed outcrop.

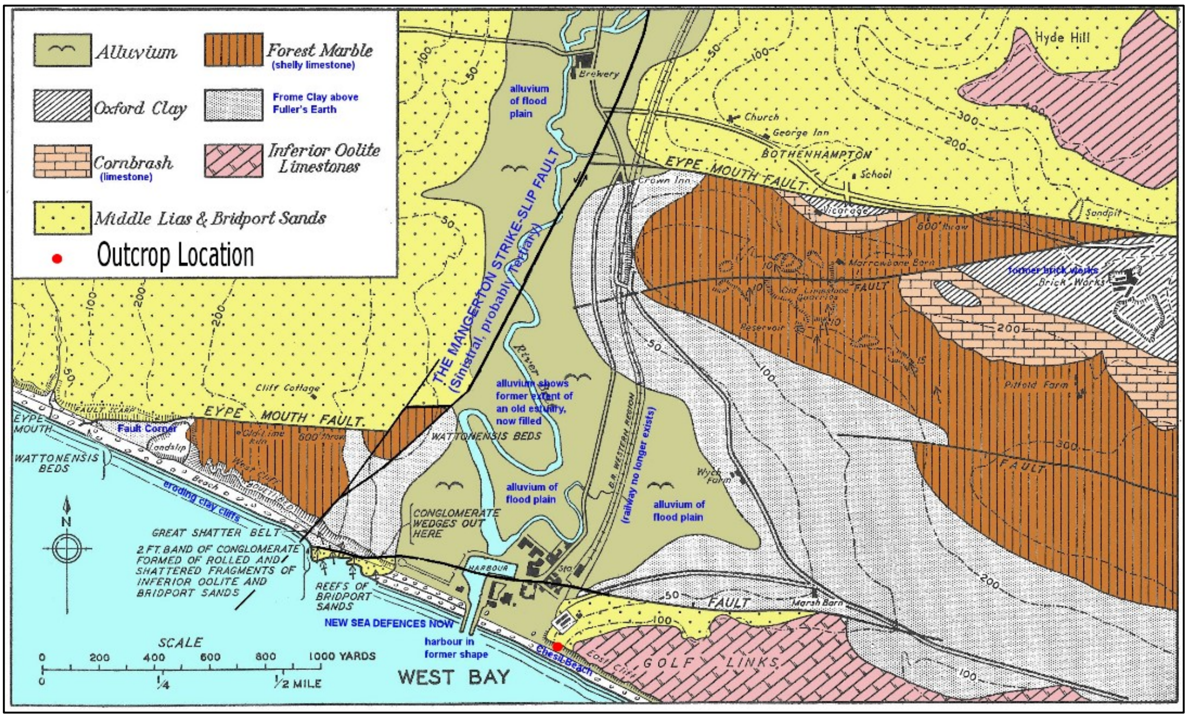


Figure 10: A Map including the geology of Bridport, West Bay. The red dot indicates the outcrop location.

Figure 10 gives an overview of the regional geology. There is a strike slip fault separating the eastern and western part of this village. This fault doesn't only structurally separate the two parts, but also separates them by age. On the eastern part we have the Bridport Sand formation and on the western part we have the Fullers Earth formation which is geologically speaking younger than the Bridport sand formation. This is quite interesting, since this is rather contrary to the general age trend at the Jurassic Coast. **Figure 11** from West (2013) gives another good insight on the geology of this area. **Figure 11** indicates that there is little influence from the nearby tectonic faulting in the Bridport Sand formation. The tectonically active part is on the western part in the Fullers Earth formation.

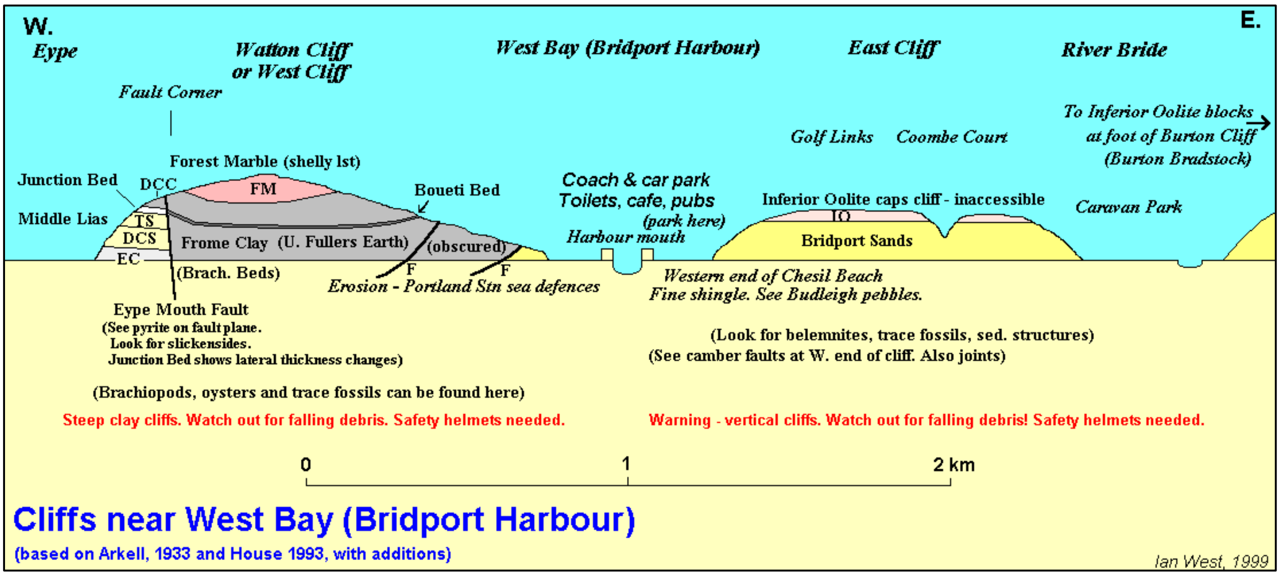


Figure 11: Front view of the geology of Bridport, West Bay

The western part with the Fullers Earth formation was also investigated, but unfortunately the cliffs in this region are extremely unstable and basically every bit is covered in landslides. Additionally it is prohibited to go near the cliffs, due to the rock fall. **Figure 12** shows parts of a massive landslide located in this formation on the western part.

Figure 12: Landslide in the Fullers Earth Formation.

The Fullers Earth formation contains clays and larger pieces of carbonate mudstones. It is a rather inhomogeneous unconsolidated formation. Due to its bad compaction and high clay content it is prone for landslides. When encountered in wells, it is known to be highly unstable and requires the use of oil based mud.

3.4 Results of the Outcrop Analysis

The first thing that is done is the creation of a geological map. To begin with the map is drafted by hand in a sketch book and later it is digitalized using the software Inkscape. For this digital version the hand drawn sketches and the pictures taken of the outcrop function as guidelines. **Figure 13** shows the digital map of the outcrop.

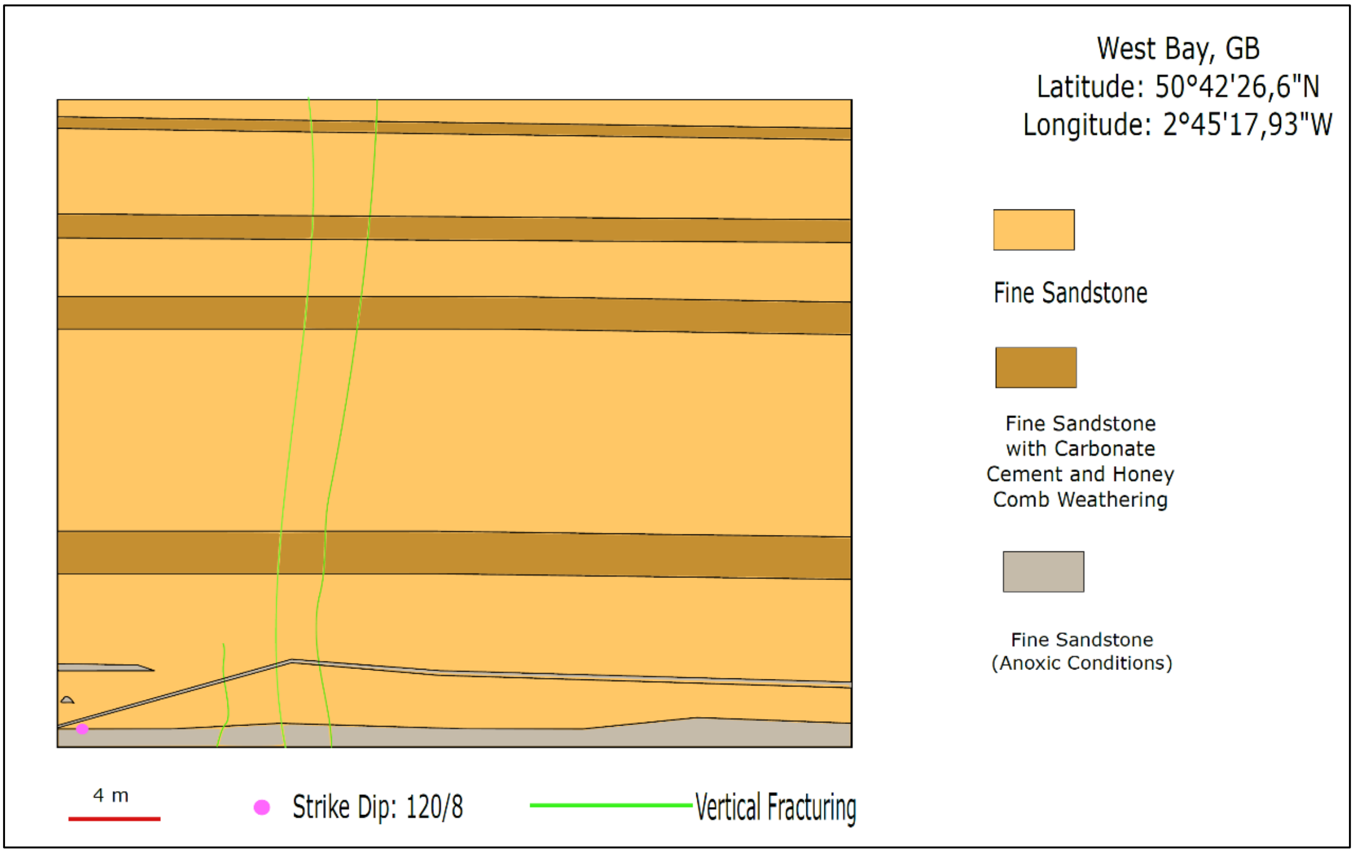


Figure 13: Digital map of the outcrop

This map includes all the layers that occur in this particular area, the natural fracturing and a Strike Dip measurement. The GPS coordinates of the location are also included as a matter of orientation. There is only one Strike Dip measurement included, since these cliffs are continuous in there strike and dip, ergo it is not necessary to display more measurements, since they yield the same result. The green lines show vertical fracturing, but no displacement of the layers. **Figure 14** shows the lower left corner of the geological map gives an idea of the fracturing that occurs in this particular part of the location.

Figure 14: The black arrows indicate the natural fractures

Multiple rock samples were collected and analyzed in the field. There are only two different types of rock occurring in this outcrop. Both are a fine sandstone with a varying carbonate content. The first sample W1 has a higher carbonate content and is therefore more competent. The other sample W2 is also a fine sandstone, which was found to be highly friable.

There are three samples taken to Austria (W1,W2 and W3), in order to be analyzed. The analysis is focusing on sedimentology and mineralogy. For the first sample W1 the porosity and permeability is evaluated by the Petrophysics Lab in Leoben. The following **Table 1** and **2** show the results for sample W1 **Fig.(15)**.

Sample Number	**W1**	**Colour**
Rock Type	Fine Sandstone	Yellow, Beige
Porosity	High, Estimated Value~30%	
Grain Size	Diameter 0,1 mm	
Sorting	Very Well Sorted	**Textural Maturity**
Sphericity	High Sphericity	Supermature
Roundness	Rounded	
Fabric	Grain Supported	
Mineralogy	Quarz ~95%, Mica (Biotit, Muskovit)	**Compositional Maturity**
Carbonate Content	Positive, High	Quarz Arenite

Table 1: Results of the analysis for sample W1

Sample W1	Length	Diameter	Mass	Volume Total	Grain Volume
	cm	cm	g	cm³	cm³
Plug 1	2,12	2,42	17,94	9,72	6,55
Plug 2	2,11	2,43	19,25	9,76	7,03
Plug 3	2,13	2,43	19,1	9,89	6,95
Plug 4	2,11	2,41	18,45	9,62	6,72
	Density Total	Grain Density	Por(Pyknm)	Por(Pyknm)	Permeability
	g/cm³	g/cm³		%	mD
Plug 1	1,85	2,74	0,33	32,61	51,52
Plug 2	1,97	2,74	0,28	28	25,42
Plug 3	1,93	2,75	0,3	29,74	39,12
Plug 4	1,92	2,75	0,3	30,17	47,76

Table 2: Results of the laboratory analysis for sample 1

The following **Equation 1** from Zoback (2007) is used to estimate the rock strength of the sample based on the data from the core experiments.

$$UCS = 277 * e^{-10*\phi} \qquad \text{Eq. 1}$$

The result of this estimate is a UCS (Unconfined Compressive Strength) of 12,5 MPa. This is a rather low result and indicates a weak formation.

Figure 15: Picture of sample W1

Table 3 shows the results for sample W2 **Fig.(16)**. This is the sandstone with a lower carbonate content and therefore it is quite friable.

W2	Colour
Fine Sandstone	Yellow, Beige, Orange
Very High, Estimated Value>30%	
Diameter 0,08 mm	**Textural Maturity**
Well Sorted	Supermature
High Sphericity	
Rounded	
Grain Supported	
Quarz ~95%, Mica (Biotit), Lithic Fragments ~3%	**Compositional Maturity**
Positive, Low	Quarz Arenite

Table 3: Results of the analysis for sample W2

Unfortunately it is not possible to perform core experiments with sample W2 since it is very friable and brittle. It would not be possible to cut a high quality plug out of this rock, since it would certainly break.

For this sample a quantitative assumption about the rock strength is not possible to make, since the porosity value is not available. If compared to the hand specimen of sample W1 a qualitative estimate of the UCS can be made, since sample W2 has a higher porosity than W1 the UCS needs to be lower than 12,5 MPa. This result indicates an extremely weak and unconsolidated formation.

Figure 16: Picture of sample W2

Table 4 shows the results for the analysis of sample W3 **Fig. (17)**. It is again a fine sandstone, with the highest calcite content of all the samples. Due to its higher calcite content the porosity value is significantly lower than in sample W1 and W2. The porosity of this sample is also not measured but estimated in comparison with the values from sample W1.

Sample Number	**W3**	**Colour**
Rock Type	Fine Sandstone	Dark Grey
Porosity	Medium	
Grain Size	Diameter 0,08 mm	**Textural Maturity**
Sorting	Very Well Sorted	Supermature
Sphericity	High Sphericity	
Roundness	Rounded	
Fabric	Grain Supported	
Mineralogy	Quarz ~95%, Calcit Cement	**Compositional Maturity**
Carbonate Content	Positive	Quarz Arenite

Table 4: Results of the analysis for sample W3

The estimated value for the porosity of sample W3 is a value between 15 to 20 %. With this porosity range using Equation 1 the UCS is estimated. The result is a range between 62 to 37,5 MPa.

Figure 17: Picture of sample W3

4. Lyme Regis

4.1 General Information

Lyme Regis in Dorset is the location of the second investigation. Lyme Regis is located at the southern coast of England in Dorset around 40 kilometers east of Exmouth **Fig.(18)**. From a geological point of view it provides cliffs of the Lower Jurassic and the Lower Lias. The outcrop is composed of the Blue Lias formation and the Shales with Beef formation.
Lyme Regis is chosen, due to its high coastal cliffs that provide a good insight into their geology, since the strata are clearly visible. The cliffs are easily accessible via the beach at low tide. Lyme Regis is a world famous site for paleontology, which for drilling correlation purposes is highly useful if an exploration team choose to use micropaleontology or intend to core formations and require dating offsets. This outcrop is known as Church Cliffs. It is especially interesting for drilling issue such as gas, since this formation contains an excellent source rock which has significant cleavage and folding, which is often encountered in petroleum exploration operations.

Figure 18: Google Maps view of Lyme Regis

The outcrop that was mapped can be reached via the sea wall and the beach. It is to be noted, that it is only possible to reach the location at low tide. Safety is critical so it is also very important to gather information about the tides prior to working at the cliffs in order to allow a safe research.

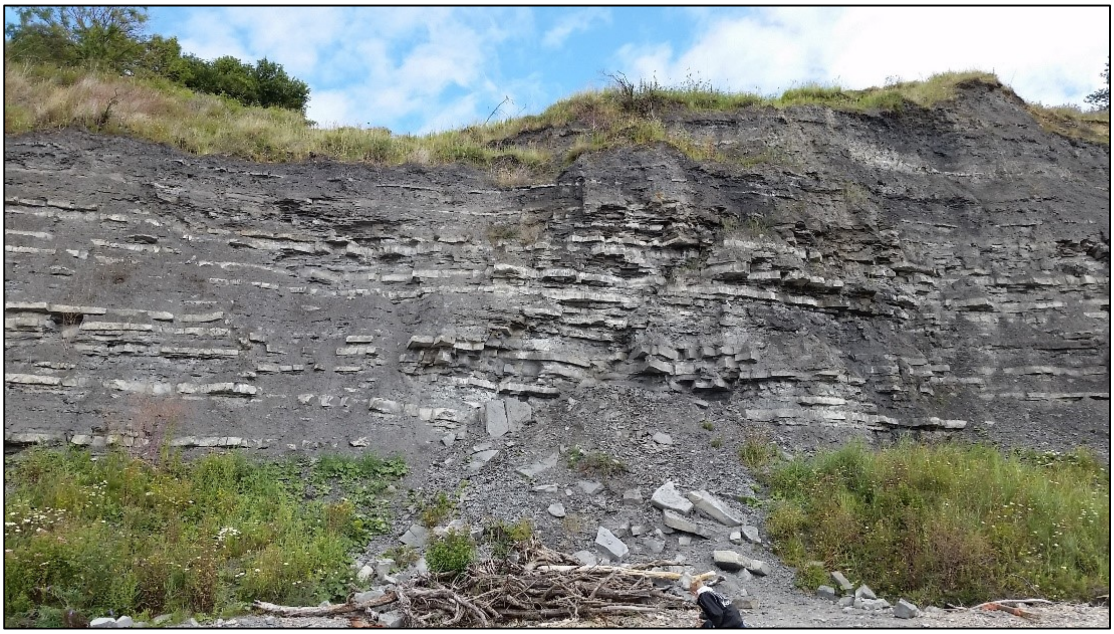


Figure 19: The Church Cliffs outcrop

Figure 19 gives an idea of the outcrop and the scale of the Blue Lias bedding. Faulting and micro fractures are clearly visible.

4.2 Geology of Lyme Regis.

The formations visible at Church Cliffs **Fig.(20)** in Lyme Regis are the Blue Lias formation and the Shales with Beef formation. The Blue Lias formation is of Lower Jurassic origin and consists of shales, marls and lime stones. The shales are quite weathered, while the carbonates are rather more resilient and not as weathered. The layers are carbonate mudstones, which form bands of around 20-30 cm in thickness. These carbonate bands are rather continuous in lateral extension, but sometimes they are interrupted with vertical fractures, which could be caused by rock fall and or weathering processes.

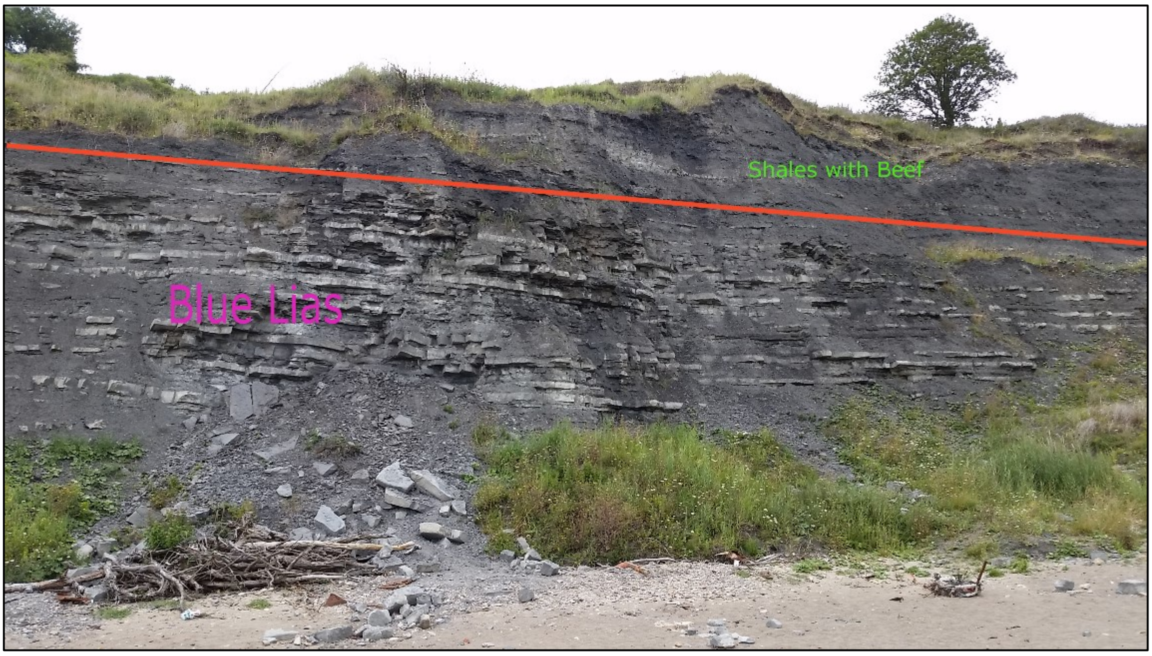


Figure 20: The red line marks the separation between Blue Lias and Shales with Beef

The carbonate mudstones have a light grey to white color and a rather high hardness. The shales between the lime stones are dark black, but once exposed to the surface they are very weathered and therefore sometimes appear to be grey. The shales have a strong bituminous smell and are very organic rich. This organic rich shale has very fine fissile layers, with a lot of fossils embedded in them. **Figure 21** shows a sample of the organic rich shale that is found as rock fall close to the cliffs.

Figure 21: Very thin laminated organic rich shale

Fossils that can be found in this formation are: Ammonites, Ichthyosaurs, Pleisiosaurs and others. The lower parts, ergo the older parts contain mostly Ammonites. Higher up in the succession the amount of marine fauna increases. According to West (2015) this is due to the fact that the Blue Lias Formation is the first normal marine sediment that was created due to transgression of the ocean over the supercontinent Pangea. Ergo the marine fauna increases upwards because the water was deepening. The amount of organic matter in these shales is absolutely outstanding. **Figure 22** shows Ammonites found in within a shale layer.

Figure 22: Ammonites within the shale at Lyme Regis

West (2015) states that the shales at Lyme Regis are not thermally mature, but they are thermally mature offshore, between Swanage and the Isle of Wight. The Blue Lias formation is a source rock for the Wytch Farm oil field, where it has yielded huge quantities of oil. In addition West (2015) states that the shale has a content of clay minerals of ~85%. This high clay content can cause wellbore stability problems when drilling through it with the wrong mud. Drilling through this formation is only possible using an inhibitive mud system such as an OBM (Oil Based Mud).

The following **Figure 23** by West (2015) gives an idea about the Blue Lias cycles.

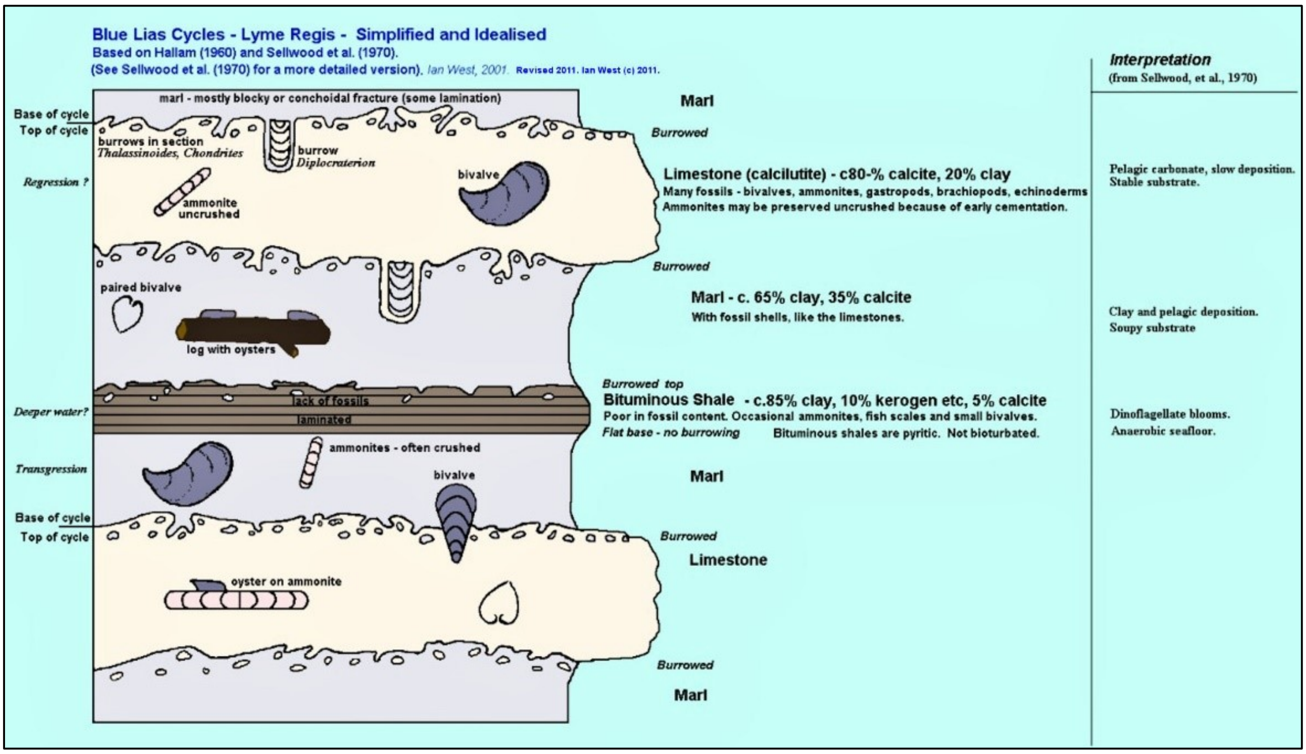


Figure 23: Cycles of the Blue Lias

The fossils that can be found in the Blue Lias formation can be used to determine the age of the individual layers. The age determination using fossils is referred to as biostratigraphy.

The Blues Lias formation contains several normal faults. These faults are clearly visible and the displacement of the layers ranges from 20 to 50 cm. This region is tectonically active and there are strong forces acting on the rock. These faults pose several drilling related problems. When drilling through a fault like displayed in Figure 10 the trajectory may be deflected and this could cause a missing of the target. It has to be evaluated whether the faults are permeable or not. If the fault is permeable it could transmit an overpressure into the wellbore, which may cause severe well control problems. Additionally faults can lead to wellbore stability problems. Since these faults may not be visible on the seismic data due to resolution reasons it is crucial to understand that there can still be faults in a formation like the Blue Lias, even though they are not visible at the seismic images.

The Shales with Beef formation is also of Lower Jurassic origin but younger than the Blue Lias formation. It has a thickness of around 25 m. It consists of thinly interbeded organic rich mudstone and calcerous mudstones. There are several beds of lime stones. The term beef originates from thin beds of calcite. The Shales with Beef formation is also a very good petroleum source rock

Figure 24 from West (2015) shows the Jurassic strata of Dorset and displays the age of the two mentioned formations at Church Cliffs.

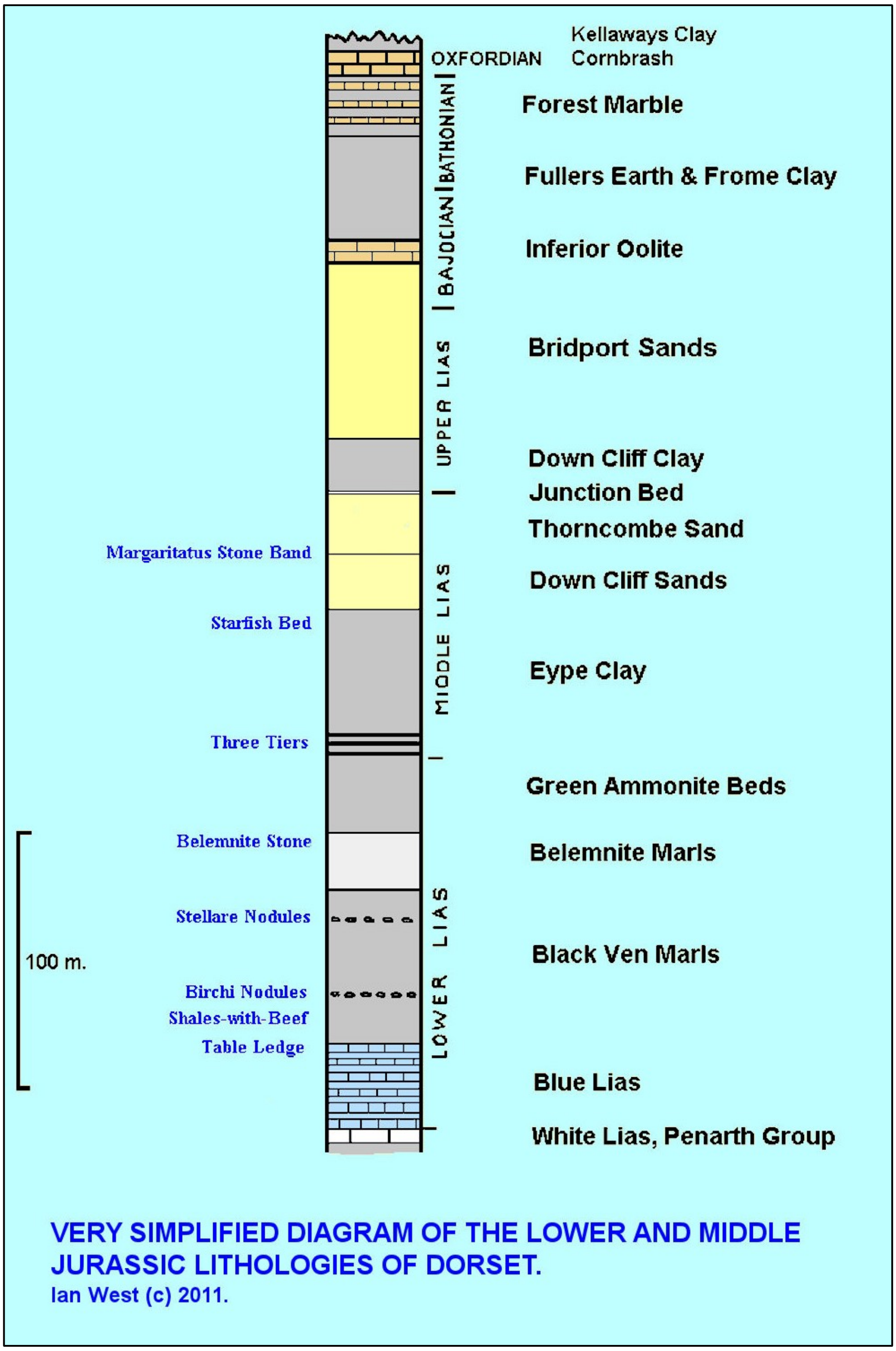


Figure 24: The two observed formations the Blue Lias and the Shales with Beef are both of Lower Jurassic age

The formations above the Shales with Beef formation are not observed due to vegetation. There are outcrops further to the east, where the rock is fully exposed. These outcrops are not taken into consideration.

4.3 Outcrop Analysis

The outcrop containing the formations that are examined is located at the eastern part of Lyme Regis. The outcrop is reached via the sea wall and the beach during low tide. The outcrop is a part of the Church Cliffs. The formations that are encountered are the Blue Lias formation and partially the Shales with Beef formation. The analysis focuses on the Blues Lias formation, since this is going upwards from the beach and is therefore easily accessible. The Shales with Beef formation is on top of the Blue Lias and therefore to high up to be safely reached. **Figure 25** by West (2015) shows the outcrop location.

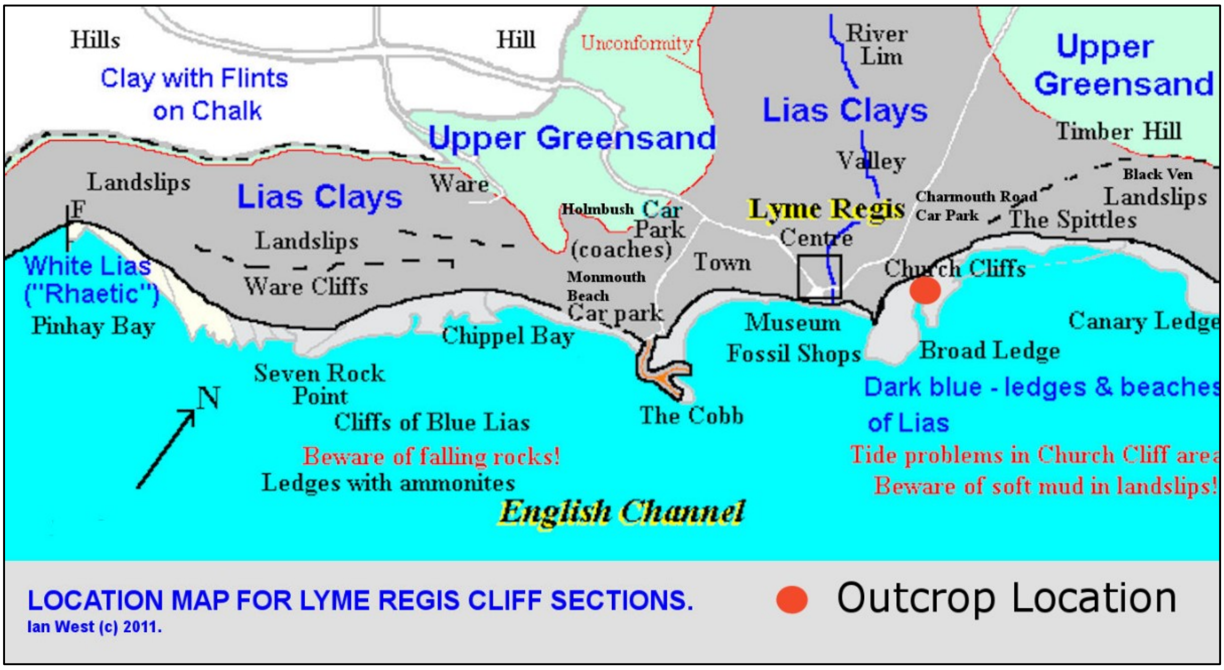


Figure 25: Geological map of Lyme Regis including the outcrop location

The rock types that are examined in the Blues Lias formation are carbonate mudstones and organic rich shales.

In the outcrop there are strong tectonic forces acting. Several normal faults are observed. Additionally the whole formations is quite unstable. Massive landslides occur in this area and it is also prone for rock fall.

4.4 Results of the Outcrop Analysis

To begin with a geological map is created. At first the outcrop size that is to be mapped is defined. Then the main layers are measured and the outcrop is sketched. Using these sketches and the pictures that are taken the map is digitalized using the software Inkscape. The following **Figure 26** shows the geological map of the outcrop.

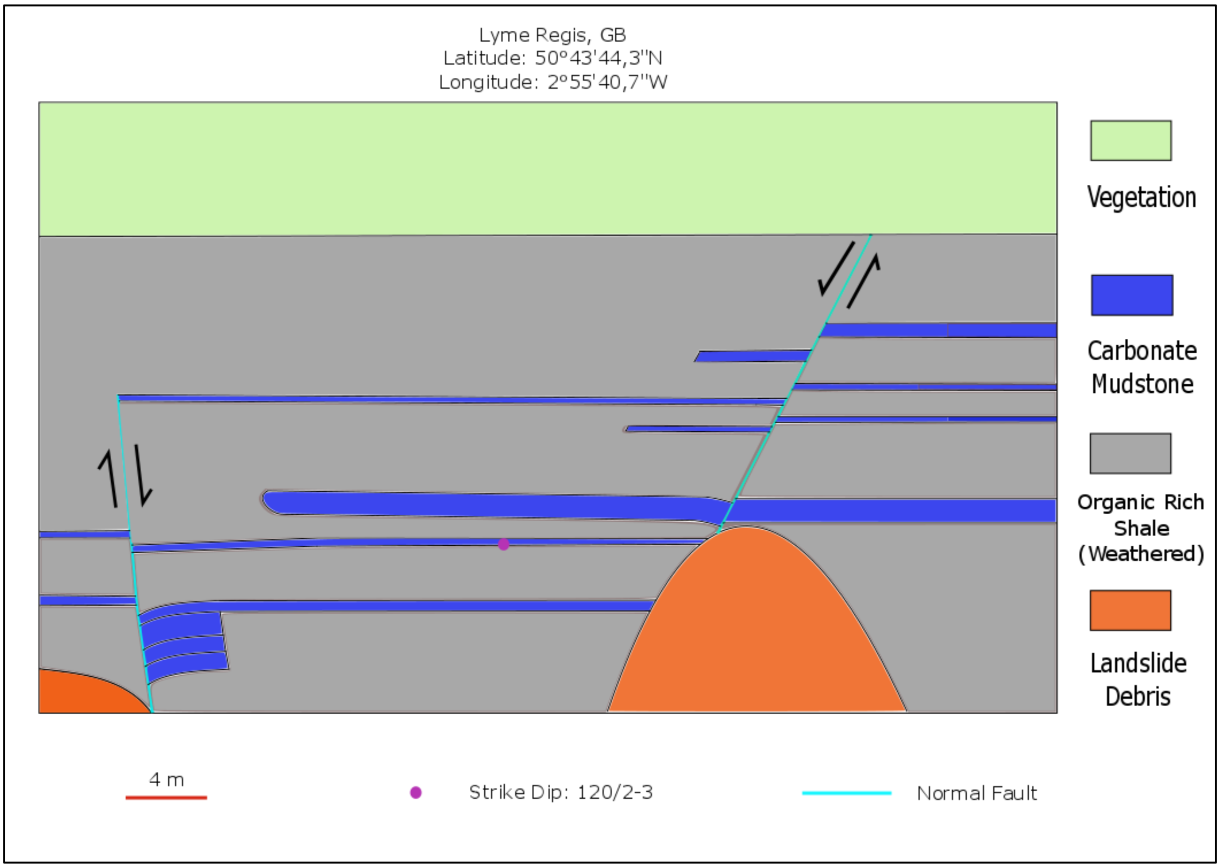


Figure 26: A digital map of the outcrop including all layers, strike dip measurement and faulting

The outcrop is 40 m wide and around 20 m high. The map includes all layers of organic rich shale and carbonate mudstone. The upper part is not possible to define since there is vegetation, but presumably this is the shales with beef. The layers of carbonate mudstone are rather laterally continuous. There are two landslides covering parts of the outcrop.

This outcrop is of particular interest because of its structural features. There are two normal faults located at the outcrop. Together they form a very prominently visible graben structure. This structure is very well visible, due to the carbonate mudstone bands that provide a good insight on the amount of displacement. **Figure 27** shows the normal fault at the right hand side of the outcrop.

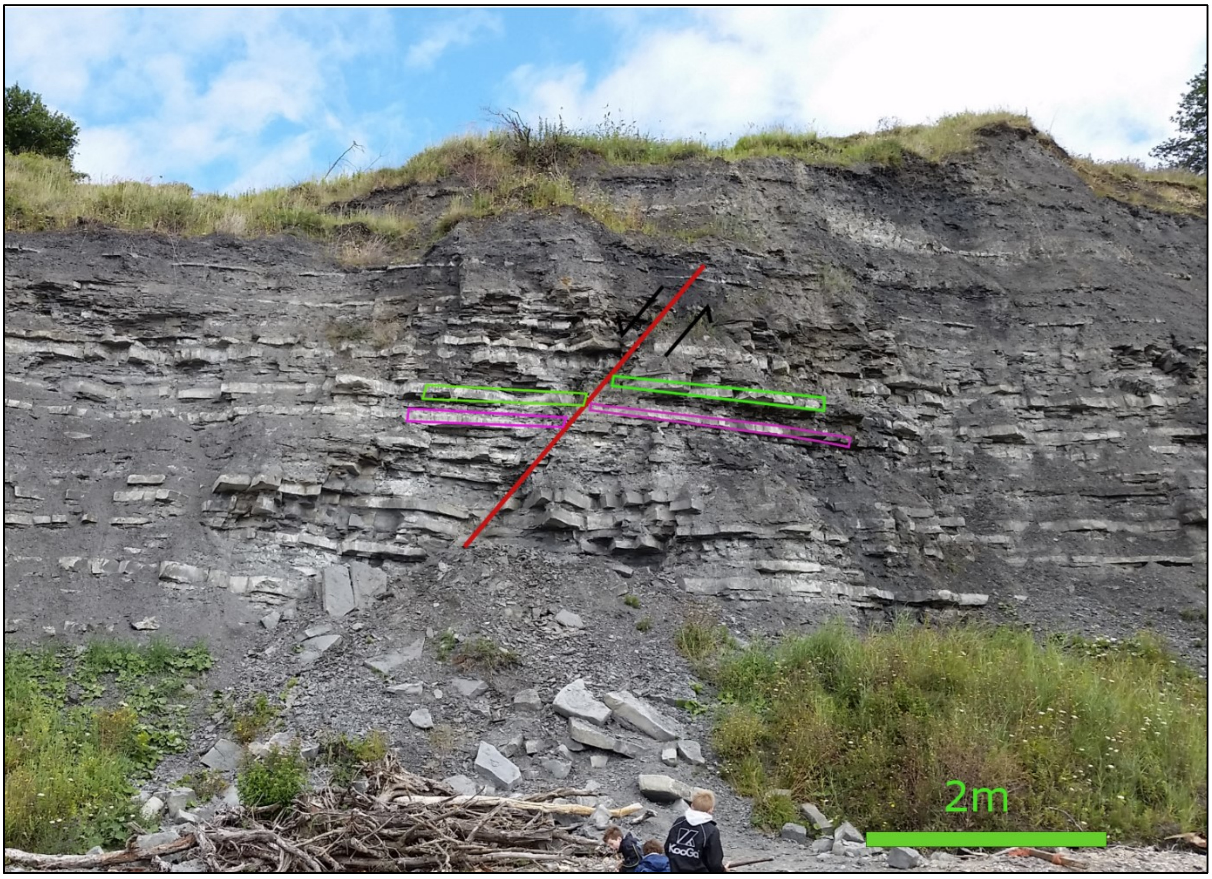


Figure 27: Illustration of the displacement of the normal fault on the right hand side of the outcrop

There are multiple samples taken in the field. Two samples are brought to the lab for further analysis. The mineralogy and the sedimentology are analyzed. The first sample is a carbonate mudstone. It is of white color and rather compacted and hard.

The second sample LR2 is an organic rich shale with a massive organic content. It has a black color and a bituminous odor. Some ammonites are found in this shale.

Both rocks are of marine origin. The Blue Lias formation can be considered an excellent source rock.

The following **Table 5** shows the results for sample LR1 **Fig.(28)**.

Sample Number	**LR 1**
Rock Type	Carbonate Mudstone
Porosity	Low ~5%
Grain Size	Not Visible
Mineralogy	Calcite
Colour	Grey

Table 5: Results of the analysis for sample LR1

With the estimated porosity of 5 % a value for the UCS can be correlated using the following **Equation 2** from Zoback (2007)

$$UCS = 135.9 * e^{-4.8*\phi} \qquad \textit{Eq. 2}$$

The result of this calculation is a UCS of 107 MPa. This is a high value and represents a hard formation. This is a valid result, since it is very hard to acquire this sample even with the use of a steel hammer.

Figure 28: Hand specimen of sample LR1

The following **Table 6** shows the results for sample LR2 **Fig.(29)**.

Sample Number	**LR 2**
Rock Type	Oil Shale
Porosity	Very Low
Grain Size	Not Visible
Mineralogy	Clay Minerals, Very High Organic Content
Colour	Dark Black
Sedimentary Textures	Fossils (Ammonites)
Smell	Strong Bituminous Smell

Table 6: Results of the analysis for sample LR2

With the estimated porosity of 5 % a value for the UCS can be correlated using the following **Equation 3** form Zoback (2007).

$$UCS = 1.001 * \phi^{-1.143} \qquad \text{Eq. 3}$$

The result of this calculation is a UCS of 31 MPa. This means that the shale layers in this formation have a rock strength that is only one third of the rock strength of the carbonate bands that occur in this formation. For the bit design in this formation it is crucial to understand, that within a few meters the rock strength can significantly change. So the bit needs to be selected in order to be able to drill the soft and the hard layers of this formation

Figure 29: Hand specimen of sample LR2

5. Watchet

5.1 General Information

The third and last location that is researched is Watchet in Somerset. Watchet is chosen due to its significant tectonically formed structures and its distinct and clearly visible transition from Triassic to Jurassic. Watchet is located about 14 km east of Minehead **Fig.(30)**. It is situated at the Bristol Channel. The chosen outcrop is reached via the beach at low tide. It is to state, that the difference in water level in this region is up to 12 meters, so this has to be considered while performing the outcrop analysis, in order to avoid hazardous situations.

Figure 30: Google Maps view of Watchet

Watchet is very suitable for an outcrop analysis, since its shore provides cliffs that are vegetation free and rather well visible. The cliffs west of the town are investigated upon. The formations in imminent vicinity to Watchet are late Triassic. This formation is known as the Mercia Mudstone formation and furthermore the Red Keuper Marls. The Mercia Mudstone is a common formation and is widely spread across the UK. Outcrops can be found in multiple locations such as: Wessex Basin, Carlisle Basin or the East Midlands.

Further to the west, the formation changes quite distinctly and rapidly from late Triassic to early Jurassic. This early Jurassic formation is the early Lias or Hettangian. The Hettangian is slightly older then the Blue Lias that is investigated in Lyme Regis. This formation consists of lime stones and shales. It has similar characteristics to the Blue Lias formation in Lyme Regis.

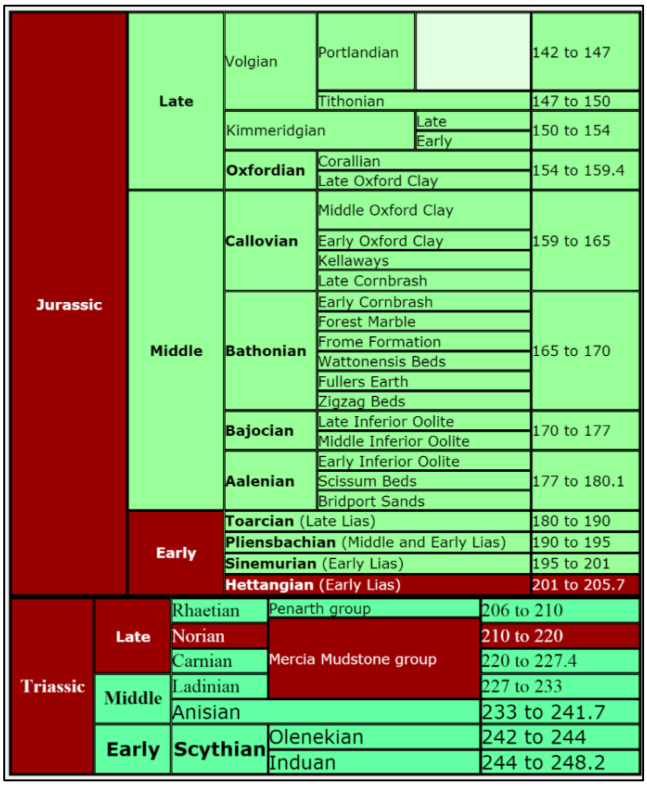
The following **Figure 31** shows the Mercia Mudstone formation right next to the harbor of Watchet.

Figure 31: The Mercia Mudstone Formation close to the harbor of Watchet

5.2 Geology of Watchet

The formations visible to west of Watchet harbor are the Mercia Mudstone and the Hettangian early Lias. Both are very easy to distinguish and the boundary between them is clearly visible.

The Mercia Mudstone is of Triassic age as shown in **Figure 32** from Cruickshanks.



Jurassic	**Late**	Volgian	Portlandian		142 to 147
			Tithonian		147 to 150
		Kimmeridgian		Late	150 to 154
				Early	
		Oxfordian	Corallian		154 to 159.4
			Late Oxford Clay		
	Middle	**Callovian**	Middle Oxford Clay		159 to 165
			Early Oxford Clay		
			Kellaways		
			Late Cornbrash		
		Bathonian	Early Cornbrash		165 to 170
			Forest Marble		
			Frome Formation		
			Wattonensis Beds		
			Fullers Earth		
			Zigzag Beds		
		Bajocian	Late Inferior Oolite		170 to 177
			Middle Inferior Oolite		
		Aalenian	Early Inferior Oolite		177 to 180.1
			Scissum Beds		
			Bridport Sands		
	Early	**Toarcian** (Late Lias)			180 to 190
		Pliensbachian (Middle and Early Lias)			190 to 195
		Sinemurian (Early Lias)			195 to 201
		Hettangian (Early Lias)			201 to 205.7
Triassic	**Late**	Rhaetian	Penarth group		206 to 210
		Norian	Mercia Mudstone group		210 to 220
		Carnian			220 to 227.4
	Middle	Ladinian			227 to 233
		Anisian			233 to 241.7
	Early	**Scythian**	Olenekian		242 to 244
			Induan		244 to 248.2

Figure 32: Time Scale including the age of the Mercia Mudstone and the Hettangian Early Lias Group

The Mercia Mudstone in Watchet consists of different rock types. The largest part is a brown siliciclastic mudstone. This mudstone is consolidated and has a very low porosity. It can be considered as a seal rock for a potential reservoir. In between of this mudstone there are veins of anhydrite. The presence of anhydrite is a clear indicator for a shallow marine environment of deposition. At this particular outcrop only anhydrite was found, but it is very likely that this formation contains additional different evaporitic rocks. Anhydrite is deposited through evaporation of shallow marine sea water and precipitation of the dissolved minerals. An anhydrite find may indicate the occurrence of other evaporite rocks such as gypsum halite and sylvite (also known as sylvine). **Figure 33** shows a vein of anhydrite in the mudstone. It is important to understand the link between the different evaporitic rock types and the sequence of deposition, in order to be able to take the right measures against the problems created by the different rock types.

The anhydrite in this formation is very consolidated, hard and brittle. The anhydrite lenses are a challenge for the bit design, since the mudstone has a rather low hardness, but the anhydrite has a higher hardness. The bit needs to be able to drill through the soft mudstone and the hard anhydrite sections.

Figure 33: Veins of anhydrite imbedded in the mudstone

Additionally the Mercia Mudstone formation contains smaller layers of green siltstone. This green color originates from anoxic and reduced conditions.

The Hettangian formation is of early Jurassic age. It consist of limestone layers and shales. The limestone is a carbonate mudstone. They have a grey color and a very low porosity. The shales are organic rich and have a strong bituminous smell.

In both rock types there are multiple fossils to be found. The fossils are of marine origin such as: Ammonites **Fig.(34)** or Belemnites **Fig.(35)**.

Figure 34: Ammonite found in carbonate mudstone near Watchet

Figure 35: Belemnite fossils found near Watchet

This region is also known for its outstanding structural geology. This is an indication that this region is subjected to high tectonic forces. Multiple structures like faults or folds can be observed. Figure 36 shows an example of a syncline anticline combination. The green line in **Figure 36** schematically highlights an individual layer to better display the magnitude of the bend.

Figure 36: Extreme folding of the layers due to tectonic compression.

This syncline anticline combination originates from strong compressive tectonic forces. When drilling through a fold like this, it is inevitable that several layers are encountered more than once. This can be an issue for the orientation and directional control of the well, especially when the structure is on a larger scale than the one provided here.

Another issue in a structure like this is the problem with rock strength anisotropy. Zoback (2007) states that the presence of weak bedding planes can have a strong effect on the formation strength. Additionally Zoback (2007) says that the angle of the applied stress has a great effect on the strength of the rock.

If the angle of the applied stress is between 30° and 60° the rock strength will be weakened due to the slip on the weak bedding plane. This needs to be considered when planning a trajectory especially in tectonically active regions similar to the investigated outcrop, since it leads to wellbore instability issues. This syncline anticline structure could be considered an example for a structural trap in a hydrocarbon system, if it were on a larger scale. Typically the hydrocarbons would be trapped in the crest of the anticline part of the fold.

5.3 Outcrop Analysis

The outcrop at Watchet can be accessed easily near the harbor at Watchet. The formations encountered at the outcrop is the Mercia Mudstone of the late Triassic age. The outcrop is reached by foot via the beach. It is around a 10 minute walk away from the village. **Figure 37** shows a satellite image of the outcrop location.

Figure 37: Satellite image of the location (google maps)

The rock types that are examined in the outcrop analysis are a siliciclastic mudstone and an anhydrite. The whole formation is deposited in a shallow marine environment. The presence of anhydrite allows this assumption, since it is an evaporite.

The outcrop is chosen because of its immaculate display of tectonic forces acting. This outcrop has a reverse fault. This fault is extremely well visible and of particular interest, due to the fact, that the fault plane is filled with an anhydrite vein. **Figure 38** shows a detailed view of the outcrop.

Figure 38: Reverse fault in the outcrop. Phil Bailey as scale (1.72m).

5.4 Results of the Outcrop Analysis

For the analysis a geological map is created. At first the outcrop size that is to be mapped is defined. Then the main layers are measured and the outcrop is sketched. Using these sketches and the pictures that are taken the map is digitalized using the software Inkscape. The following **Figure 39** shows the geological map of the outcrop.

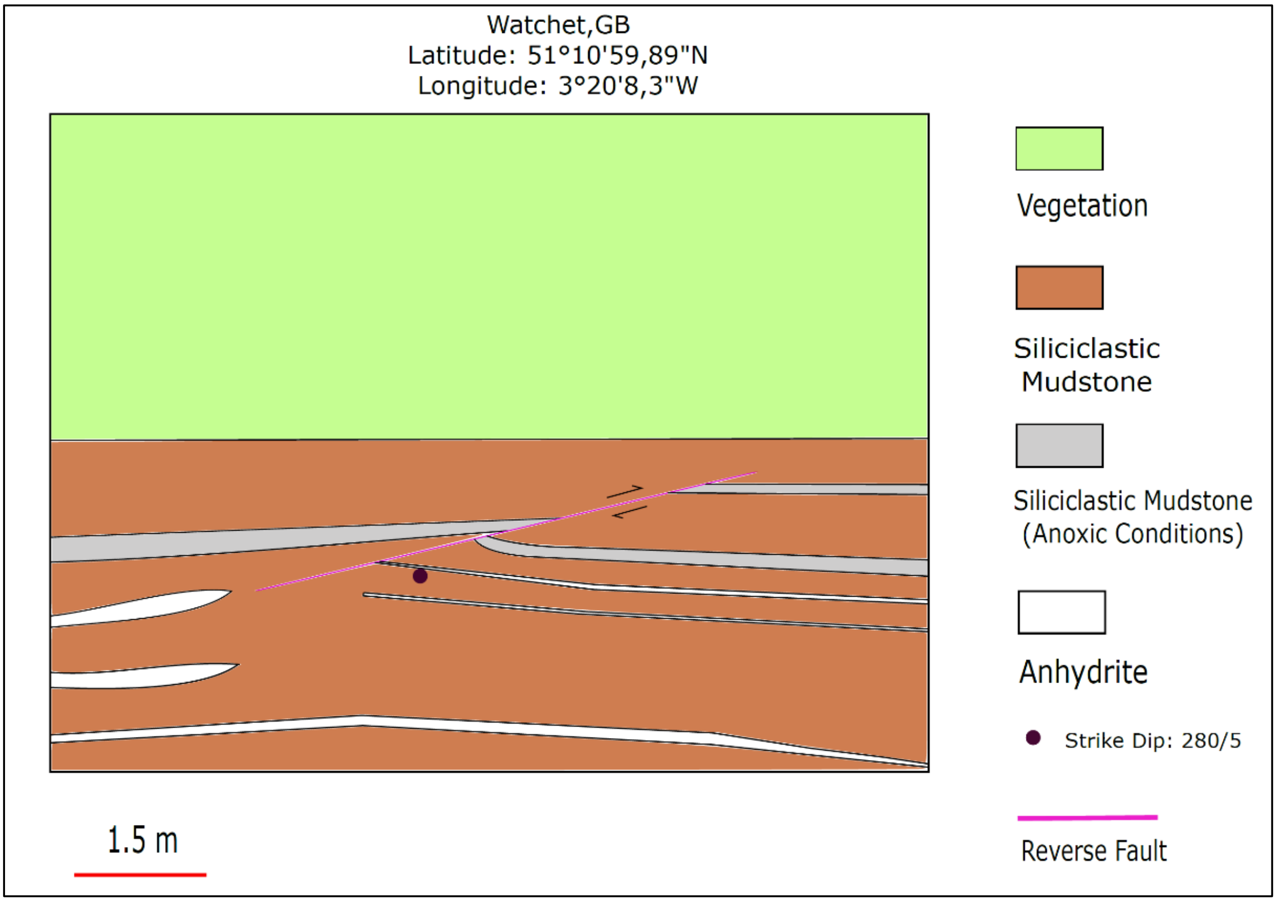


Figure 39: Digital map of the outcrop including all layers.

The outcrop that is m has a width of 12 meters and a height of around 4 meters. The part that is located higher than 4 meters is unfortunately not visible, because it is covered in vegetation.

The layers that are analyzed are the siliciclastic mudstone and the anhydrite. The layers of mudstone are the main part of the outcrop. They are laterally continuous. The layers of anhydrite are not continuous, but they occur in small veins and lenses. Additionally the fault plane is anhydrite.

There is a reverse fault at the outcrop that is very easy to observe. This fault developed due to compressive tectonic forces.

There are multiple samples taken in the field. Two samples are brought to Austria in order to investigate them in detail. The mineralogy and the sedimentology is analyzed.

The first sample WA1 is the siliciclastic mudstone. The mudstone is of red to brown color. It has a very low porosity and is consolidated. It contains quarz and clay minerals. It is deposited in a shallow marine environment of deposition.

The second sample WA2 is an anhydrite. The anhydrite is of white color. It has no porosity and is very hard. Anhydrite consists of $CaSO_4$ and it is an evaporite and therefore a clear indicator for a shallow marine environment of deposition.

The following **Table 7** shows the results of the analysis for sample WA1 **Fig.(40)**.

Sample Number	**WA 1**	**Colour**
Rock Type	Siliciclastic Mudstone	Red, Brown
Porosity	Low, <5%	
Grain Size	Diameter<0,0039 mm	**Textural Maturity**
Sorting	Very Good	Imature
Mineralogy	Quarz, Clay Minerals	**Compositional Maturity**
Carbonate Content	Negative	Mudstone

Table 7: Results of the analysis for sample WA1

Figure 40: Hand specimen of sample WA1

The following **Table 8** shows the results of the analysis for sample WA2 **Fig.(41)**.

Sample Number	**WA 2**
Rock Type	Anhydrite
Porosity	~0%
Mineralogy	$CaSO_4$
Carbonate Content	Negative
Colour	White

Table 8: Results of the analysis for sample WA2

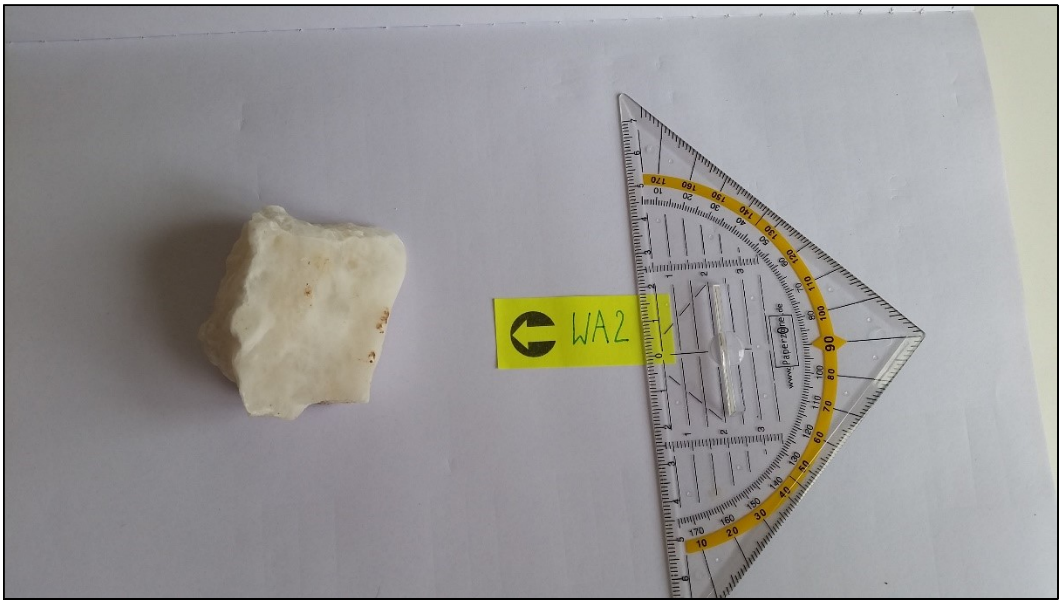
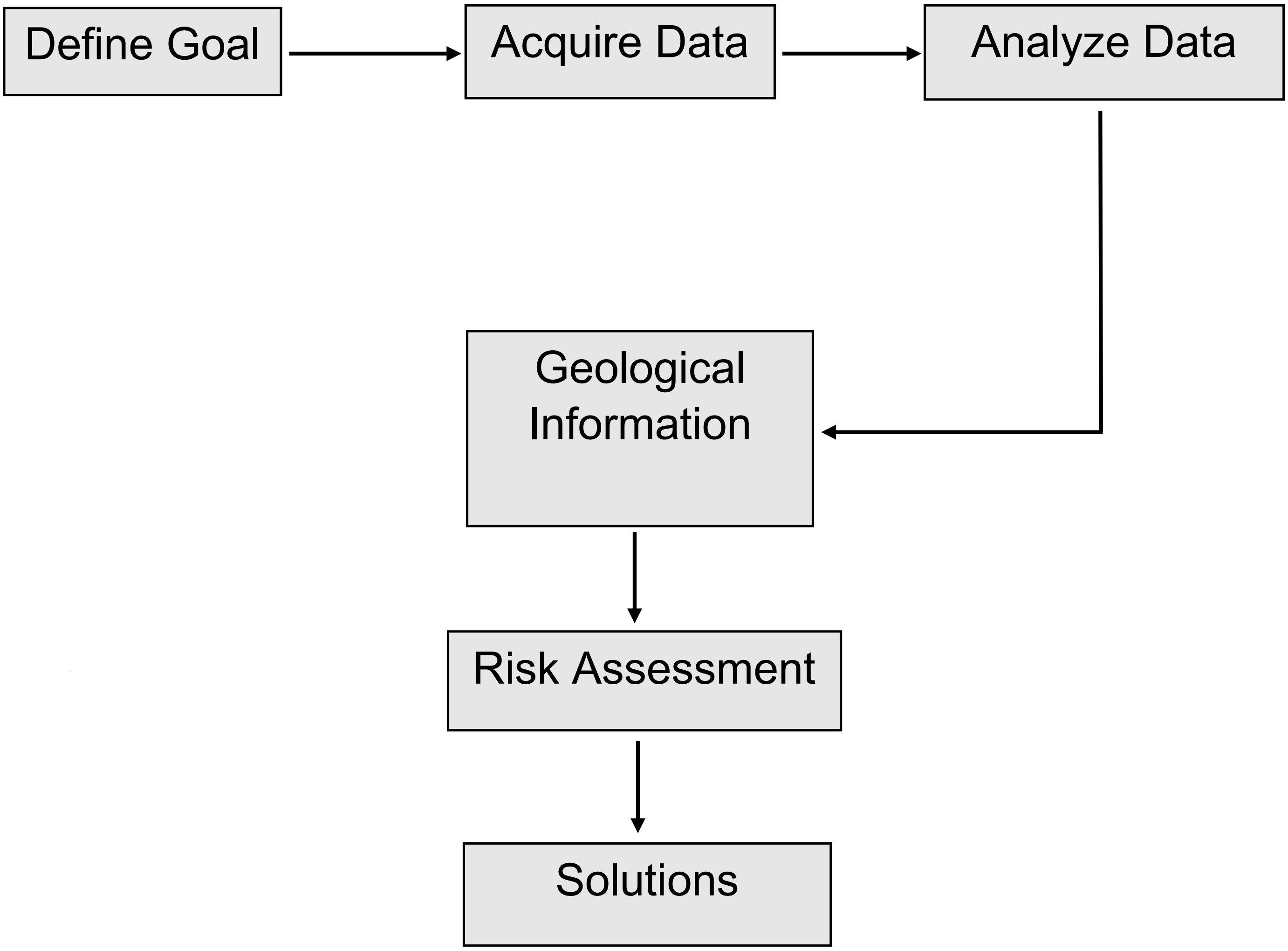


Figure 41: Hand specimen of sample WA 2

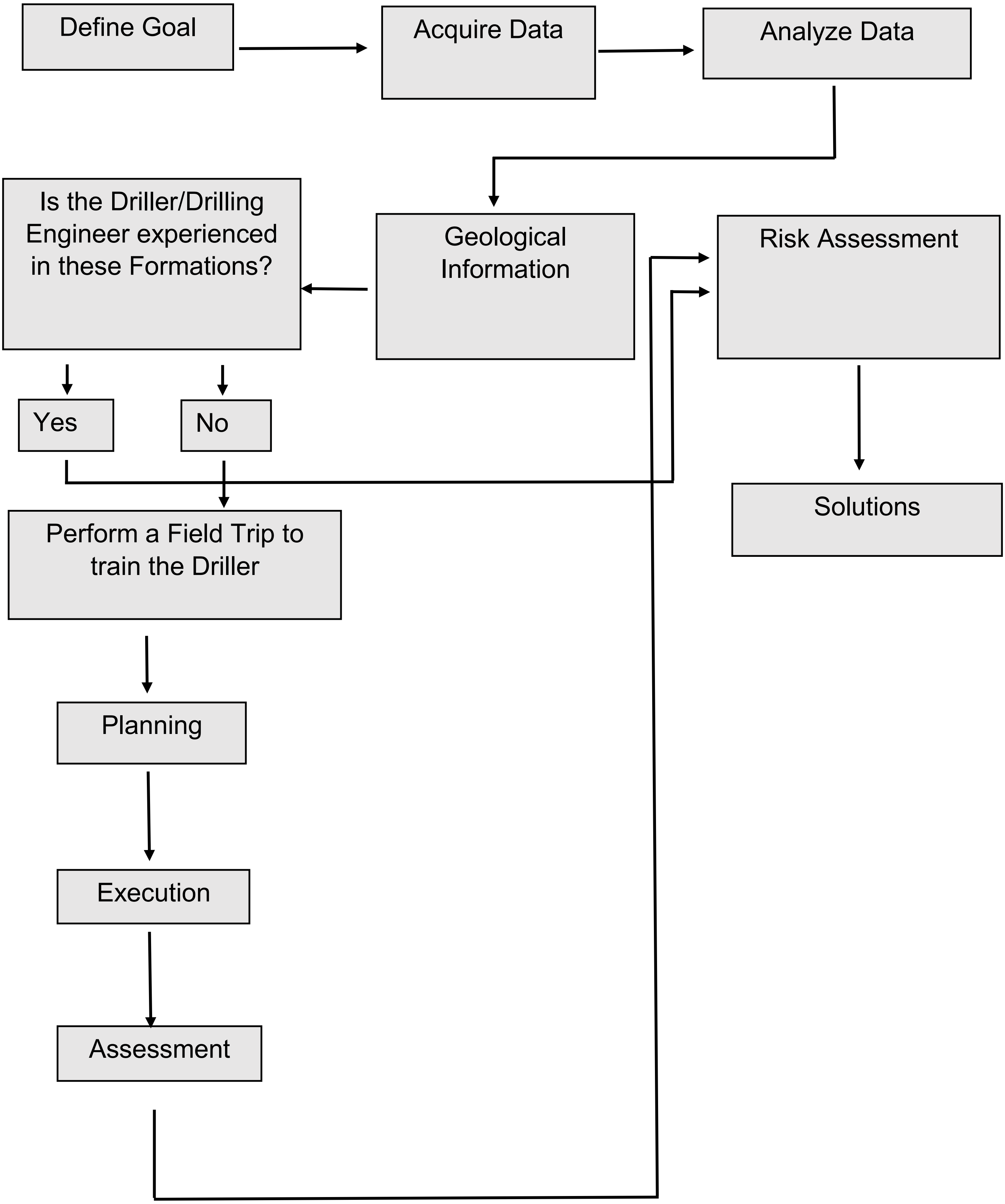
6. Improved Workflow for Exploration

The following workflow presents the potential conventional approach for the well planning sequence in exploration. This workflow is quite static in terms of the experience of the acting personnel, since it does not include the opportunity to directly train the staff. If the formations that are to be drilled are completely new for the drilling engineer as well as the driller it is absolutely necessary to gather as much information about the formations characteristics as possible. In a potential conventional workflow like this information is mostly indirect and not first hand. These sources can be seismic data, geological maps, data from offset wells and others. A very easy way to increase the available knowledge is presented in the new and improved workflow. This method is to take the responsible people like the driller and drilling engineer to outcrop analogues of the downhole formations and to investigate the potential drilling hazards in situ. This should be done in the form of field trips, which are specially designed to match the desired formations. These outcrop studies should be performed following the methodology of the studies in Bridport, Lyme Regis and Watchet that were carried out in this thesis.

6.1 Potential Conventional Workflow for Exploration Wells



6.2 Improved Workflow for Exploration Wells



6.3 Definition of Workflow Steps

Define Goal

Before any operation is planned and executed major goals have to be defined. For an exploration well this goal is to find and recover hydrocarbons at a certain geographical location in a pre-defined geological pay zone.

Acquire Data

In order to properly plan a well data needs to be gathered. It is of crucial importance to gain access to all available data sources. The more data is available the more risks can be reduced. This leads to an increased chance of a successful operation.

Data Sources:

- Seismic data
- Log data
- Offset wells
- Core data
- Geological maps

Geological Information

The result of the data analysis is geological information. This information will be later used for drilling risk analysis and is an important step in the planning of an exploration well. The type of information and the availability ranges from project to project.

Geological information:

- Cross sections
- Mineralogy
- Structural geology
- Stratigraphy
- Rock properties
- Information about hydrocarbons
- Sedimentological background

Risk Assessment

Once the geological data is at hand a risk analysis is carried out based on the findings. This analysis should identify what type of geological setting in the formations leads to what type of drilling risk. The following list states a few potential geological risks. Of course there exist many more risks in different formations.

Geological formation risks:

- Shale formation→ wellbore instability
- Highly permeable formation→ fluid losses
- Severe folds→reduction of UCS (Unconfined Compressive Strength)
- Mineralogy→varying rock hardness
- Salt formation→closure of the wellbore
- Salt formation→wash outs

Solutions

The last step in the improved workflow is to find solutions for the problems that are caused by the drilling risks. These solutions need to be integrated in the well plan in order to prevent hazardous situations and to provide an efficient execution of the well. The following list states the solution for the previously named geological risks.

Solutions for the geological formation risks:

- wellbore instability→inhibitive mud design
- fluid losses→LCM (Lost Circulation Material) in the mud
- reduction of UCS (Unconfined Compressive Strength)→drill the formation in the right angle
- varying rock hardness→correct bit selection
- closure of the wellbore→reduce uncased time
- wash outs→saturated WBM (Water Based Mud)

Perform a Fieldtrip to train the Driller

This should be done when the driller that executes the well and or the drilling engineer who plans the well has never experienced similar formations in real life. Drillers often lack knowledge about geology, this can lead to bad decision making. The solution for this problem is to train the field staff and the planning staff, by performing field trips. These field trips aim to show the driller/drilling engineer similar formations that they will experience in the exploration wells. The emphasis is on visualizing formations that will cause problems, it is of crucial importance to understand the real magnitudes and behavior of these formations.

The workflow for this field trip consist of three phases, these phases can be modified for each different field trip in order to increase efficiency. The proposed workflow is based on the field trip that was carried out for this thesis, to prove the value of the implementation of field trips for further gathering of information into the workflow of the well delivery process.

1. Planning

- Define outcrop specifications: formation type/age etc.
- Look for outcrop that suits the specifications: recommended area for the North Sea is the Jurassic Coast of Dorset
- Define required equipment: mini permeameter, handheld gamma ray, rock strength testing devices etc.
- Make travel arrangements

2. Execution

- Look for suitable and representative location
- Measure the length of the location
- Measure thickness of the layers
- Sketch the outcrop
- Measure Strike/Dip
- Take samples
- Analyze samples
- Look for sedimentary structures
- Make additional measurements
- Evaluate the drilling risks of the outcrop

3. Assessment

- Evaluate the field data
- Integrate the field data in the decision making process

- Use the field data to find proper solutions for the risks

The following **Table 9** show the advantages and disadvantages of this workflow

Advantages	**Disadvantages**
Increases the skillset of the driller/drilling engineer	It will create additional cost
Gives the opportunity to see the "downhole" formations at the surface	Finding a representative outcrop is difficult
Increases the amount of available information	Success depends on the motivation of the participants
Leads to better decision making	If the wrong outcrop is investigated wrong conclusions can be drawn
Provides design solutions based on risks	Needs to be absolutely professional
It is a very structured and clear workflow	Has health risks, due to potential rock fall
Can be applied for multiple disciplines	Since it is outdoors continuous bad weather can lead to an unsuccessful field trip
It is interdisciplinary	

Table 9: Advantages/ Disadvantages of the new workflow

6.4 Post Well Review Analysis

Another possible application for the educational field trips suggested in the improved workflow is post well reviews. Once a well has been completed it is of crucial importance to investigate the encountered problems in order to increase overall efficiency and safety of future operations. If there were technical problems that caused significant costs the team should be taken to outcrop analogues in order to visualize the encountered issues. A potential scenario for this method can be for instance that a producing layer is softer than expected and now it causes sand control problems. In this case the team could go to an outcrop like at Bridport in order to see the effect of calcite content on rock hardness. The main benefit of this method again is that it is relatively cheap compared to its potential reward. Not only the issues and hazards can be better understood, but also the overall knowledge about geology and drilling of the team will be increased.

7. Data Analysis of the Cook Field Well 21/20a-2

7.1 General Information

The cook field is an offshore oilfield located in the North Sea around 175 km to the east of Aberdeen. It was discovered in 1983 with the exploration well 21/20a-2. The oil has an API gravity of 35°. The reservoir pressure is 9700 psi, which is highly over pressured. The bubble point pressure lies at 3400 psi.

The peak oil rate is assumed at 20.000 bpd and the reserves are estimated 12 and 23 million barrels of oil and 15 billion cubic feet of gas.

The reservoir layer is located at a depth of 12500 ft. in the Humber Group. The reservoir lies at the top of a dome structure. The recovery mechanism for this reservoir is natural depletion, but gas lift capability is included in the production wells for the later life.

The field is producing since 2000 from a development well that was drilled in 1999.

Oil is transported away with a shuttle tanker, while the gas is transported away via the SEGAL pipeline. **Figure 42** from Offshore Magazine (2013) shows the exact location of the cook field on a map of the North Sea blocks.

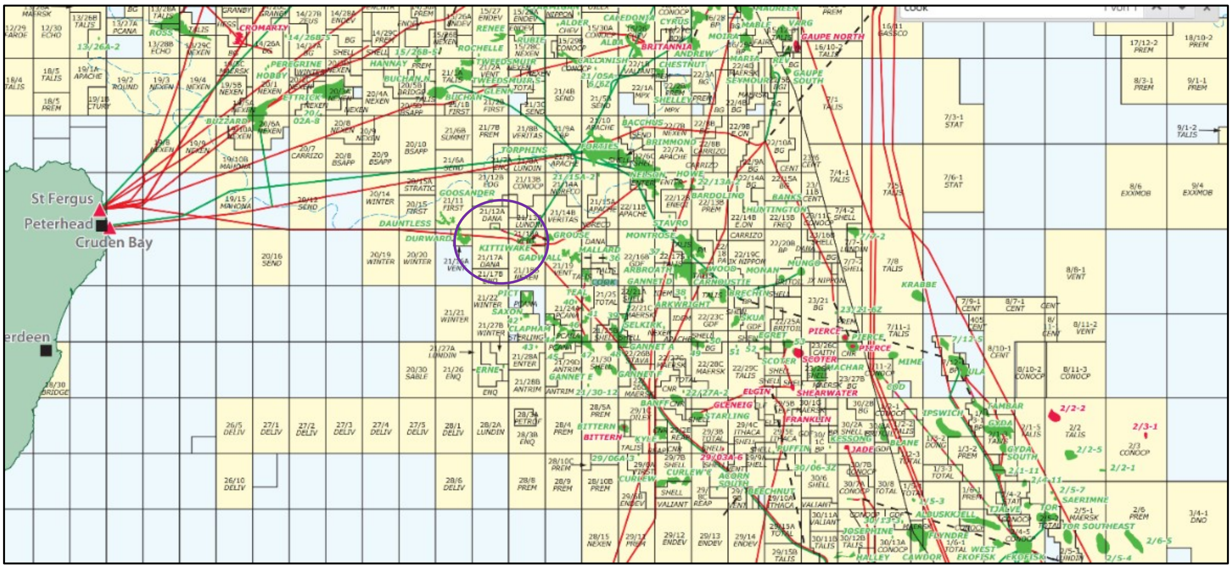


Figure 42: Exact location of the analyzed well from the Offshore Magazine (2013)

7.2 Analysis

The third objective is to analyze data of an offset well to the observed and investigated lithology of Dorset and Somerset. The well that is analyzed is a well from the cook field in the North Sea. The analyzed well 21/20a-2 was drilled by Western Oceanic in 1983 for the operator Shell.

The analyzed well is a vertical well with the target zone at a depth of 12500 ft. The data that is used in this investigation for the geology is log data. The available logs are gamma ray, resistivity, porosity and density log. Additionally used are recordings about gas content, Rate of Penetration (ROP), Weight on Bite (WOB) and Revolutions per Minute (RPM).

Furthermore information about the pressure, partially about the used equipment and to a small extend about the daily reports are available.

All of this data is investigated and conclusions about the solutions for the associated geological drilling problems are drawn.

7.3 Geology of the Offset Well and its implied Drilling Challenges

The Geology of the offset well is documented from 700 m downwards. It starts in the Quaternary and terminates in the upper Triassic. In this region there is a gap from the upper Jurassic to the upper Triassic, meaning that the layers of the lower Jurassic are missing. This could be due to erosional processes in the times of deposition or due to the lack of sediment supply from the hinterland. The missing lower Jurassic contains the layers of the Bridport formation and the Blue Lias formation, these layers are observed in the fieldtrip. Formations comparable in this strata to the ones observed in the fieldtrip are the sands of the Humber Group, the sands of the Nordalad Group and the Kimmeridge Clay. The data that is available gives a good insight of the lithology of this well.

Nordaland Group

The Nordaland group from 700 ft to 4100 ft is the highest formation in the succession of the well. It is set in the Pleistocene, Pliocene and Miocene. These formations are located in the Quaternary and Tertiary.

700 ft.-1300 ft.

This part contains a medium sandstone. It is sub-angular to angular, well sorted and has shell fragments and wood fragments in it. Additionally it is slightly calcareous.

The Gamma Log shows a rather blocky log pattern, which indicates a constant energy level.

The fossils prove that it must be a marine environment of deposition. The origin of the wood fragments could be drift wood from currents or maybe could also have a glacial background.

Drilling through this sandstone is a challenge due to several reasons. It is a rather porous sandstone and therefore lost circulation is an issue. The mud has to be designed to provide a good filter cake and to prevent fluid losses. Another important factor is the bit selection, since the sandstone is a calcareous sandstone with varying calcite content. A shallow marine environment of deposition like we encounter here, is always dependent on the sediment supply of the hinterland. Once the supply of terrigenous sediment is reduced the sediment changes from a rather siliceous rich to a calcite rich sediment. This has vast implications on the hardness of the rock and the bit selection. The parts, which have a lower calcite content can be considered more friable and less consolidated, while the parts with more calcite content have a much higher hardness and are rather resilient. The alternating calcite content can't be determined with the gamma log, but the porosity log gives quite a good insight on this. A higher calcite content is associated with a lower porosity, since the calcite cement also precipitates in the pores. The porosity in the sandstone changes quite distinctly and rapidly, this is due to the change in calcite content.

The ROP (Rate Of Penetration) data in this section proves these assumptions, since we see a much higher ROP in the sections with a higher porosity compared to the ROP in the sections with lower porosity. This gives quite a good insight on the fact that even though a formation has a uniform environment of deposition, it can still be rather variable within itself due to changing conditions at times of deposition. Factors contributing to this effect may be climate changes, burial speed and others.

This phenomenon of changing calcite content in the sandstone is also observed in the fieldtrip. In the Bridport Sand formation the characteristics of the sandstone changes very rapidly from a friable sandstone with lower calcite content to a hard and resilient sandstone with a very high calcite content. These rapid alterations pose a difficult challenge, since they are hardly predictable in a formation, that has never been drilled before, due to the fact that they happen in very thin layers of a few centimeters up to two or three meters. This small magnitude makes it impossible to display it in a seismic. **Figure 43** gives an idea about the change in calcite content in the Bridport sand formation and its magnitude.

Figure 43: The grey layers have a higher calcite content. (Hammer held for Scale by Phillip Bailey)

The gas content in this formation is 0%. There are no gas readings recorded at all. The pore pressure in this part is equal to the hydrostatic pressure.

Using Equation 1 from Zoback (2007) the rock strength of this formations is estimated. The value for the porosity is based on the data of the porosity log. The following **Table 10** provides the result for the rock strength correlation.

Formation Lithology	UCS [Mpa]	Hardness
High Calcite Sandstone	137	Strong
Low Calcite Sandstone	23	Weak

Table 10: Rock strength data

1300- 4100 ft.

This part consists mainly of claystone. In the upper region there are several layers of sandstone. The clay is dark grey and blocky. Partially it is calcareous and even silty. There are occasional stringers of soft dolomitized limestone. These sediments were deposited in a deep marine environment of deposition.

Starting at a depth of 2000 ft. there appears shallow gas in the claystone. This has to be considered when drilling through this formation. The gas reading ranges between 2.5 and 5 %. There are hardly any peaks and the average gas reading can be considered around 2%.

At a depth of around 3000 ft. the formation becomes an abnormal pressure zone. From this zone downwards overpressure is encountered.

When drilling through this formation the mud has to be designed properly. Since this formation has a vast amount of clay minerals an Oil Based Mud (OBM) or a Synthetic Based Mud (SBM) must be used, in order to guarantee wellbore stability and prevent clay swelling.

The rock strength of this section is estimated using Equation 2 with porosity data from the porosity log. **Table 11** shows the result of the correlation.

Formation Lithology	UCS [Mpa]	Hardness
Mudstone	52	Medium

Table 11: Rock strength data

Hordaland Group, Montrose Group and Rogaland Group

These groups are set in a depth of 4100 ft. to a depth of 8900 ft. They appear in the Miocene, Oligocene, Eocene and Paleocene. They are all part of the Tertiary.

4100- 8000 ft.

In this part of the Hordaland Group there is a variation of claystone and limestone. In the upper region there are massive bands of claystone. These bands have a thickness of a few hundred feet. They are non calcareous, silty in part, firm and blocky. Generally they have a dark and grey color.

Starting from a depth of around 5000 ft. the succession changes from claystone to a mixture of claystone and limestone. This limestone is often dolomitized and therefore very hard.

The ROP data shows clearly a rapid increase of drilling speed in the calcite layers. This can be an indication for an improper bit design. The chosen bit obviously works significantly better in the harder calcite formation than in the softer clay formation. A bit for medium hard formations may show a better performance.

In order to drill through this section the choice of bit is really important, since it has to show a good performance in hard and soft formations.

For the mud selection the high content of clay minerals has to be considered. It is of utter importance to select an inhibitive mud system to prevent clay swelling and to guarantee wellbore stability.

Another key factor is the location of the casing shoe in this formation. The layers change quite rapidly, since they are not very thick, it is desirable to find a location with a consistent lithology. It is not wanted that the casing shoe is set at the bedding plane of 2 different rock types.

The gas shows are similar to the formations above. The average value of total gas is around 2,5%.

The rock hardness is evaluated using both Equation 2 and Equation 3 from Zoback (2007) based on data from the porosity log. The following **Table 12** shows the results for the rock strength correlation.

Formation Lithology	UCS [Mpa]	Hardness
Mudstone	52	Medium
Limestone	117	Strong

Table 12: Rock strength data

8000-9000 ft.

In this region there occur layers of sandstone. In the upper part the sandstone is a medium sand with a moderate sorting and a decent porosity. In the lower part the sandstone becomes more fine grained and friable.

This layer is a potential reservoir layer, but the resistivity log indicates a very low value and therefore it does not contain any oil or gas.

Another good indicator that this is no reservoir, is the gas reading which is very low in this region, it shows values of around 1 % of total gas or even a bit less.

Between the layers of sand there are again layers of hard limestone, which is a challenge for the bit. It has to show a good performance in hard and soft formations.

The environment of deposition is open marine. The deposition of the sands is dependent on the sediment supply from the hinterland.

Using the Equations 1-3 from Zoback (2007) the hardness of the rock is estimated. The following **Table 13** shows the results of the correlation

Formation Lithology	UCS [Mpa]	Hardness
Mudstone	52	Medium
Limestone	117	Strong
Sandstone	61	Medium

Table 13: Rock strength data

Chalk Group

The Chalk Group is set at a depth of 8900 ft. to a depth of 10550ft. It is part of the Maastrichian, the Campanian-Turonian and the Cenomanian. They are all of Cretacious age.

8900- 10550 ft.

The upper part of this section contains around 200 ft. of chalk followed by 80 ft. of marl. Underlying these two layers is a 1000 ft. thick layer of chalk, followed by 300 ft. of marl and 150 ft. of chalk.

The chalk has a creamy white color. It is non uniform partly it is a hard and brittle limestone and partly it is very soft and chalky. It has a very low porosity to no porosity. There are some gas shows in this formation, including shows of hydrogen gas.

The Marl that appears in the upper part is dark, grey and earthy. It has 70 % calcite content and 30% clay minerals.

The Marl that appears in the lower part is brown to red. It has around 30-50% clay minerals and 50-70% calcite. It is rather soft and amorphous.

The Chalk Group is a challenge, since the limestone is very hard and resilient, while on the other hand the marl is soft and amorphous. Additionally the high clay content is again an issue for clay swelling and wellbore stability.

The total gas reading averages around 1% or even less, but there are several hydrogen shows. This has to be considered since hydrogen is a very explosive gas.

The rock strength of this section can be found in the following **Table 14**.

Formation Lithology	UCS [Mpa]	Hardness
Limestone	120	Strong

Table 14: Rock strength data

Cromer Knoll Group

The Cromer Knoll Group is set from 10550 ft. to a depth of 11855 ft. It is part of the Albian, Late Barremian, the Middle Barremian, the Late Hautervian, the Early Hautervian, the Valanginian and the Early Valanginian. They are all part of the Cretacious.

10550- 11460 ft

The upper part of this section is made up of claystone. The claystone is red to brown and has around 60 % clay minerals, 30 % quarz silt and 10 % carbonaceous material. Some parts also contain glauconite. Glauconite is an authigenic mineral, which means that it is deposited during the sedimentation process of the rock in situ. Glauconite is deposited in a marine environment of deposition. The high content of clay minerals is an issue for clay swelling. The mud has to be designed in an inhibitive way, in order to prevent any reaction of the formation with the mud.

In the middle part of this section there appear stringers of hard dolomite, followed by moderately hard layers of claystone. This alternating rock hardness needs to be considered for the bit design, as it has to be able to drill through a formation of non-uniform rock hardness.

In the lower part there are sandstones. They are loosely bound, well sorted and fine grained. They have a clay content of around 10%. They have a very poor porosity and eventually they are grading to siltstone.

From a depth of 10600 ft. the abnormally high pressure gradient increases significantly and therefore narrows the mud weight window quite extremely. This makes it difficult to drill the sections below, since it limits the possibilities to adapt the mud weight and requires a way higher amount of precision in the operations.

The rock strengths for this section can be seen in the following **Table 15**.

Formation Lithology	UCS [Mpa]	Hardness
Mudstone	52	Medium
Limestone	120	Strong
Sandstone	140	Medium

Table 15: Rock strength data

11460- 11850 ft.

This part contains a soft siltstone. This siltstone is grading to a claystone. The claystone is soft blocky and calcareous. There is a trend in the calcite content in this claystone, increasing it downwards.

Underlying the claystone there is a limestone. This limestone is hard, firm and blocky.

This section contains very strong gas readings, with an average total gas content of 3%.

The rock strength in this section was estimated and the results are presented in **Table 16**.

Formation Lithology	UCS [Mpa]	Hardness
Mudstone	52	Medium
Limestone	84	Strong

Table 16: Rock strength data

Humber Group and Below

The Humber Group reaches from a depth of 11850 ft. to 12700 ft. It is part of the Late Volgian, the Early Volgian, the Kimmeridgian and the Late Oxfordian. They are all part of the Late Jurassic. Below the Humber Group there is the Rhaetian of the upper Triassic.

11850-12300 ft.

This section is the most interesting one in the whole well, since it contains the hydro carbon bearing layers.

The upper part consists of 80 ft. of shale. This shale is known as the Kimmeridge Clay formation. It is an extremely important source rock in the North Sea. Many reservoirs in the North Sea contain hydrocarbons due to primary migration from the Kimmeridge Clay. This formation contains 80% clay minerals, 0-15% calcite and 5-20% bituminous organic matter. With up to 20% TOC it is of extremely good source rock quality. The shale is black in color, fissile, hard and blocky. For drilling through this shale the mud system has to be inhibitive and mustn't allow any reaction of the clay with water. During the fieldtrip a similar formation is analyzed. This formation is the Blue Lias formation of the lower Jurassic found in Lyme Regis. **Figure 44** gives an idea about the properties of this rock type. The organic content is so high that it is full of organic matter and even fossils. The smell is strong and bituminous. It is rather fissile, this means that it has very thin layers along which fractures are easily induced.

Figure 44: Visualization of the fissile layers in the shale formation.

Underlying the shale there are layers of siltstone that have stringers of dolomitic limestone between them.

The siltstone is soft and friable and it has a poor porosity. It has some residual oil content, but the petrophysical properties are not high enough for development.

The layers of limestone are very hard and have also got a very poor porosity.

The rapidly changing hardness of the formations in this section need to be considered in the bit design.

At a depth of 12500 ft. there is the reservoir sandstone layer. The sandstone is a quartz sandstone with a fine to rarely medium grain size. It is angular to rounded, grain supported and poorly cemented. The porosity is very good to good. With the depth the calcite content increases and therefore the porosity decreases.

In these sand layers the ROP shows a strong increase. This increase can be correlated with the high overpressure in the reservoir layer. A high overpressure is linked to an ROP increase since it reduces the “chip hold down effect”, which is important for hole cleaning. It is to be stated that such an increase of ROP is also a sign for a kick and needs to be handled carefully.

This section has the highest gas readings of up to 10% of total gas. The gas content occurs in peaks meaning, that the average gas content is around 3%. This high gas content has to be handled correctly in order to prevent any well control issue.

The rock strength in this section was estimated using Equation 1-3 form Zoback (2007). The following **Table 17** shows the results.

Formation Lithology	UCS [Mpa]	Hardness
Shale	20	Very Weak
Limestone	84	Strong
Sandstone	38	Weak

Table 17: Rock strength data

12300-13100t.

This section contains a siltstone that is gradually fining to a claystone.

The siltstone is soft, friable and calcareous. Partially it is sandy and there are traces of limestone.

At a depth of 12900 ft. it is purely claystone. This claystone is blocky, silty, hard and well cemented.

The gas reading of this section is quite high and shows values of up to 6%.

The rock strength in this section was evaluated using Equation 2 from Zoback (2007). The following **Table 18** provides the results.

Formation Lithology	UCS [Mpa]	Hardness
Claystone	52	Medium

Table 18: Rock strength data

Reservoir Section

The reservoir is a sandstone reservoir. It consists of medium to fine sand. The reservoir is located from a depth of 12100 ft. up to a depth of 12300 ft. The reservoir quality decreases with depth, since the grain size decreases and it becomes more and more cemented. In the upper part it has a moderate porosity, which decreases with depth. The OWC (Oil Water Contact) is located at a depth of 12200 ft. The reservoir is an oil reservoir.

8. Well Plan used by Western Oceanic

8.1 Trajectory

The target of the well is in the Humber Group, which is set in the upper Jurassic. The target is a medium sandstone with a thickness of 180-200 ft. The total depth of the well is 13150 ft. and it has a vertical trajectory. **Figure 45** shows a seismic image of the location including the trajectory of well 21/20a-2.

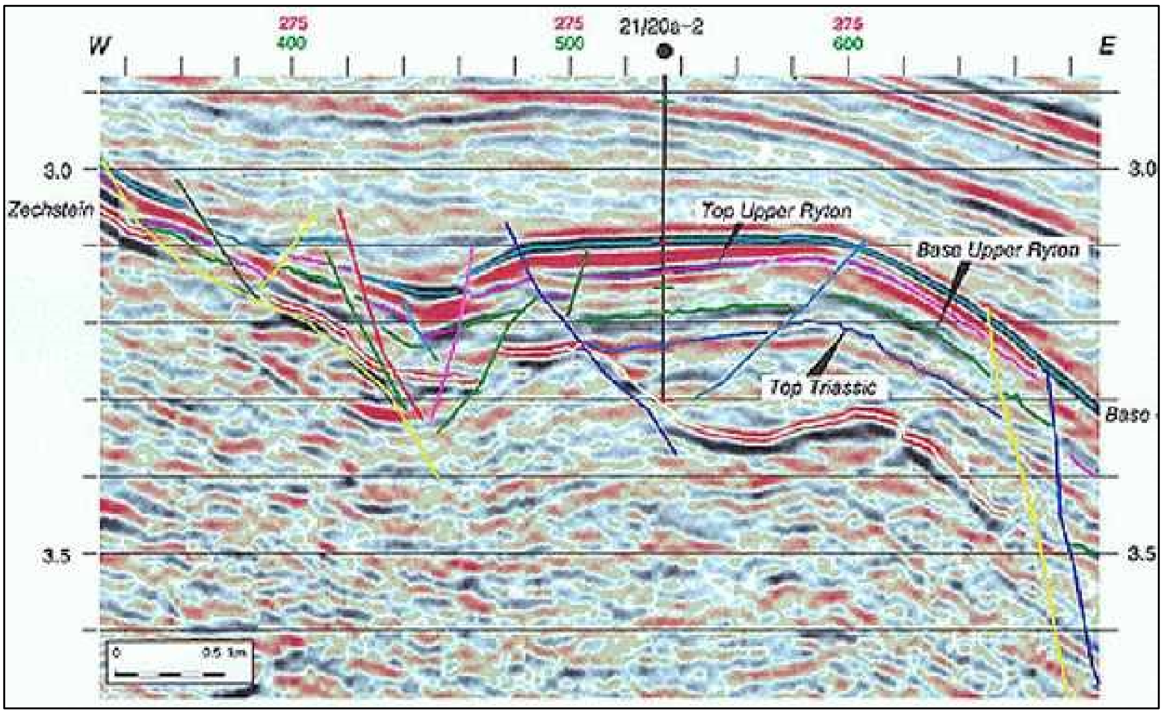


Figure 45: Seismic image of the trajectory of the vertical well 21/20a-2

8.2 Mud Weight Window and Casing Setting Depths

The casing schematic is done according to the available pressure data **Fig.(46)**. The mud logging data is provided by Anadrill mud logging services owned by Schlumberger. For the fracture pressure data from offset wells is used. Figure 5 contains the fracture pressure and the pore pressure. Additionally the grey line indicates the normal hydrostatic pressure, in order to visualize the amount of over pressure. The formations do not contain any hydrogen sulfide or carbon dioxide, therefore regular casing grades are used, since there is not any need of special corrosion protection.

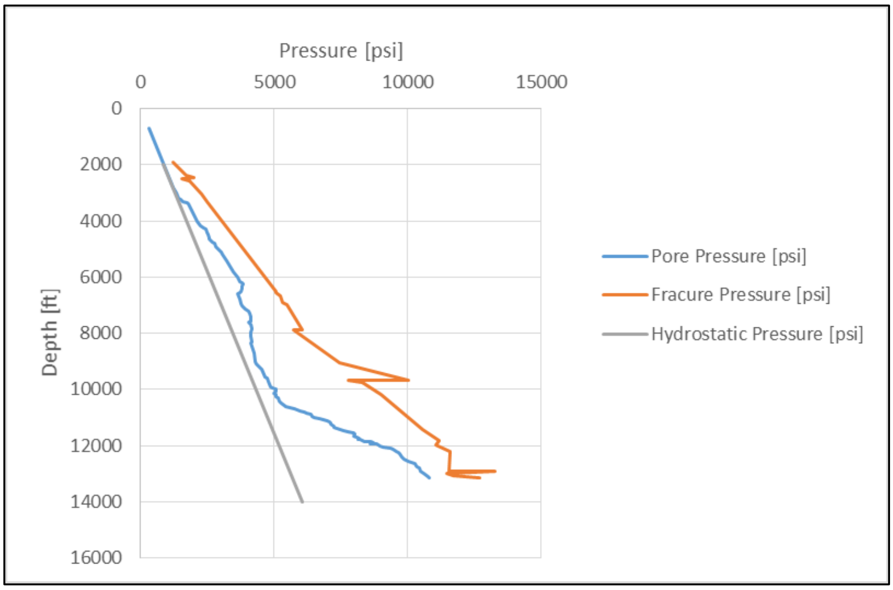


Figure 46: Pressure data

The well contains a total of five sections. It has a conductor casing, a surface casing, two intermediate casings and a production liner

The casing schematic is the following:

- 36” hole ➔ 30” casing ➔ setting depth 670 ft.
-
- 26” hole ➔ 20” casing ➔ setting depth 2020 ft.
-
- 17 ½” hole ➔ 13 3/8” casing ➔ setting depth 6525 ft.
-
- 12 ¼” hole ➔ 9 5/8” casing ➔ setting depth 11453 ft.
-
- 8 3/8” hole ➔ 7” liner ➔ setting depth 13160 ft.

Table 19 presents the data of the used casings, including the grades and nominal weights.

Casing Data		
Size	Quality	Weight
[inch]	[-]	[lb./ft.]
30"	X-52	310
20"	K-55	94
13 3/8"	L-80	72
9 5/8"	P-110	53,5
7"	P-110	29

Table 19: Casing data

8.3 Mud Systems

Conductor Section 36”

The first section up to a depth of 670 ft. is drilled with sea water and bentonite. This is a common practice in offshore operations. The conductor section is drilled without any Blow out Preventer (BOP) and the cuttings are disposed on the sea floor, due to this reason only sea water is allowed to be used in order to prevent any pollution to the in situ eco systems

Since it is drilled without a BOP and with sea water there are no logs run and therefore there is no detailed information about the lithology of the formations encountered in this section.

Surface Section 26”

The surface section is set from 670 ft. to a depth of 2020 ft. This section contains mostly fine to medium sands and clays. In order to drill this section safely and successfully the mud system needs to have filtration loss control, due to the partially permeable sands and it needs to be inhibitive to prevent reactions with the clay minerals. **Table 20** shows the properties of the mud used in this section.

Mud Data		
Property	Value	Unit
Mud Weight	10,5	[ppg]
Viscosity	60	[cp]
Plastic Viscosity	20	[cp]
Yield Point	8	[psi]
Gel Strenght	4/7	shear 10s/10min
Chlorites	not Available	[ppm]
Oil Content	71	[%]
Solids Content	10	[%]
Oil Water Ratio	not Available	[%] of liquid

Table 20: Mud properties for the surface section

This mud system is an Oil Based Mud (OBM), with an oil content of 71%. This high oil content is needed in order to prevent any reaction whatsoever of the clay minerals with the drilling mud. An OBM is inhibitive to clay reactions, since its continuous phase is base oil and not water. The water that is present in the OBM is a brine with a high chloride content. Usually the chlorides come from potassium chloride salts. These salts help preventing the hydration of the clay minerals.

First Intermediate Section 17 ½”

The first intermediate section is set from a depth of 2020 ft. to a depth of 6525 ft. This section contains clay stones with multiples stringers of dolomite and limestone. There are no permeable formations like sandstones present, ergo fluid losses are not an issue. The main challenge for the mud system in this formation is the high content of clay minerals in the formations. **Table 21** shows the data for the mud for this section.

Mud Data		
Property	Value	Unit
Mud Weight	11,7	[ppg]
Viscosity	73	[cp]
Plastic Viscosity	37	[cp]
Yield Point	20	[psi]
Gel Strenght	10/15	shear 10s/10min
Chlorites	300000	[ppm]
Oil Content	62	[%]
Solids Content	18	[%]
Oil Water Ratio	76/24	[%] of liquid

Table 21: Mud properties for the first intermediate section

This mud system is an OBM with a very high chloride content in the brine. This chloride content prevents the reaction of the clay minerals with the mud.

Second Intermediate Section 12 ¼"

The second intermediate section is set from a depth of 6525 ft. to a depth of 11453 ft. This section contains in the upper part mainly clay stones with occasional stringers of limestone and dolomite, in the middle part it contains sandstones and in the lower part it contains chalk and marl. The challenges for the mud design in this section are the fluid loss control properties in the permeable sands and the reactivity of the clay minerals in the clay stone and the marl. **Table 22** shows the properties of the mud for this section.

Mud Data		
Property	Value	Unit
Mud Weight	13,9	[ppg]
Viscosity	69	[cp]
Plastic Viscosity	39	[cp]
Yield Point	28	[psi]
Gel Strenght	13/27	shear 10s/10min
Chlorites	295000	[ppm]
Oil Content	60	[%]
Solids Content	23	[%]
Oil Water Ratio	78/22	[%] of liquid

Table 22: Mud properties for the second intermediate section

This mud system is again an OBM with a very high saline brine to prevent clay swelling.

Production Section 8 3/8"

The production section is set from a depth of 11453 ft. to a depth of 13160 ft. This section contains in the upper part the Kimmeridge Clay formation. This is a shale formation with a very high clay content. The shale is followed by the reservoir sandstone. This sandstone is permeable and it gradually changes into a siltstone of inferior permeability. This is the most critical section for the mud, since there is a highly reactive shale formation and permeable sandstone that mustn't be contaminated. It is of utter importance to prevent any clay reaction with the mud, but also prevent excessive fluid losses in the formation that might damage the reservoir. **Table 23** shows the mud data for the production section.

Mud Data		
Property	Value	Unit
Mud Weight	16	[ppg]
Viscosity	62	[cp]
Plastic Viscosity	35	[cp]
Yield Point	20	[psi]
Gel Strenght	13/27	shear 10s/10min
Chlorites	331000	[ppm]
Oil Content	58	[%]
Solids Content	23	[%]
Oil Water Ratio	86/14	[%] of liquid

Table 23: Mud properties for the production section

This OBM system has a huge concentration of chlorides in the brine. This is necessary since the drilled formation is a shale with a vast amount of clay minerals and thus a high swelling potential.

8.4 Bit Selection

Conductor Section 36”

There is no information about the bit selection available. It can be assumed that a standard 26” roller cone with a 36” hole opener was used before the conductor was set.

First Intermediate Section 26”

This section is drilled with a Smith SDT roller cone bit. This bit is for soft formations with a small compressive strength.

Second Intermediate Section 12 ¼”

The upper part is drilled with a Smith SVH roller cone bit for hard formations

The lower part that contains the chalk formation is drilled with a Smith F2 TCI bit for soft to medium hard formations

Production Section 8 3/8”

This section is drilled with various roller cone bits including Smith SVH for hard formations, Smith SDGH for soft formations and Smith F2 TCI bit.

9. Well plan for the outcrop layers

9.1 Task Description

The task for the second objective is to plan a hypothetical well on the outcrops. For this task a few general assumptions have to be taken into consideration in order to provide a realistic scenario. Since the individual outcrops only represent separate formations of up to 40 m in height, it makes no sense to create a well plan for such a small layer. Additionally upscaling is not a viable option. In order to create a realistic scenario the data of a real well is chosen as reference data. The selected data originates from the North Sea well 21/20a-2 that was drilled by Western Oceanic in 1983. It is important to choose a well that is located in the North Sea, since the formations in the analyzed outcrops can also be encountered in the North Sea. Unfortunately the lithology in the provided data lacks the Lower Jurassic formations that are analyzed in the field. Below the Upper Jurassic occurs the Upper Triassic. This could be for instance due to lacking sedimentation at this time or due to excessive erosion. In the scenario for the hypothetical well the Upper Triassic is replaced with the Lower Jurassic, namely the Bridport Sand Formation is included as an additional target horizon. This scenario is not far off reality and could exist in the North Sea. For the creation of the well plan the software package Landmark by Halliburton is used.

9.2 Trajectory

The trajectory of the well follows the trajectory of well 21/20a-2. The available survey data is used to create the well path in Halliburton Compass. It is a simple vertical trajectory with a TVD (True Vertical Depth) and an MD (Measure Depth) of 13.000 ft. **Figure 47** shows a plot of the trajectory. The trajectory can stay the same, since there are no problems occurring with deviation of the planned well path due to dipping formations.

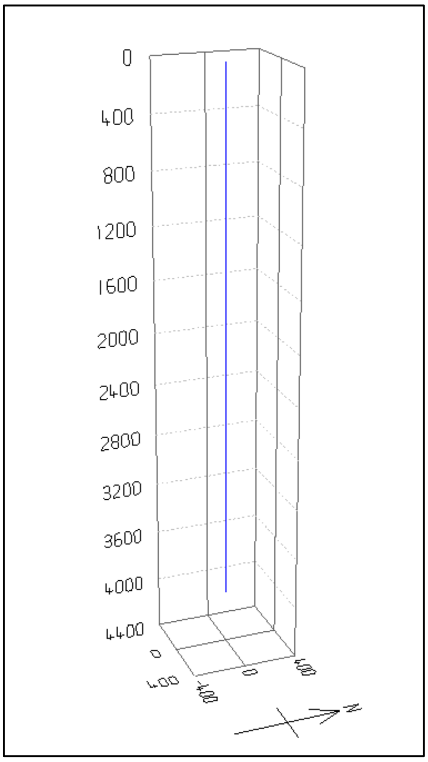


Figure 47: The trajectory of the outcrops follows the trajectory of well 21/20a-2

9.3 Casing Schematic

The casing schematic of the well consists of five different sections. The following **Table 24** shows detailed casing schematic information. For the casing selection a smaller solution is provided compared to the one from Western Oceanic. This smaller diameter solution has the advantage that it is cheaper and can be drilled faster than a larger diameter. For an exploration well a smaller diameter is quite useful, although it is to state that this is not a slim hole solution.

Section	Diamter [inch]	Setting Depth [m]
Conductor	30	213
Surface	18 5/8	610
First Intermediate	11 3/4	1981
Second Intermediate	8 5/8	3475
Production	5	3993

Table 24: Casing schematic information

Figure 48 illustrates the casing schematic and gives insight on the cement column heights.

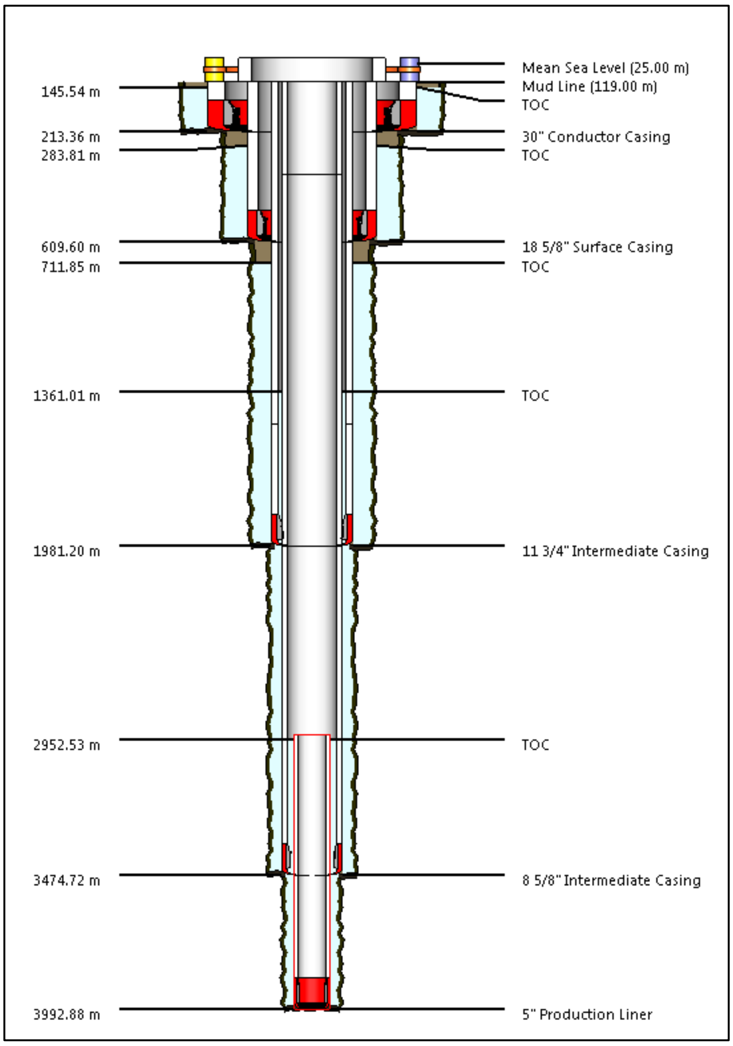


Figure 48: Casing schematic

The tri-axial check for the provided casing design is done in the software Stress Check. The results for these calculations can be found in Appendix A.

9.4 Bottom Hole Assembly (BHA)

The BHA for the surface section consists of a roller cone bit, followed by a near bit stabilizer and a bent housing motor. Additionally there is a measurement while drilling tool (MWD) located above, in order to be able to follow the given trajectory. For the case of stuck pipe a hydraulic drilling jar is also included. The motor and the MWD tool are not absolutely necessary, but they are extremely useful in this operation, since they provide an increased amount of accuracy.

The BHAs of the other sections below have similar components, but of course they vary in size. Unfortunately the software package provided to the university by Halliburton has a limited tool catalogue. This is the reason, why every BHA has a roller cone bit in the illustration, even though the recommended bit is a different one. The software doesn't provide any other options for the required sizes, therefore the chosen bits are provided separately in the next part.

The following **Figure 49** illustrates in detail the components of the drill string for the surface section.

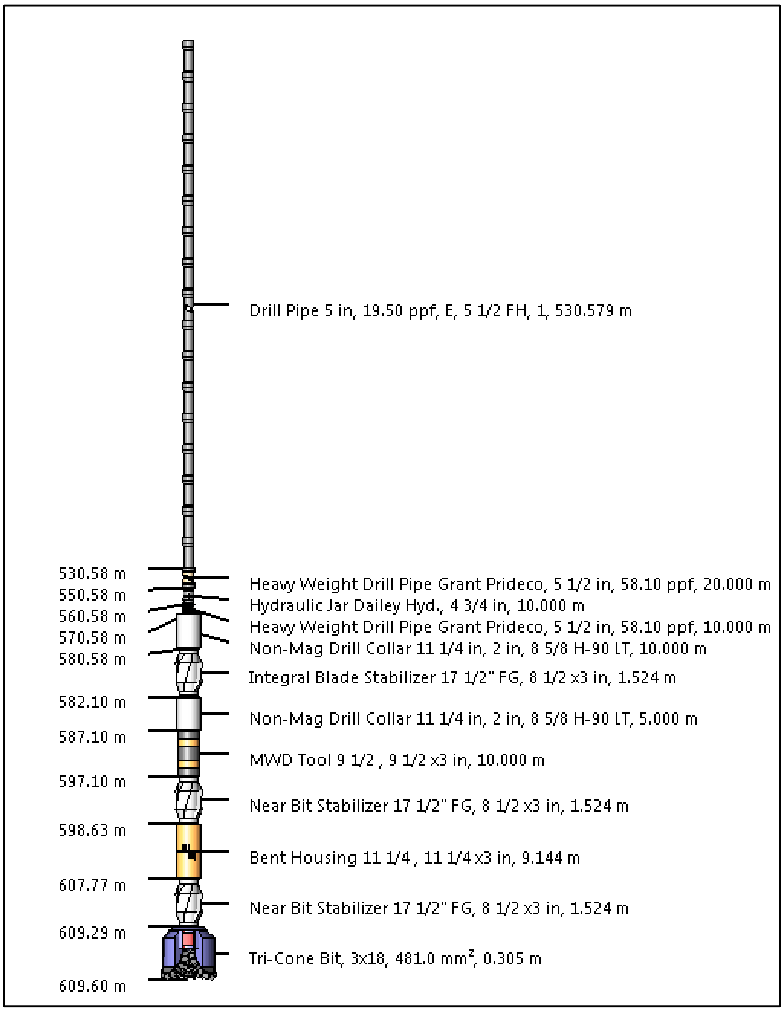


Figure 49: BHA information

The torque and drag calculations for the BHA of the different sections is provided in Appendix A.

9.5 Bit Selection

The bit selection is based on the geology of the sections that have to be drilled. The following **Table 25** shows the chosen bits and provides insight on their advantages for the challenges created by the formations. All the selected bits are products of the Smith Company owned by Schlumberger and can be found in the product catalogue.

Section	Recommended Bit	Formation Bit Challenge	Advantage
Surface	24" Explorer Premium TCI Roller Cone Bit	Varying UCS from 23-137 MPa	Shows a superior performance in soft to hard formations
First Intermediate	16" Standart PDC Matrix Bit	Different rock types with varying hardness. Soft claystone with hard stringers of limestone	Offers optimum performance for varying rock types
Second Intermediate	10 5/8" Explorer Premium TCI Roller Cone Bit	First part contains hard carbonates, while second part contains soft chalk	Shows a superior performance in soft to hard formations
Production	6 1/2" Spear Shale-Optimized Steal-Body PDC Bit	Kimmeridge clay poses multiple challenges to the bit such as bit balling or plugged nozzles	Reduces bit balling and cuttings that pack to the bit in shale/clay formations

Table 25: Bit selection

9.6 Hydraulic System

The information about the design of the hydraulic system can be found in Appendix A. This includes insight about the used mud system, pump rates and detailed pressure loss calculations. Furthermore all calculations are supported by graphs and pie charts of the losses.

10. Data Analysis of Eirozes 1 (Offshore West Africa)

The fourth objective is to analyze data from a real well that is drilled in the field with the focus on geological setting and provided drilling solutions. For this particular task an example from the offshore region of West Africa is chosen. The investigated well Eirozes-1 is located in block 4 A around 200 km away from Guinea Bissau. The well was drilled by Premier Oil West Africa in 2007. The following **Figure 50** from Ross (2007) shows the exact location of the well.

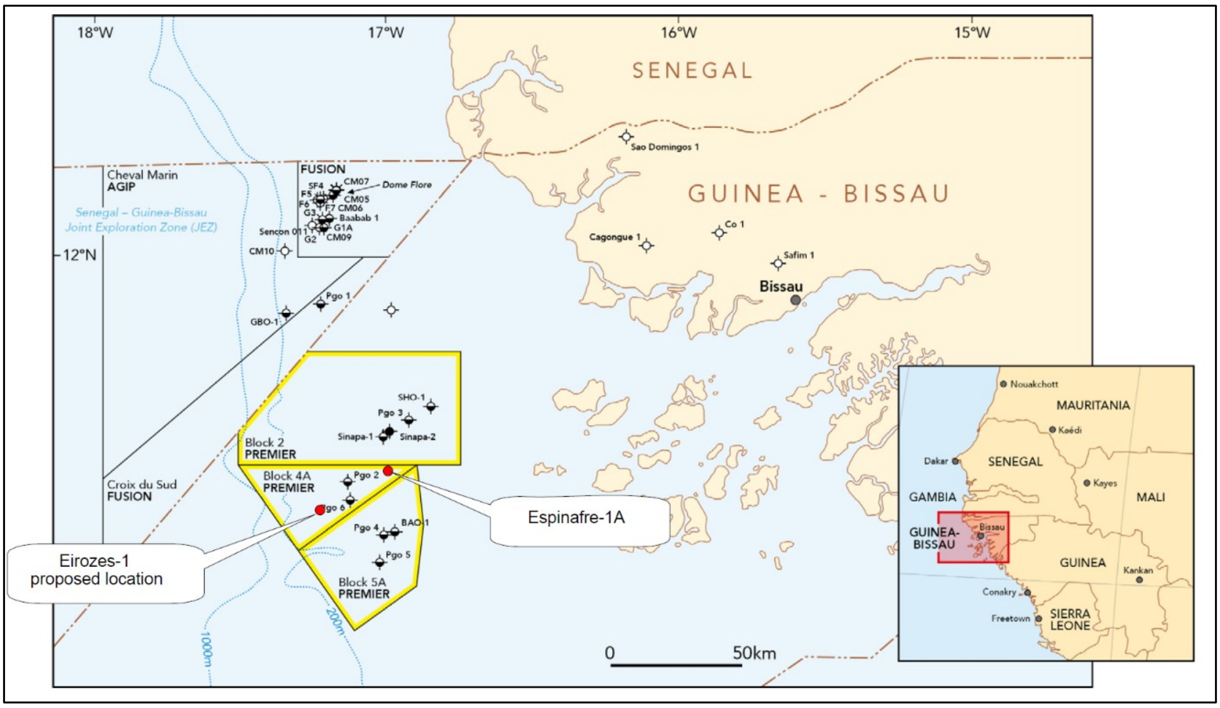


Figure 50: Map including the location of well Eirozes 1

The analyzed well is a deviated well with a TVD (Total Vertical Depth) of 2230 m and a MD (Measure Depth) of 2252 m. The KOP (Kick off Point) is located at a depth of 1200 m. The well is located at a passive continental margin, there is a lot of structural complexity in this region caused by local salt diapirs.

The target zone of the well is the Albian sands of the Lower Cretaceous. These sands truncate towards the north eastern flank of the Eirozes salt diaper and are expected to be a hydrocarbon bearing layer. According to Skelhorn (2007) the salt was deposited in the Jurassic and Triassic time. The rising of the diapirs took place mainly during the Late Cretaceous, when the hinterland and the passive continental margin saw an uplift. As a result of this uplift there was coarse material deposited over the platform area in a shallow marine environment, this new overburden pressure started the mobilization of the diapirs.

For the analysis there are multiple data sources available. Used data is the drilling program by Premier Oil West Africa BV, the geological completion report by Premier Oil West Africa BV, log data and daily drilling reports.

All of this data is investigated and conclusions about the solutions for the associated geological drilling problems are drawn.

10.1 Lithology of the Well Eirozes 1 and its implied Drilling Challenges

The lithology of the well Eirozes 1 is documented starting from a depth of 200 m TVD and downwards to a depth 2230 m TVD. The stratigraphy starts at the Tertiary and terminates in the lower Cretaceous. In the uppermost age the Tertiary the most important formations we find are the Miocene, the Oligocene and the Paleocene formation. Underlying the Tertiary is the Upper Cretaceous. In this age we find the Maastrichian, the Campanian, the Santonian, the Turonian and the Cenomanian formation. The lowermost age is the Lower Cretaceous. In this age we encounter the Albian and the Aptian formation.

Tertiary

The Tertiary age is located from the sea bed up to a depth of 1083 m TVD. This age consists in detail of the Top Miocene, the Base Miocene, the Oligocene, the Middle Eocene, the Lower Eocene and the Paleocene.

Top Miocene 246.5 to 409 m MD

Up to a depth of 200 m there is no information about the lithology available, since the log starts below this line.

The part below 200 m contains a massive sandstone body. This sandstone is loose and not very compacted. It has a medium sorting and a grain size from fine to medium. It has a moderate to good porosity. Generally speaking there is a trend observable in the gamma log that the grain size increases upwards. This bell shape indicates an increased energy level. There are some trace limestones that are encountered. These limestones are mudstones with a very high hardness.

The environment of deposition is shallow marine, since there are occasional macro fossil finds.

The ROP (Rate of Penetration) in this section is constant at a value of 33.0 m/h.

Under the sandstone this section consist mainly of a limestone with varying characteristics. It varies between a packstone, a grainstone and a mudstone. The formation has a moderate to high hardness and there appear occasional traces of a soft and slightly sticky claystone.

The main challenge when drilling through this section is the possibility of fluid losses. Since the sandstone is not cemented and has a medium porosity it is possible to face severe fluid losses when drilling through this formation. In order to prevent losses the mud has to be designed to provide a good filter cake. Ergo it is essential to have good bridging particles and LCM (Lost Circulation Material) in the mud.

An additional challenge is the varying rock hardness, which is an issue for the bit design of this section. The bit has to be designed to be able to drill the soft sands and the hard limestones.

For the estimation of the rock hardness of this particular section Equation 1 and 2 from Zoback (2007) are used. The following **Table 26** shows the results of the correlations.

Formation Lithology	UCS [Mpa]	Hardness
Limestone	110	Strong
Sandstone	38	Weak

Table 26: Rock strength data

Base Miocene 409 to 703 m MD

This section consist of a calcareous claystone, with occasional dolomitic clasts. The claystone is very soft, sticky and locally grading to siltstone. The dolomite clasts are well cemented and hard to very hard. Additionally there are thin beds of limestone towards the lower part of this section.

The ROP at this section is 21 m/h and increases in the regions of higher calcite content. The gamma ray log shows a constant energy level.

The biggest issue in this section is the high amount of clay minerals in the formation. The mud system needs to be an inhibitive system that does not allow any reactions of the clay minerals with water in order to prevent swelling and wellbore instability.

The rock strength in this section is estimated using Equation 2 and 3 from Zoback (2007). The following **Table 27** shows the results for the estimates.

Formation Lithology	UCS [Mpa]	Hardness
Limestone	110	Strong
Claystone	52	Medium

Table 27: Rock strength data

Oligocene 703 to 761 m MD

This section is very inhomogeneous and consist of various types of rocks. These rock types are different limestones with occasional stringers of calcareous claystone. The limestone is mudstone or grainstone, which is hard to very hard and in some parts it is silicified and cherty. This chert appears as nodules and is very hard. The claystone is soft and it is clearly visible in the gamma log, since it is represented by large peaks in the log.

The ROP in this section is at an average value of 13 m/h. The main challenge in this section is the hardness of the rocks for the bit design, since we face soft claystone and extremely hard chert nodules. The chert nodules cause very rough drilling conditions. Additionally the mud design has to be inhibitive again, due to the high amount of clay minerals in the claystone stringers.

For the estimate of the rock hardness Equation 2 and 3 form Zoback (2007) were used. The following **Table 28** presents the results of the correlation. The estimate for the chert is based on the Attewell and Farmer (1976).

Formation Lithology	UCS [Mpa]	Hardness
Claystone	52	Medium
Limestone	110	Strong
Chert	>160	Very Strong

Table 28: Rock strength data

Eocene 761 to 998 m MD

This is another section with a varying limestone containing occasional chert nodules, followed by stringers of soft calcareous claystone. The limestone appears in the form of mudstone, packstone or wackestone. It is firm to hard and has nodules or bands of chert in it. The chert is extremely hard.

There is around 1% of background gas present and the average ROP is 19 m/hr.

The drilling challenges for this formation are the same as in the Oligocene. These is the extremely hard chert followed by soft stringers of calcareous claystone, which is an issue for the bit design. Furthermore the mud design needs to be inhibitive to prevent clay reactions.

The rock strength in this section is similar to the Oligocene and can be found in the upper Table 28.

Paleocene 998 to 1146 m MD

The dominating facies in this section is a calcareous claystone with thin limestones grading to calcareous siltstones. The carbonate content in the claystone decreases with depth, this is due to increased terrigenous sediment supply at the time of deposition. There are no chert nodules anymore.

The ROP increases with decreasing carbonate content, indicating that the rock hardness decreases proportionally to the carbonate content.

In this section the mud design is very important, since the high amount of clay minerals can lead to swelling and eventually wellbore instability. For the rock strength estimate of this section Equation 2 and 3 from Zoback (2007) were used. The following **Table 29** shows the results of the estimates.

Formation Lithology	UCS [Mpa]	Hardness
Limestone	84	Strong
Claystone	52	Medium

Table 29: Rock strength data

Upper Cretaceous

The Upper Cretaceous goes from a depth of 1146 m MD up to a depth of 1907.5 m MD. The formations of this age are in detail the Maastrichian, the Campanian, the Santonian, the Turonian and the Cenomanian. All these formations are explained in detail in the following paragraphs.

Maastrichian 1146 to 1240 m MD

This section consists of massive claystone layers with occasional lenses of siltstone and very few small beds of limestone. The claystone is very soft and sticky. It has a high content of clay minerals and tends to swell. The siltstone is also soft and crumbly and parts of it are slightly dolomitic.

There are no hydrocarbon shows in these siltstone lenses and the ROP averages at a value of 30 m/h.

When drilling this formation the most important thing is to have a highly inhibitive mud in order to prevent swelling. Since it is a rather uniform and homogeneous formation with a uniform rock hardness it is not challenging for the bit design. A bit designed to drill a soft formation gives a good performance.

The estimate for the rock strength of this section is done using Equation 2 from Zoback (2007). The following **Table 30** shows the results of the estimate.

Formation Lithology	UCS [Mpa]	Hardness
Claystone	45	Medium

Table 30: Rock strength data

Campanian 1240 to 1678 m MD

The lithology of this formation is similar to the one in the Maastrichian. There are massive claystone bands with small sandy to silty clasts and lenses. The claystone is soft and tends to be sticky. Furthermore it has a high amount of clay minerals with a tendency to swell. The sandstone in the lenses has a fine grain size it is poorly sorted. In consequence of its poor sorting the porosity is low.

The ROP shows also a similar performance and has an average value of 30 m/h. The gamma ray log stays at the same level which indicates a constant energy level.

The issue in this section for drilling is the tendency of the clay to swell due to the high content of clay minerals. Another problem is bit balling, because of the stickiness of the claystone. This has to be taken into consideration for the bit design.

Since the lithology of this section is similar to the previous one the rock strength is also not varying and can be found in Table 30.

Santonian 1678 to 1743 m MD

This section contains claystone, calcareous claystone and to a small part limestone. The claystone is soft and in some parts silty. The limestone that is encountered is a mudstone, which is very hard. The lithology of this section is still similar to the previous sections. There are traces of glauconite found in the claystone. This is a clear indicator of a marine environment of deposition, since glauconite is an authigenic mineral formed during sedimentary deposition.

The ROP in this section is at a value of 24 m/h.

The drilling challenges arise mainly from the claystone. They are the potential swelling of the clay minerals due to reaction with water, which leads to wellbore instability and bit balling due to the soft and sticky nature of the claystone.

The estimate for the rock strength of this section is done using Equation 2 and 3 from Zoback (2007). The results for the estimates can be found in the following **Table 31**

Formation Lithology	UCS [Mpa]	Hardness
Limestone	87	Strong
Claystone	40	Medium

Table 31: Rock strength data

Turonian 1743 to 1857 m MD

This section contains in the upper part mainly claystone with small limestone beds, while in the lower part these limestone beds have a thickness of up to 4 m. The claystone is soft to firm and has a varying calcite content. It is partially grading to siltstone. The limestone beds are mudstones with a hardness of firm to hard. The limestone beds are easily identifiable in the gamma log, since the create peaks in the log pattern.

The ROP in this section is at a value of 23 m/h. There is only very small amounts of background gas present.

In this section a new challenge for drilling is the high variability of the rock hardness. There are very soft layers of mudstone, which are the majority of the section, but there are also hard bands of limestone with a thickness of up to 4 meters. The bit needs to be designed to drill these soft formations efficiently, but also to be able to drill through the hard limestone. The mud has to be also inhibitive to prevent clay swelling and to guarantee wellbore stability.

The rock hardness in this section is similar to the Santonian. The hardness is also not varying to the previous section and can be found in Table 31.

Cenomanian 1857 to 1908 m MD

This section contains claystone, calcareous claystone, limestone and silty limestone. The claystone is soft to firm and has a varying calcite content. Furthermore it is grading to siltstone in some parts. The limestone is a firm to hard mudstone. The mudstone appears in the lower part of this section as beds with a thickness of up to 2 meters.

The ROP in this section is 20 m/h and the background gas is negligible.

Most important for this section is to have an inhibitive mud system to prevent clay swelling and the bit needs to able to drill through the soft and the hard parts of this formation.

Information about the rock hardness of this section can be found in the previous Table 31.

Albian 1901 to 2221 m MD

The Albian formation is the target zone and the potential reservoir layer. There are large beds of sandstone, claystone, calcareous claystone and limestone. The most important layers in this formation are the sandstone layers. The sandstone has a very fine to fine grain size and it is poorly sorted. This poor sorting hand in hand with a calcite cementation leads to a poor porosity in some parts of the sandstone layers. It is to state that the sandstone has a good porosity where there is no cementation and the grains are only loosely bound. The sandstone grades to a siltstone in some parts. The claystone is soft with some glauconite mineral shows and has a variable calcite content. The limestone is a soft and sandy limestone usually grading to a calcareous sandstone.

The ROP in this section is 20 m/h and the background gas is only at a value of around 1 %.

This low background gas and the fact that there are no oil shows is a clear indicator that the expected hydrocarbons can´t be found in this section and that this is no reservoir.

When drilling through this section fluid losses are again an issue, due to the partially high porosity of the sandstone, therefore the mud needs to have a good fluid loss control. Additionally the high clay content requires an inhibitive mud system in order to prevent clay swelling and to provide wellbore stability.

The rock strength of this section was estimated using Equation 1,2 and 3 from Zoback (2007). The following **Table 32** presents the results of the estimated values.

Formation Lithology	UCS [Mpa]	Hardness
Sandstone	40-102	Medium-Strong
Limestone	110	Strong
Claystone	40	Medium

Table 32: Rock strength data

Aptian 2221 to 2252 m MD

The lowermost section is the Aptian formation and consists of claystone, siltstone and sandy lenses. The claystone is very sticky, soft and has a high swelling potential. The siltstone is soft to firm and gradually changes to silty sandstone. The sandy lenses have a fine grain size and a poor sorting. This poor sorting leads to a poor visible porosity. Additionally they have a calcite cement.

The ROP was 15 m/h and the background gas was at a very low level of 1,4 %.

For this last section the most important thing is a mud system designed to prevent clay swelling, since otherwise this would lead to wellbore stability issues.

For the rock strength estimate of this section Equation 2 from Zoback (2007) was used. The following **Table 33** presents the result of the estimate.

Formation Lithology	UCS [Mpa]	Hardness
Claystone	40	Medium

Table 33: Rock strength data

11. Well Plan for Eirozes 1

In the following analysis the well plan of the well Eirozes 1 is presented and the provided solutions are analyzed.

11.1 Trajectory

The target zone of the well is the Albian sandstone formation located at a depth of around 2000 m TVD. This sandstone formation truncates towards the north eastern flank of the Eirozes salt diapir. According to Ross (2007) the original intention was to drill a vertical well, but there is offset well data available that indicates problems due to the formation dip. For this reason the well is drilled as a deviated well with the inclination pointing towards the salt dome in order to reduce the angle between the dip and the trajectory. This has to be done to prevent a deflection of the intended trajectory. Additionally this prevents a reduction of the UCS of the rock since the angle between the trajectory and the drilled layers is 90 degrees. The following **Figure 51** from Ross (2007) shows a seismic image including the most important layers and the trajectory of the well Eirozes 1.

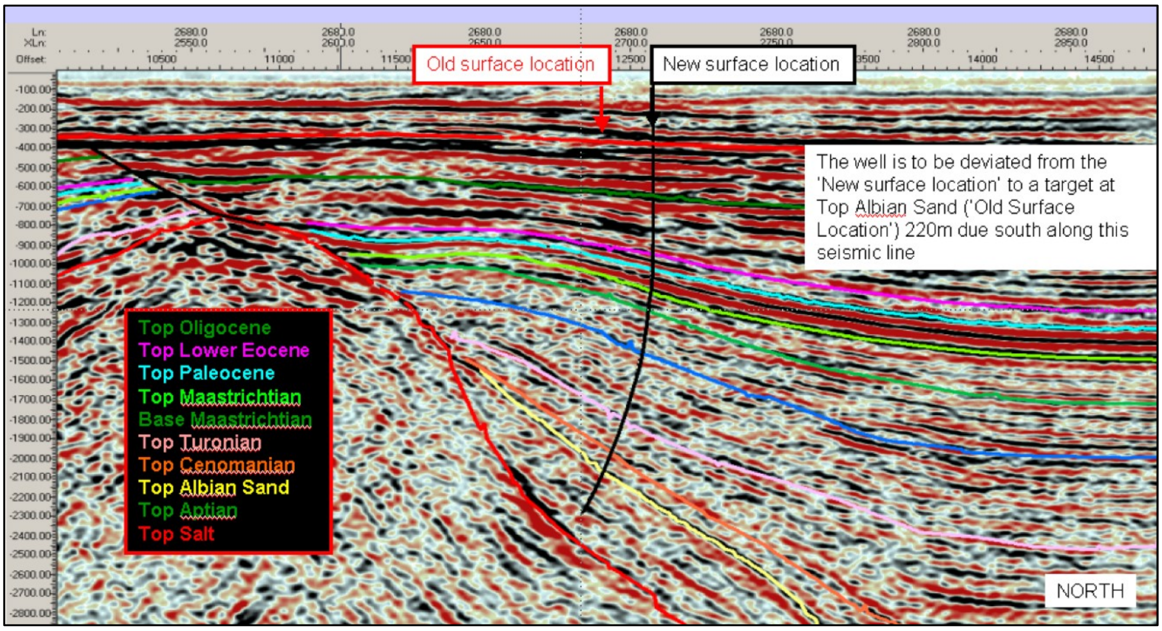


Figure 51: Seismic image including the most important geological layers and the trajectory of the well Eirozes 1

11.2 Mud Weight Window and Casing Setting Depths

Unfortunately the analyzed data does not contain a full mud weight window. The available data of the fracture pressure and the pore pressure is acquired using the d-exponent method and data from offset wells in this region. Based on the available data an estimated mud weight window is created. This mud weight window always takes the worst case scenarios into account and is therefore safe to be used. In this region up to a depth of 2000 m there is not a lot of overpressure present until a depth of 1800 m where the well starts to become moderately over pressured. The following **Figure 52** shows the created mud weight window based on the estimates from Ross (2007).

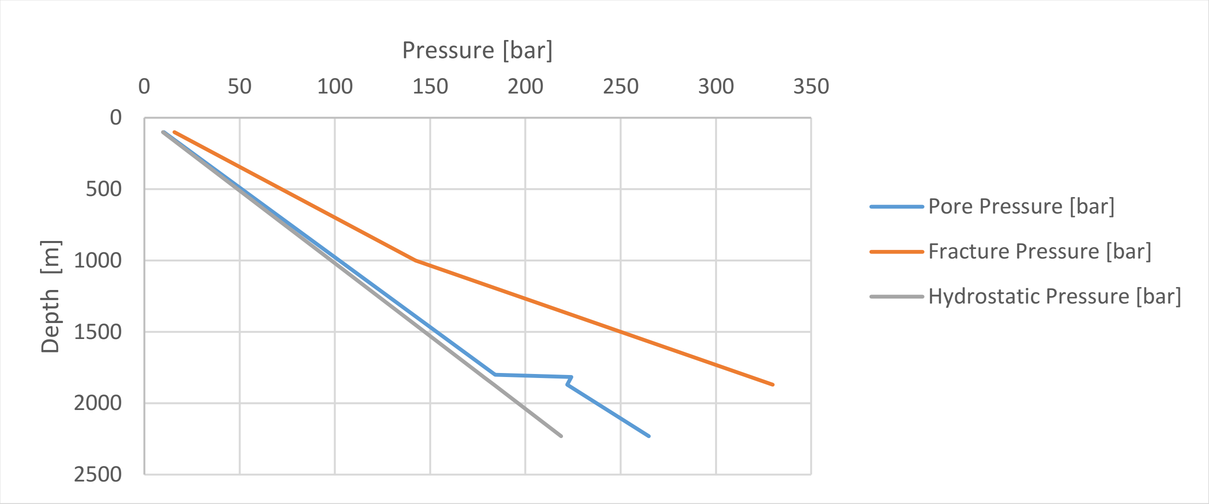


Figure 52: Pressure data of Eirozes 1

The casing schematic for this well is done according to the mud weight window. The well consists of three different sections. A conductor section followed by a surface section and a production section. The first two sections are cased, while the third section remains open hole and is later prepared for plug and abandonment.

The casing schematic was the following:

- 36” hole→ 30” casing→ setting depth at 204 m MD/TVD
- 17 ½” hole→ 13 3/8” casing→ setting depth at 900 m MD/TVD
- 12 ¼” hole→ open hole→ to a depth of 2230 m TVD/2252 m MD

The following **Table 34** shows the used casing qualities.

Casing Data		
Size	**Quality**	**Weight**
[inch]	**[-]**	**[lb./ft.]**
30"	X-52	310
13 3/8"	K55	68

Table 34: Casing qualities of Eirozes 1

11.3 Mud Systems

Conductor Section 36”

The first section up to a depth of 200 m is drilled with sea water and bentonite. The conductor section is drilled without the use of a blow out preventer and the cuttings are disposed on the sea floor. This is the reason that only products that are not hazardous for the environment can be used.

Surface Section 17 ½”

The surface section goes up to depth of 900 m. The lithology of the rocks in this formation creates one main challenge for the used drilling fluid. This challenge is potential fluid losses in the upper part of this section due to permeable sandstone bodies. The following **Table 35** shows the rheological properties of the used drilling mud.

Mud Data		
Property	Value	Unit
Mud Weight	8,6-9,2	[ppg]
Viscosity	45-60	[cp]
Plastic Viscosity	ALAP	[cp]
Yield Point	26	[psi]
Gel Strenght	1/2	shear 10s/10min
Chlorites	not Available	[ppm]
pH	8,5-9,5	[-]

Table 35: Mud properties of the surface section

The mud system is a WBM (Water Based Mud) with bentonite for viscosity and barite as a weighting agent.

Production Section 12 ¼"

This section goes from 900 m to 2230 m TVD. In this section the correct mud design is crucial for the success and safety of the well, since there are massive claystone bodies with highly reactive clay minerals located in this section. Therefore the mud system needs to be inhibitive. The following **Table 36** provides insight on the rheological properties of the used drilling fluid.

Mud Data		
Property	Value	Unit
Mud Weight	11-11,5	[ppg]
Viscosity	45-55	[cp]
Plastic Viscosity	20	[cp]
Yield Point	24-28	[psi]
Gel Strenght	4\10	shear 10s/10min
Chlorites	190000	[mg/l]

Table 36: Mud properties of the production section

The used mud is again a WBM specially designed to provide excellent clay inhibition. This is reached by adding several inhibitive chemicals that prevent clay reactions such as: Ultrahib, Ultracap and Ultrafree by MI Swaco. These chemicals suppress clay hydration and reduce the space between clay platelets so that water molecules will not penetrate and cause swelling.

11.4 Bit Selection

Conductor Section 36 “

This section is drilled with a 26” Smith XR+C bit for soft to firm formations. After the first run a 36” hole opener from Grant was used to widen the borehole

Surface Section 17 ½”

This section is drilled using a 17 ½” Smith GS03BV bit with tungsten carbide inserts. This bit can be used in sections with varying rock hardness.

Production Section 12 ¼”

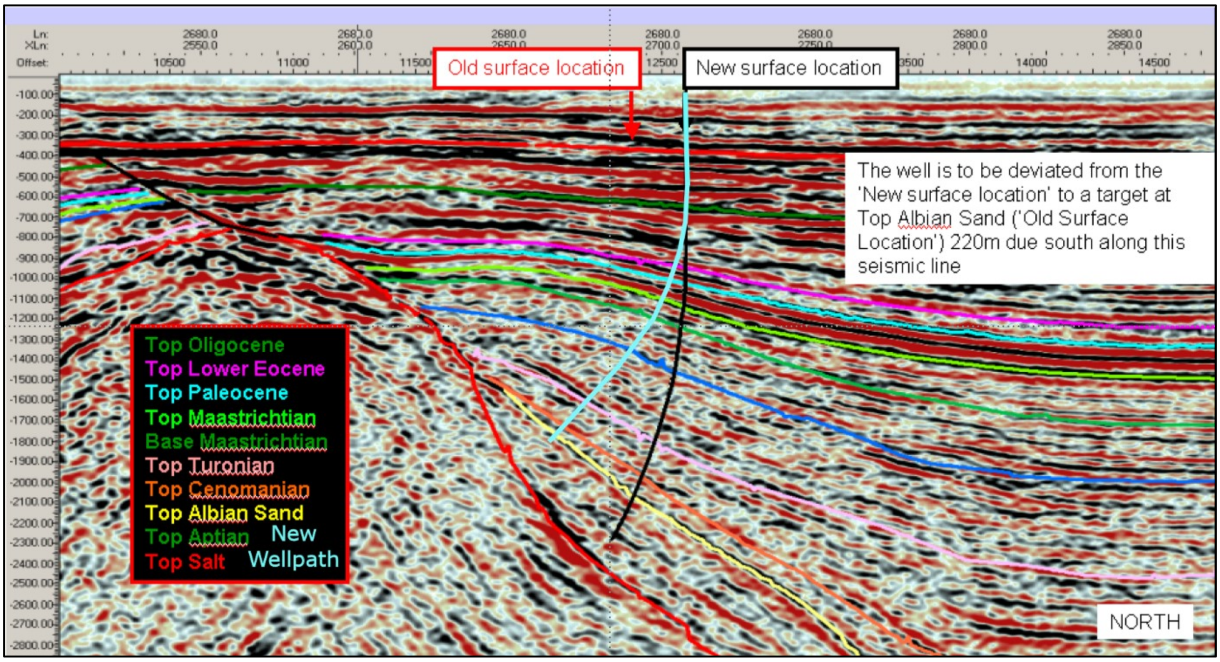
This section is drilled in two runs. In the upper part a 12 ¼” Smith GFSi01BV with tungsten carbide inserts is used. In the lower part 12 ¼ “ Reed DSX616M PDC bit is used.

12. Improved Well Plan for Eirozes 1

In this part an alternative improved well plan for the previous well Eirozes 1 is presented. The improvements are based on the observations that are provided in the data analysis of this particular well. For the improved well plan the software Landmark by Halliburton is used. The software packages utilized are Compass, Casing Seat, Stress Check and Wellplan.

12.1 Trajectory

For this well an alternative trajectory **Fig.(53)** is created. This alternative trajectory has a 400 m long vertical section followed by the kick of point. The target is slightly higher than in the original well plan and is around 500 m away from the surface location. This is chosen since the original well trajectory didn't discover any hydrocarbons in the potential reservoir layer. The new well path has the advantage that in oil and gas migration the hydrocarbons tend to migrate upwards, which makes it more likely to find oil or gas in higher part of the target layer. Additionally the new trajectory is perpendicular to the formation dip, which is the optimum in terms of rock strength and wellbore stability. Furthermore a deflection of the well path due to dipping formation is also reduced.



The well is to be deviated from the 'New surface location' to a target at Top Albian Sand ('Old Surface Location') 220m due south along this seismic line

Figure 53: New well path of Eirozes 1

12.2 Casing Schematic

The casing schematic of the well consist of three different sections. The following **Table 37** shows detailed information about the casing schematic. There are only three sections necessary, since there is not a lot of overpressure experienced before a depth of 1800 m.

Section	Diamter [inch]	Casing Grade	Setting Depth [m]
Conductor	30	X-46	120
Surface	18 5/8	J-55	656
Production	5	K-55	1700

Table 37: Information about the casing schematic

Figure 54 illustrates the casing schematic and gives insight on the cement column heights.

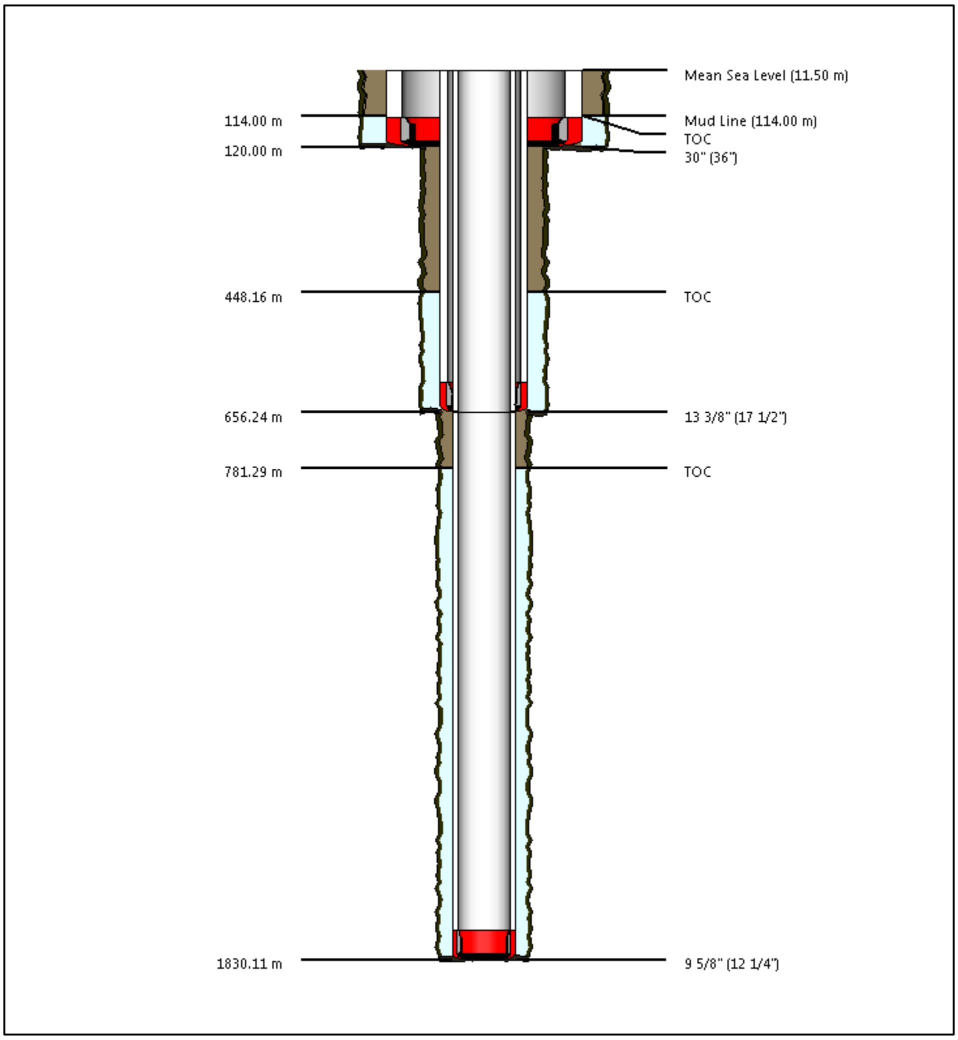


Figure 54: Wellbore schematic

The tri-axial check for the provided casing design is done in the software Stress Check. The results for these calculations can be found in Appendix B.

12.3 Bottom Hole Assembly (BHA)

The BHA for the surface and the production section consists of a PDC bit followed by a near bit stabilizer and a bent housing motor. Additionally there is a measurement while drilling tool (MWD) located above, in order to be able to follow the given trajectory. For the case of stuck

Unfortunately the software package provided to the university by Halliburton has a limited tool catalogue. This is the reason, why every BHA has a roller cone bit in the illustration, even though the recommended bit is a different one. The software doesn't provide any other options for the required sizes, therefore the chosen bits are provided separately in the next part

The following **Figure 55** illustrates in detail the components of the drill string for the surface section.

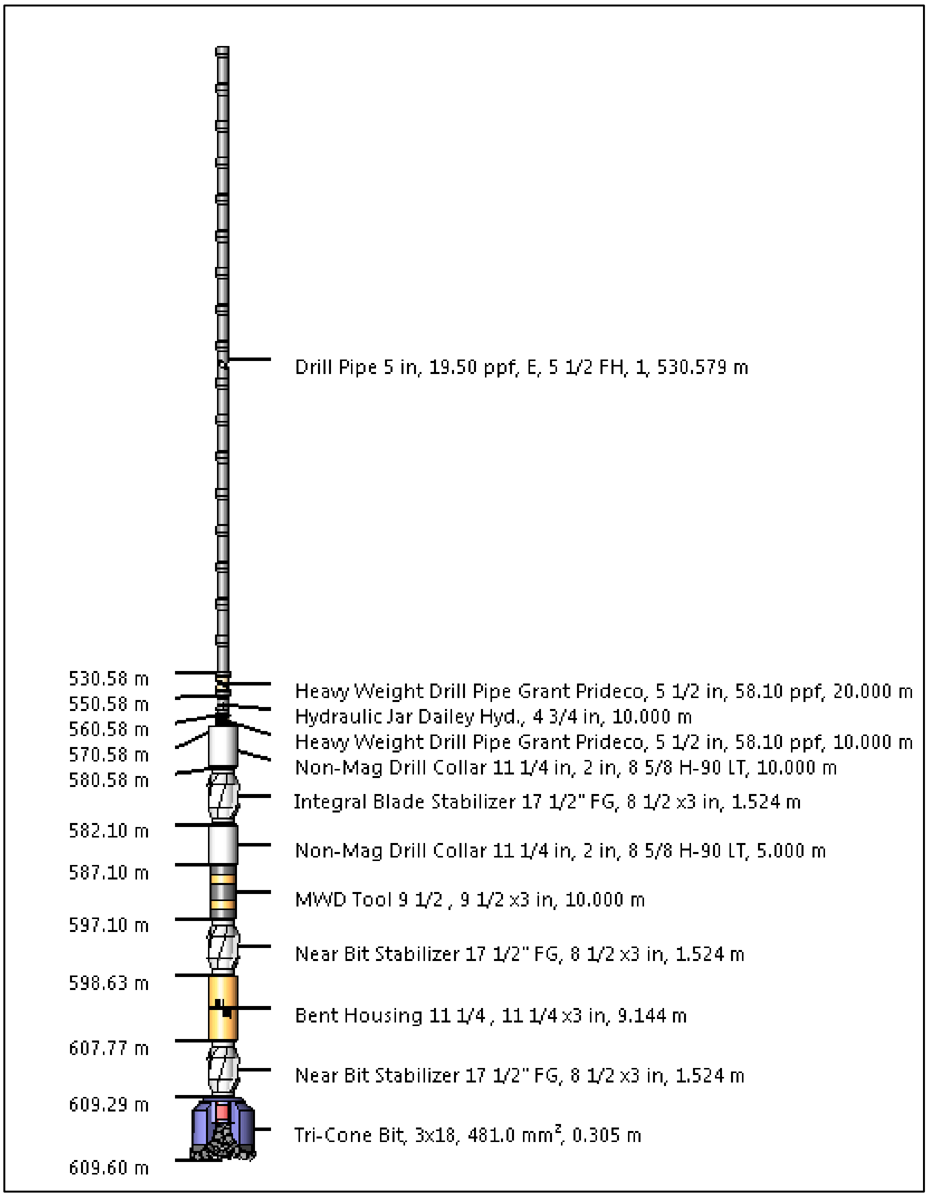


Figure 55: BHA information

The torque and drag calculations for the BHAs of the different sections is provided in Appendix B.

12.4 Bit Selection

The bit selection is based on the geology of the sections that have to be drilled. The following **Table 38** shows the chosen bits and provides insight on their advantages for the challenges created by the formations. All the selected bits are products of the Smith Company owned by Schlumberger and can be found in the product catalogue.

Section	Recommended Bit	Formation Bit Challenges	Advantage
Surface	17 1/2" Shark high Abrasion PDC Bit	Extremely high rock hardness encountered in the chert with a UCS>160 MPa	Maximum durability and ROP in highly abrasive and formations
Production	12 1/4" Standart PDC Bit	Varying lithology leads to alternating rock hardness. Very few chert nodules present	Applicable in different formations, with decent performance in all of them

Table 38: Bit selection

12.5 Hydraulic System

The information about the design of the hydraulic system can be found in Appendix B. This includes insight about the used mud system, pump rates and detailed pressure loss calculations. Furthermore all calculations are supported by graphs and pie charts of the losses.

13. Conclusion

This investigation shows the importance of information in the area of exploration drilling. The most relevant source of data in this field is geological information. Insight about mineralogy, sedimentology and structural geology is key in order to be able to identify potential problems in advance and to find proper solutions before hazardous situations can occur.

The first objective of this thesis was to perform three individual field studies, in order to analyze the geology of the formations and to draw the link to their drilling-related problems. The studies were successfully executed, and valuable information about sedimentological background, mineralogy, and structural geology was acquired. The detailed knowledge about the formations was used to investigate the drilling issues that are caused by their particular geology. A good example for this is the varying calcite content of the Bridport Sand formation, which has a direct connection to rock hardness and therefore determines the proper bit selection. Furthermore, it is concluded, that geological field studies are absolutely beneficial for drilling engineers since they lead to more sensible decisions for bit selection, mud selection and others as shown in this work.

For the second aim, an improved workflow for the planning process of exploration wells was presented. This improved workflow includes the possibility for the drilling engineers to attend an educational field trip to visit formations that will be encountered in an exploration venture. The cost of the suggested field trips is very low in comparison to the expenses needed in an exploration well, but they can be of vital importance for the safety and success of such projects. The methodology of the field trips was provided in detail in this work.

The implementation of field trips to improve data acquisition is not only limited to pre-spud well planning, but it can also additionally be used as a tool to analyze geology-related problems after the well has been completed. There is a clear benefit if the involved team goes out in the field to improve post well reviews, as again valuable parameters such as rock hardness and others can be investigated. The encountered issues can be interpreted more precisely if similar formations are investigated as outcrop analogues.

The third goal of this research was a data analysis of two individual wells. The emphasis of the analysis was the geological background of the formations drilled in the wells. This investigation allowed a detailed insight on the geological problems the companies encountered during the drilling process, such as bad bit selection or problems with fluid losses.

The last part of this thesis was the creation of alternative and improved well plans for the previously analyzed wells. The new well plans were created using the software Landmark by Halliburton. By using information from the outcrop analysis and data analysis from the previous objectives, the enhanced well plans were created. All the important steps such as trajectory, casing schematic, bit selection and hydraulic calculations were included in this work.

As a further recommendation, the author advises the creation of a catalogue with outcrop analogues for every major region in the world which has significance in oil and gas exploration. This catalogue should include locations, rock types, sedimentological background, structural geology and mineralogy. Furthermore, links should be drawn from the outcrop to potential underground sites in order to be able to find analogues that are representative in an efficient and quick manner. If wells were already drilled in similar formations the catalogue should include the encountered issues seen in real field experience. Such a catalogue alongside with field trips is a new and very direct source of information that improves every exploration project.

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Appendix A

Calculations and graphs for the alternative well plan for 21/10a-2.

Casing Stress Check

Using the software Stress Check the casing sections are tested with respect to burst collapse and tension. The software uses a “Triaxial” approach in order to calculate the safeties. These calculations were carried out for all five sections. **Figure 56** and **Figure 57** show the results for the surface section and the second intermediate section. The results for the other sections are not displayed here, since they look similar to the ones that are shown.

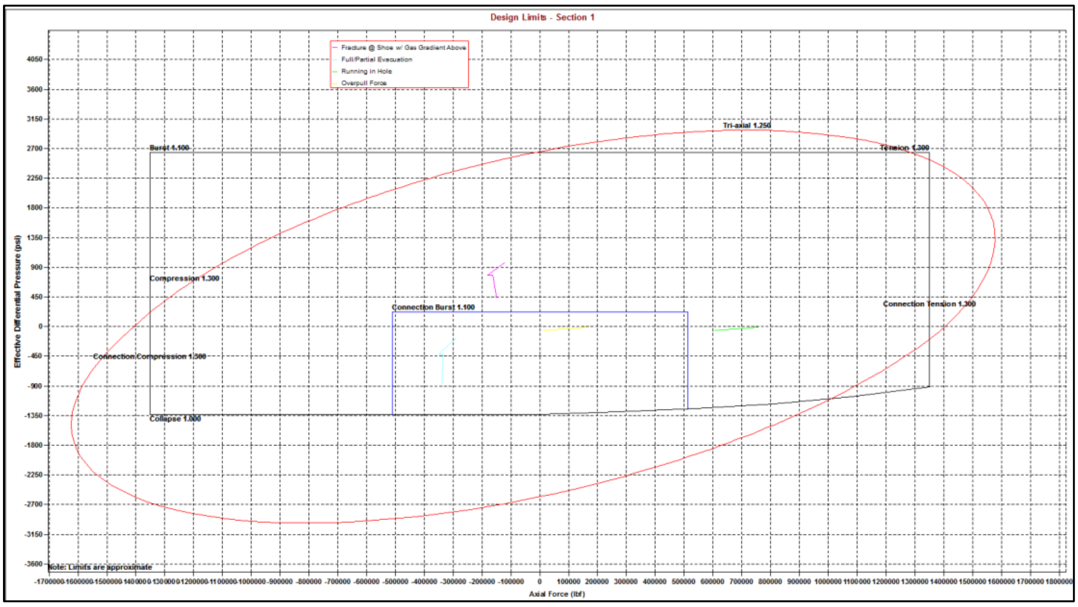

Figure 56: Results for the stress check of the surface section

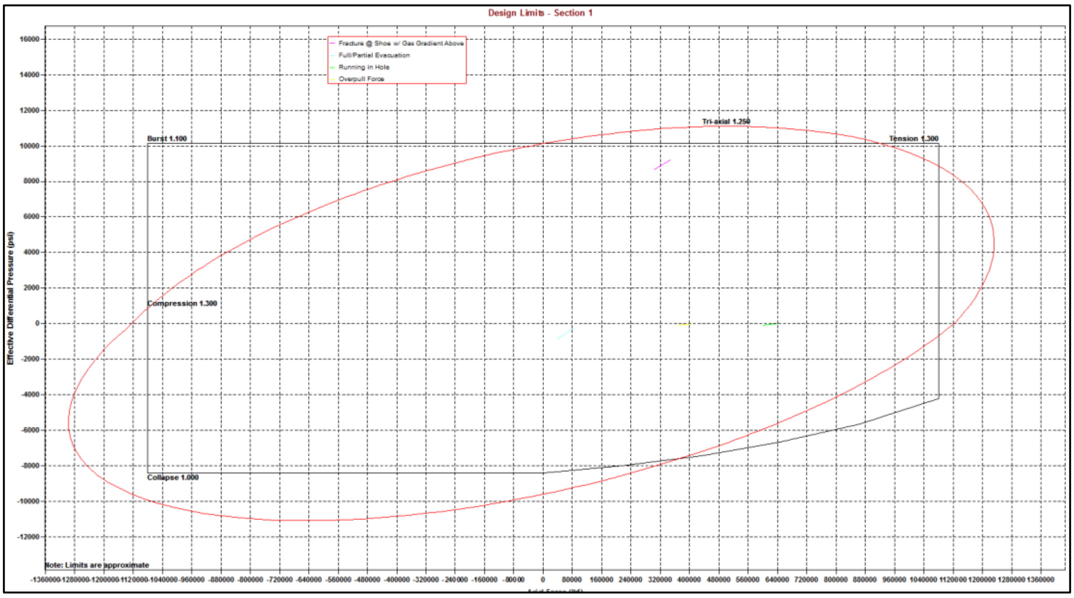

Figure 57: Results for the stress check of the second intermediate section

Torque and Drag Analysis

The torque and drag analysis is of utter importance to make sure the different sections can be drilled accurately. The software calculates tension limits, sinusoidal and helical buckling during tripping operations and during drilling. **Figure 58** to **Figure 61** show the tension plot for all drilled sections.

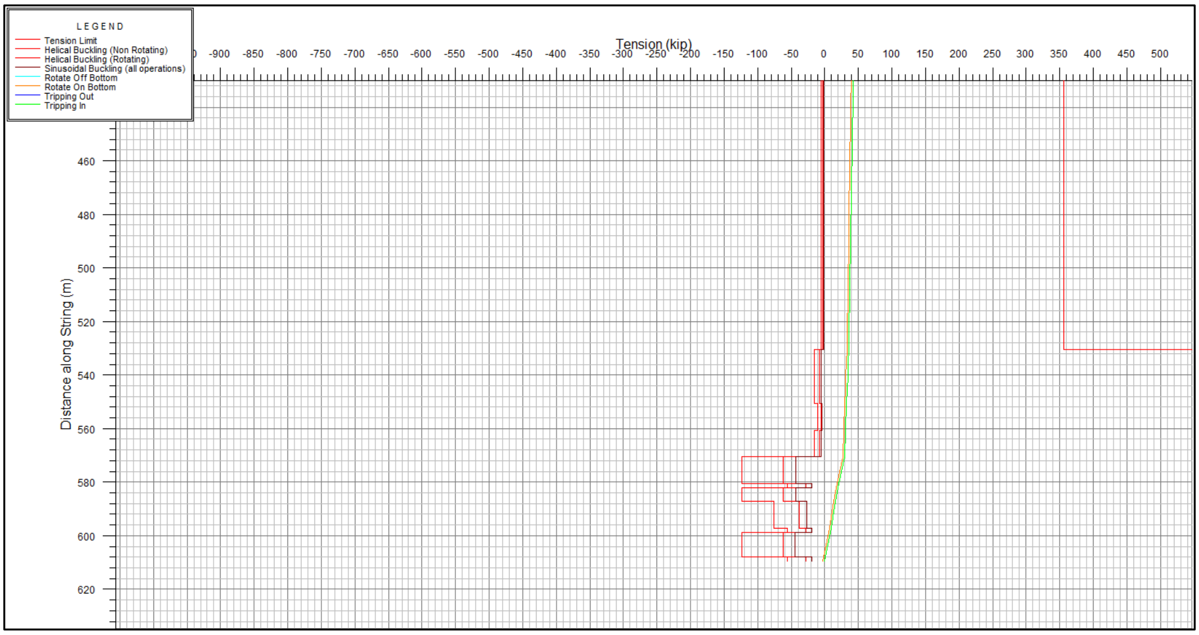

Figure 58: Tension plot for the surface section

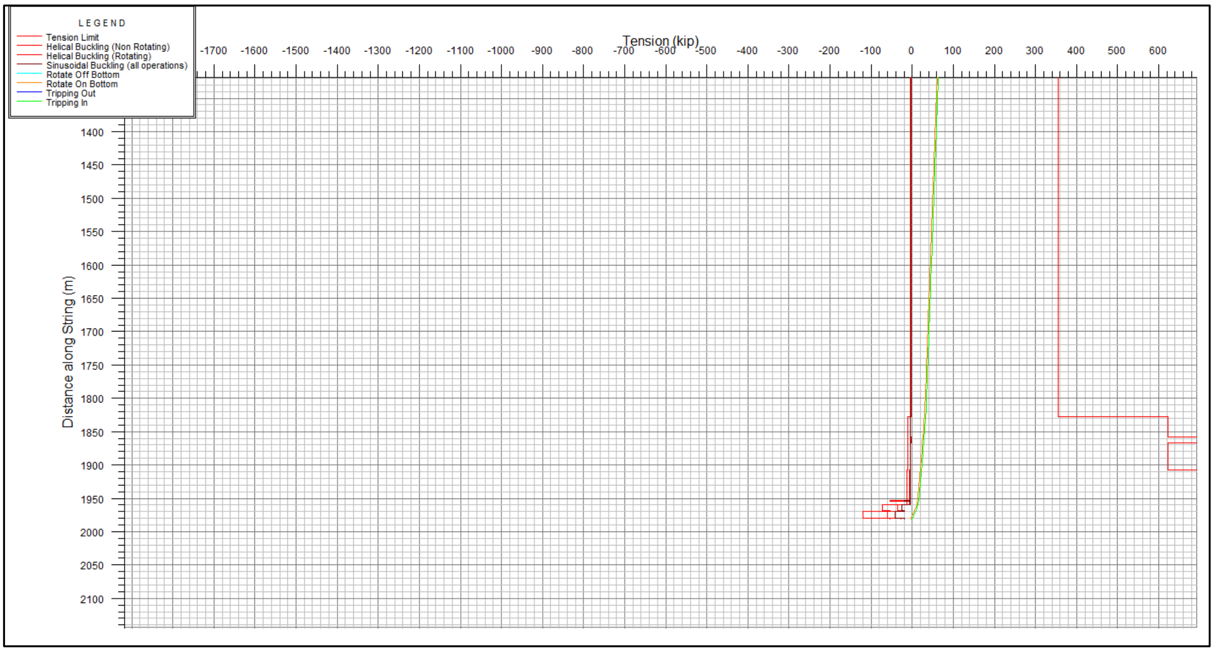

Figure 59: Tension plot for the first intermediate section

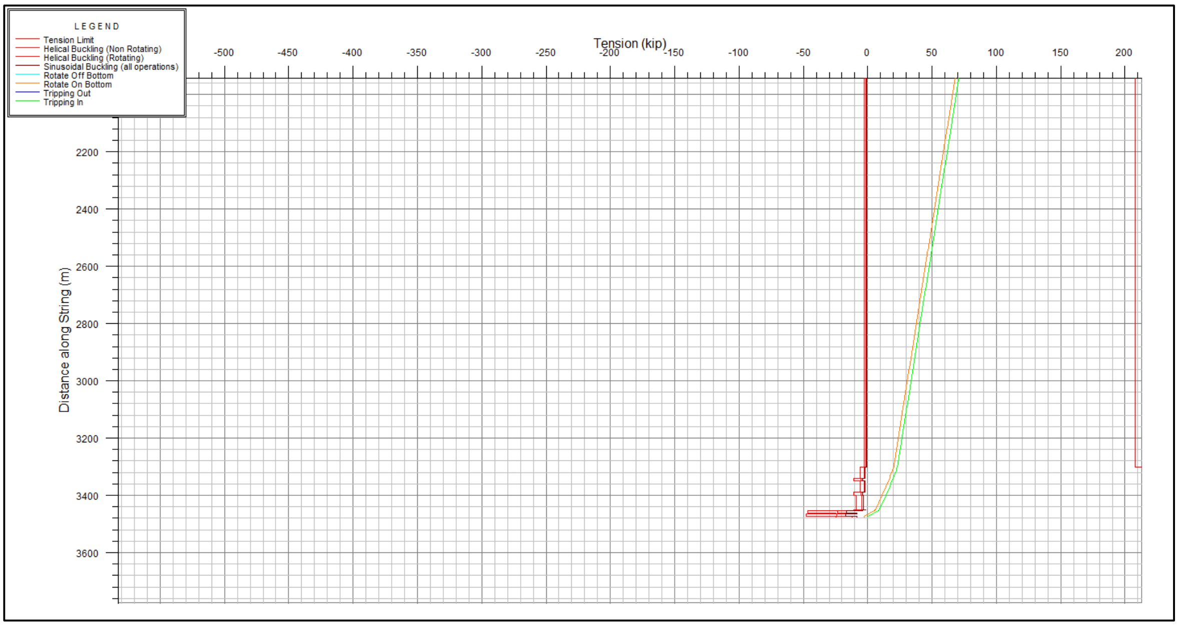

Figure 60: Tension plot for the second intermediate section

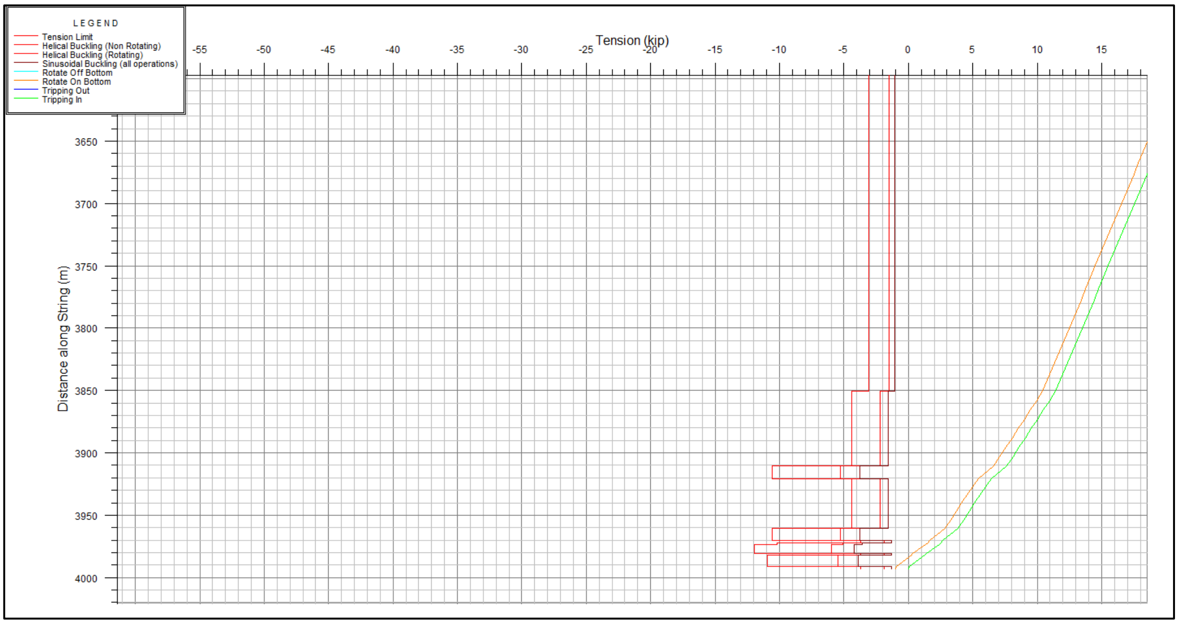

Figure 61: Tension plot for the production section

Hydraulics

Surface Section

The chosen mud for the first section is an oil based mud (OBM) with a specific gravity of 1,2. The pump flow rate is 1205 gpm and the hydraulic energy (HSI) yields a value of 3,7 .This is a reasonable value, since it should be between 2 and 5.

The following **Figure 62** shows the plot of the mud weight window and including the curve for the equivalent circulating density (ECD).

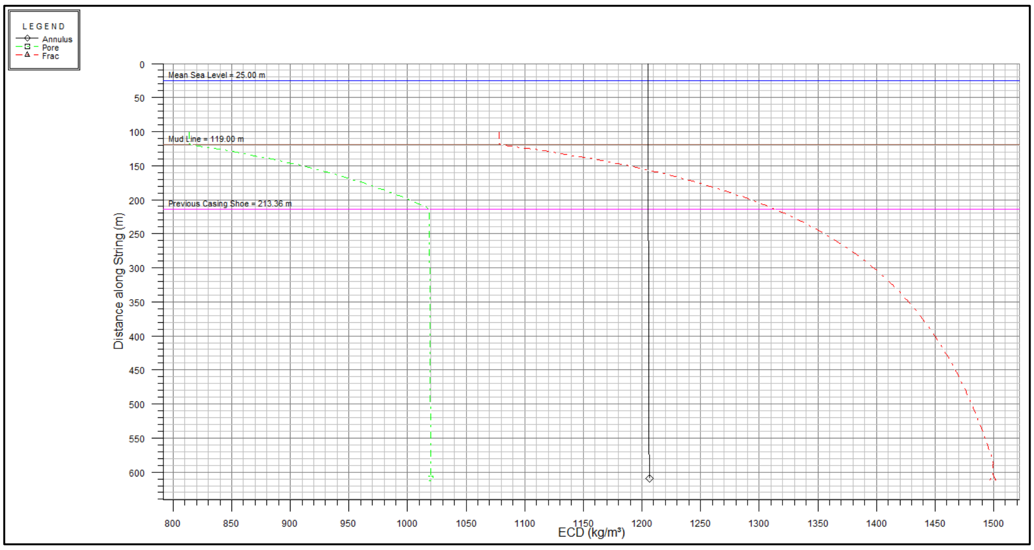

Figure 62: ECD versus depth

Figure 63 includes a pie chart that gives an idea about the pressure losses in the drill string. Over 55% of the losses arise from the bit. The other larger source of pressure losses is the drill pipes with a value of 15%.

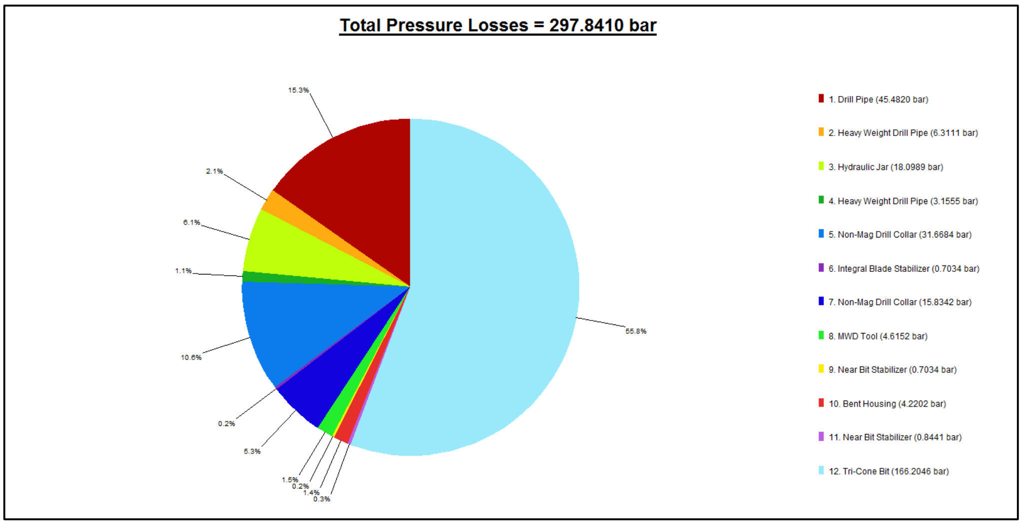

Figure 63: Total pressure losses in the drill string

Figure 64 is the so called operational plot that proves no cutting beds can be formed under the designed conditions.

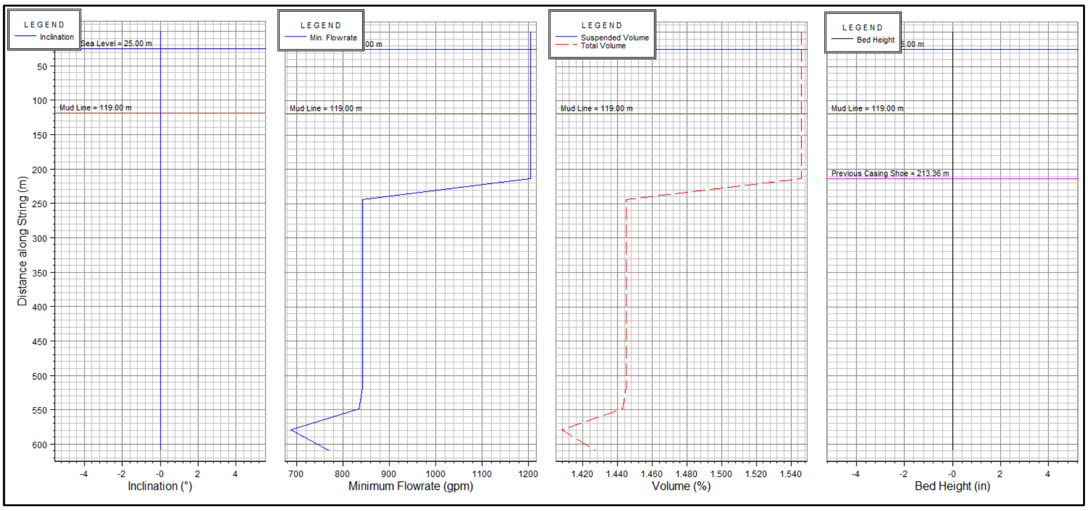

Figure 64: Operational plot for the surface section

First Intermediate Section

The chosen mud for the first intermediate section is an oil based mud (OBM) with a specific gravity of 1,45. The pump flow rate is 675 gpm and the hydraulic energy (HSI) yields a value of 2,3 .This is a reasonable value, since it should be between 2 and 5.

The following **Figure 65** shows the plot of the mud weight window and including the curve for the equivalent circulating density (ECD).

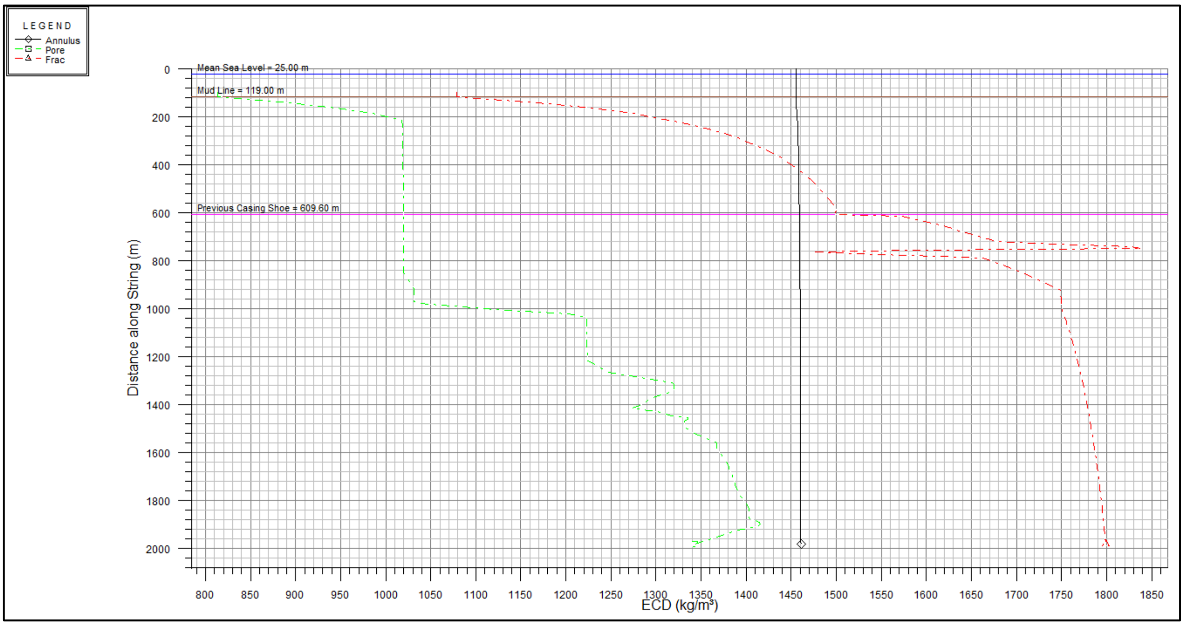

Figure 65: ECD versus depth

Figure 66 includes a pie chart that gives an idea about the pressure losses in the drill string. Over 34% of the losses arise from the bit. The other larger source of pressure losses is the drill pipes with a value of 27,1%.

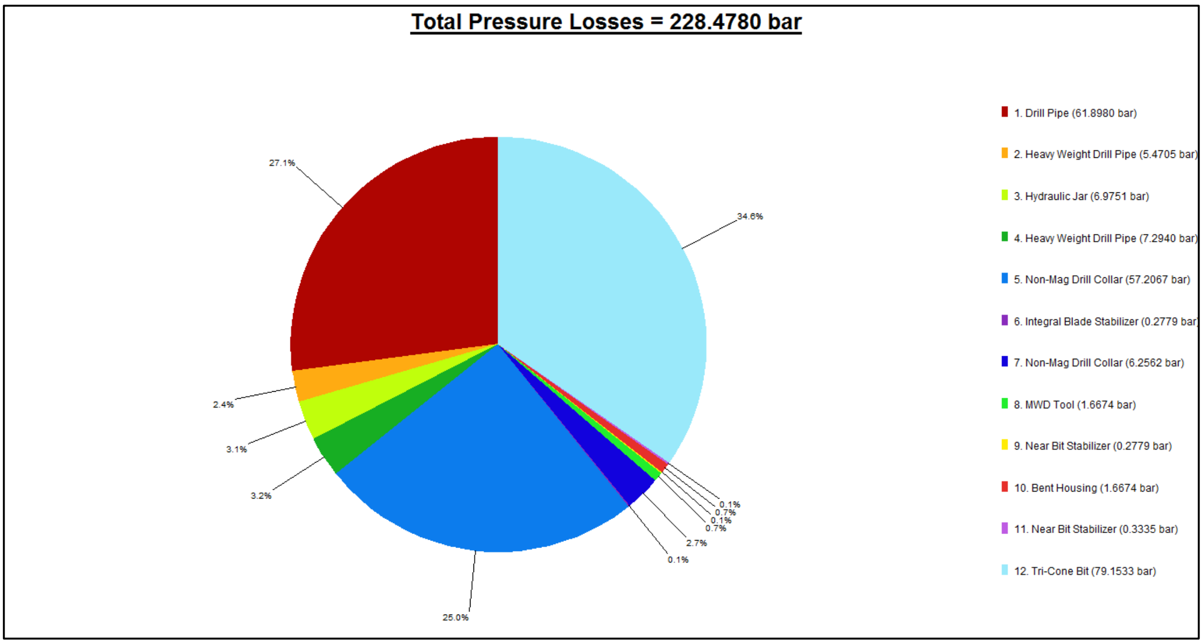

Figure 66: Total pressure losses in the drill string

Figure 67 is the so called operational plot that proves no cutting beds can be formed under the designed conditions.

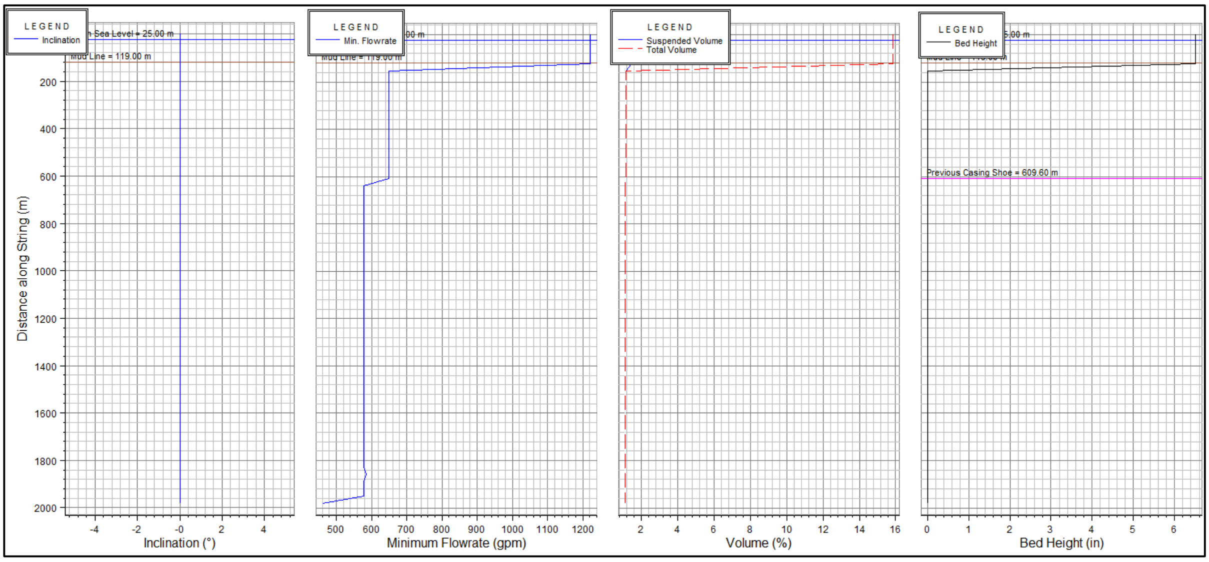

Figure 67: Operational plot for the first intermediate section

Second Intermediate Section

The chosen mud for the first section is an oil based mud (OBM) with a specific gravity of 1,5. The pump flow rate was 325 gpm and the hydraulic energy (HSI) yielded value of 2,3 .This is a reasonable value, since it should be between 2 and 5.

The following **Figure 68** shows the plot of the mud weight window and including the curve for the equivalent circulating density (ECD).

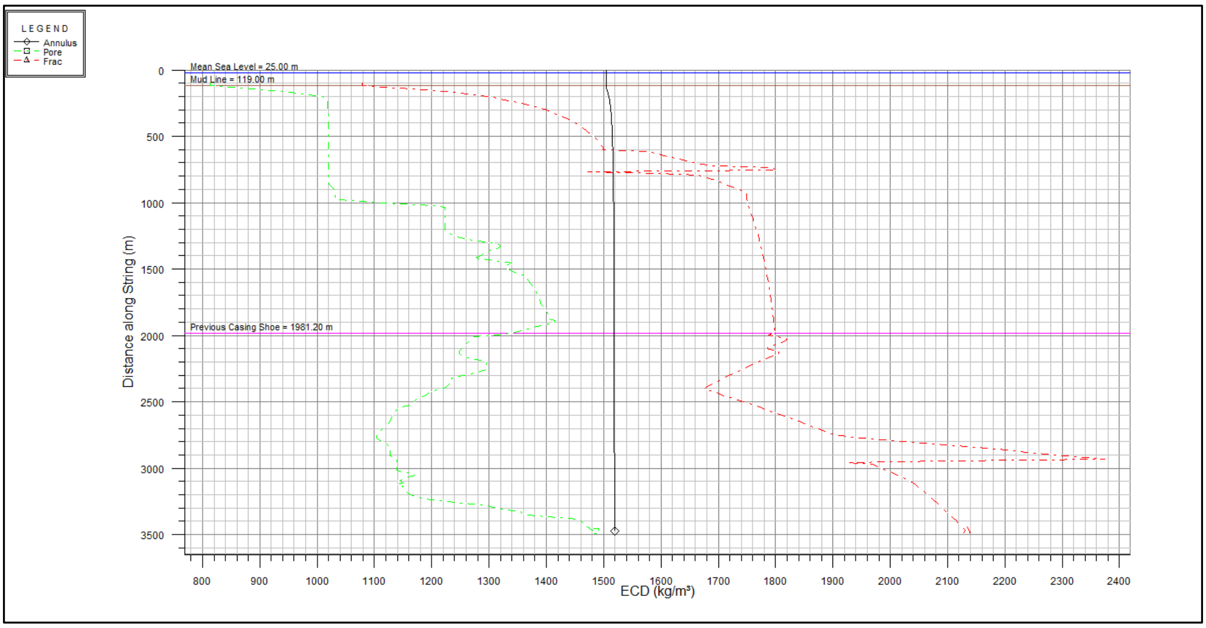

Figure 68: ECD versus depth

Figure 69 includes a pie chart that gives an idea about the pressure losses in the drill string. Over 41% of the losses arise from the bit. The other larger source of pressure losses is the drill pipes with a value of 45,8%.

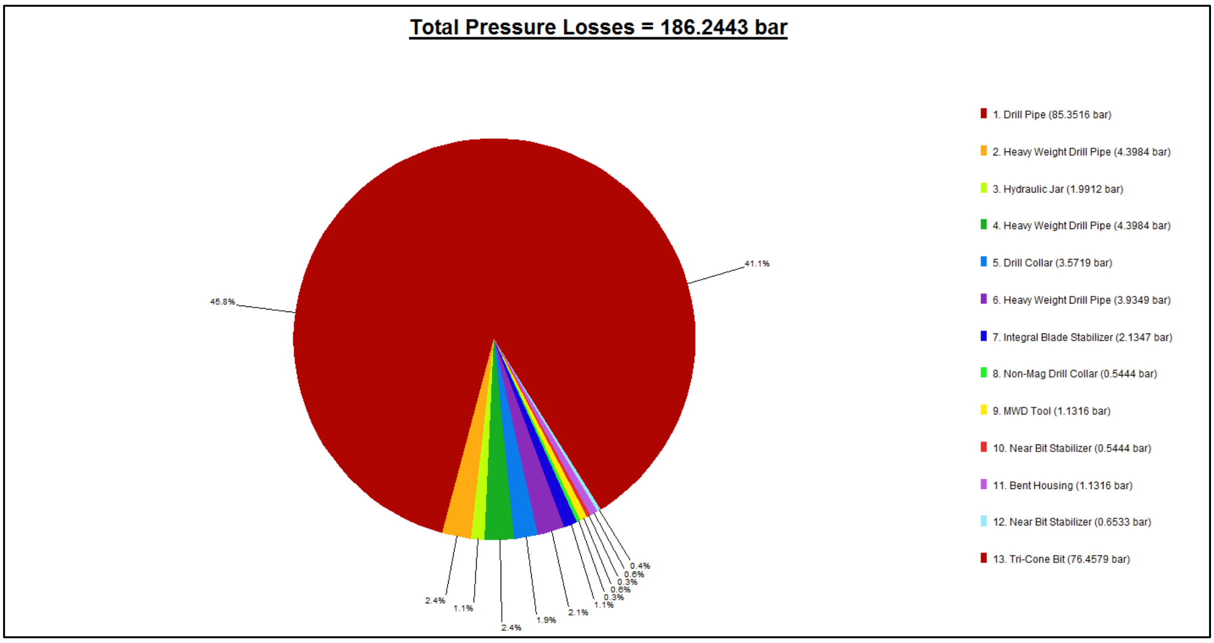

Figure 69: Pressure losses in the drill string

Figure 70 is the so called operational plot that proves no cutting beds can be formed under the designed conditions.

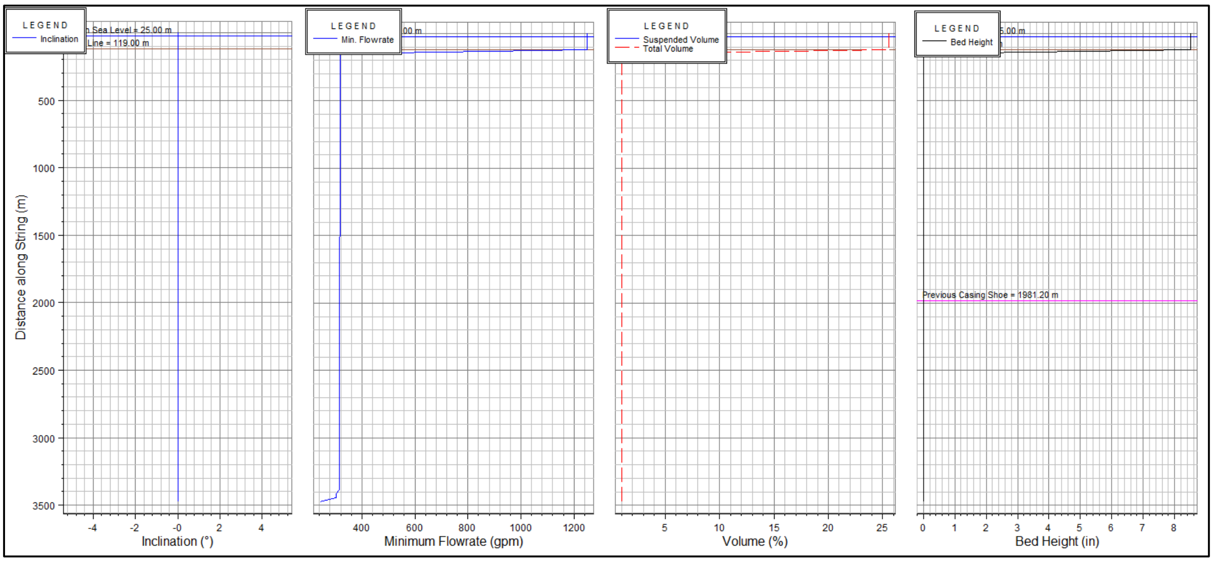

Figure 70: Operational plot or the second intermediate section

Production Section

The chosen mud for the first section is an oil based mud (OBM) with a specific gravity of 1,875. The pump flow rate is 182,5 gpm and the hydraulic energy (HSI) yields a value of 2,9 .This is a reasonable value, since it should be between 2 and 5.

The following **Figure 71** shows the plot of the mud weight window and including the curve for the equivalent circulating density (ECD).

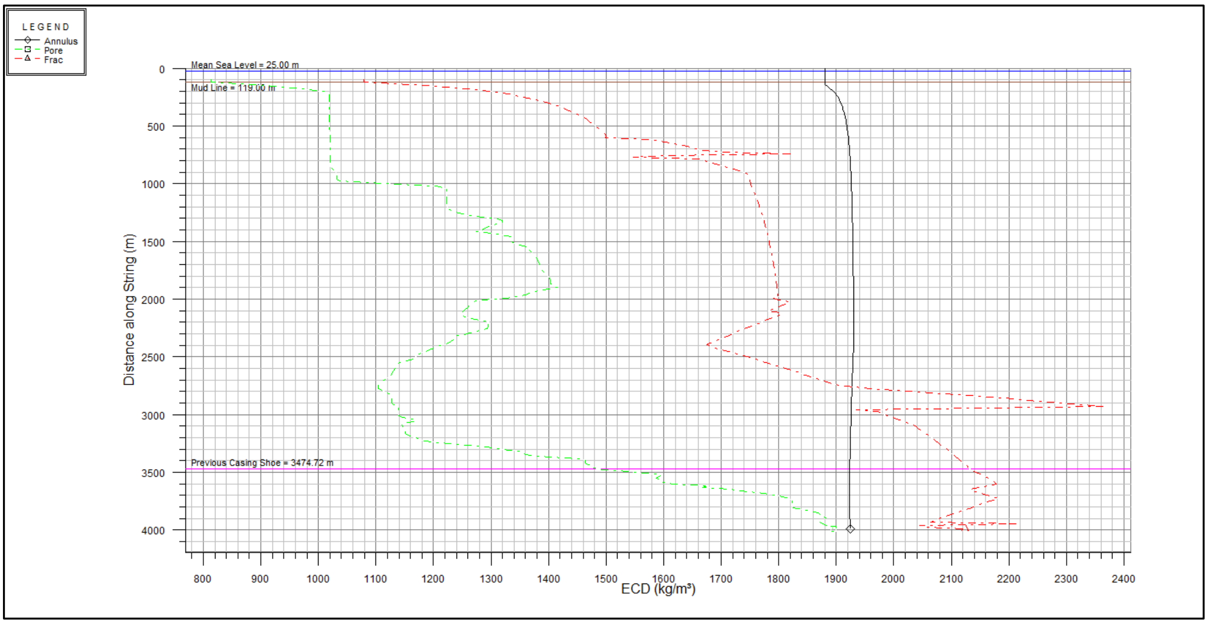

Figure 71: ECD versus depth

Figure 72 includes a pie chart that gives an idea about the pressure losses in the drill string. Over 38% of the losses arise from the bit. The other larger source of pressure losses is the drill pipes with a value of 40%.

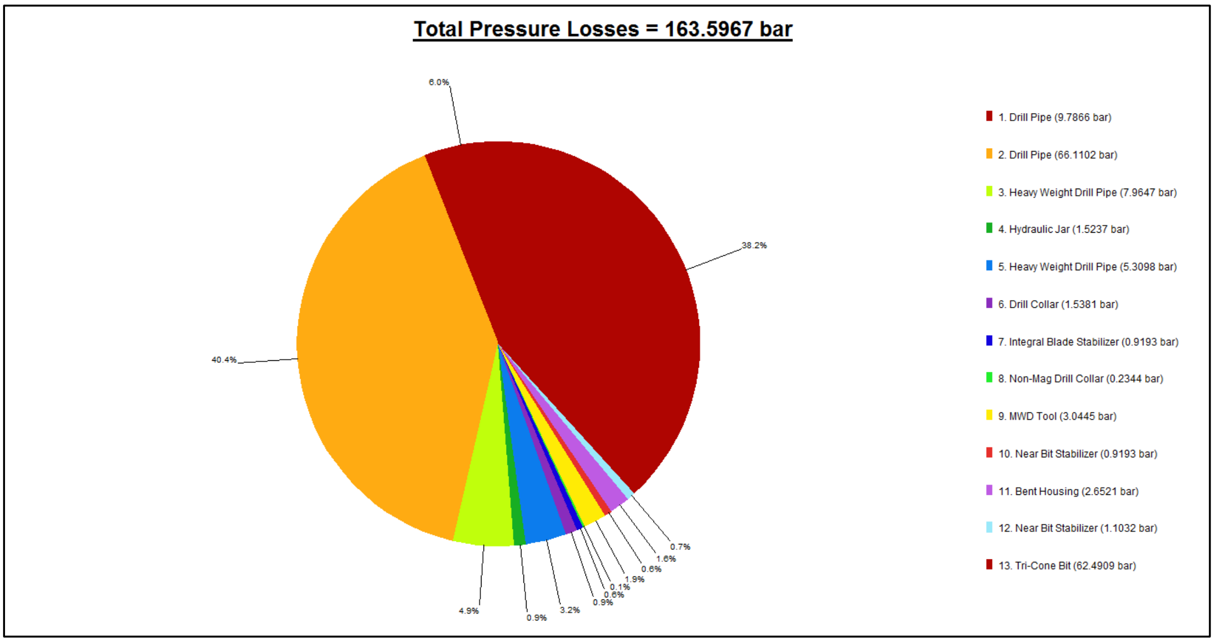

Figure 72: Pressure losses in the drill string

Figure 73 is the so called operational plot that proves no cutting beds can be formed under the designed conditions.

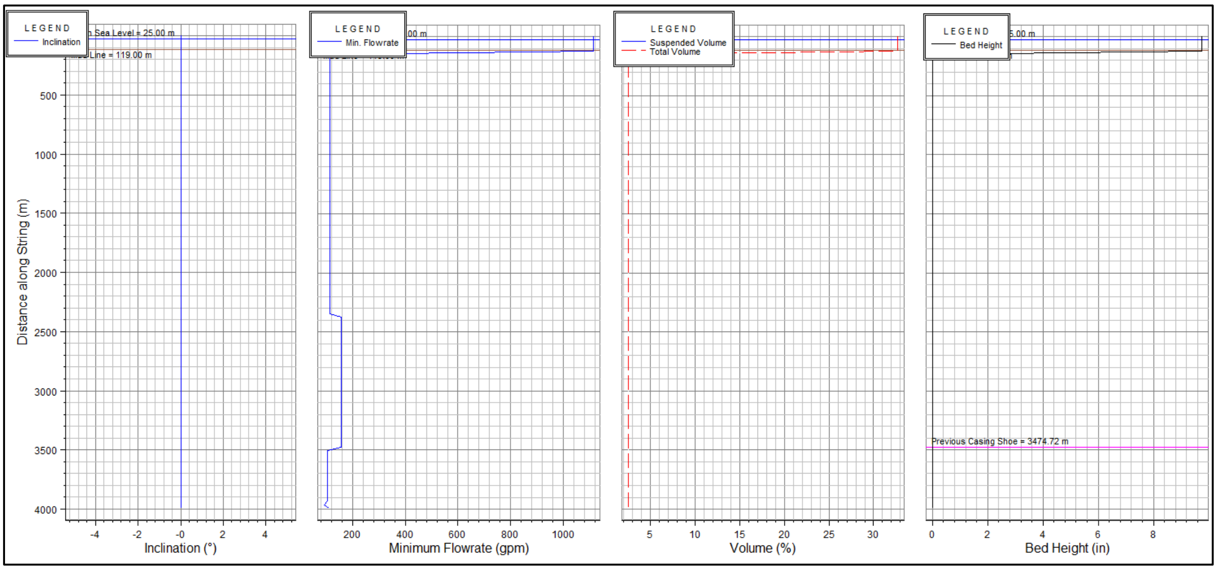

Figure 73: Operational plot for the production section

Appendix B

Calculations and graphs for the alternative well plan for Eirozes 1.

Casing Stress Check

Using the software Stress Check the casing sections are tested with respect to burst collapse and tension. The software uses a “Triaxial” approach in order to calculate the safeties. These calculations were carried out for all three sections. **Figure 74** and **Figure 75** show the results for the surface section and the production section. The results for the other section is not displayed here, since they look similar to the ones that are shown.

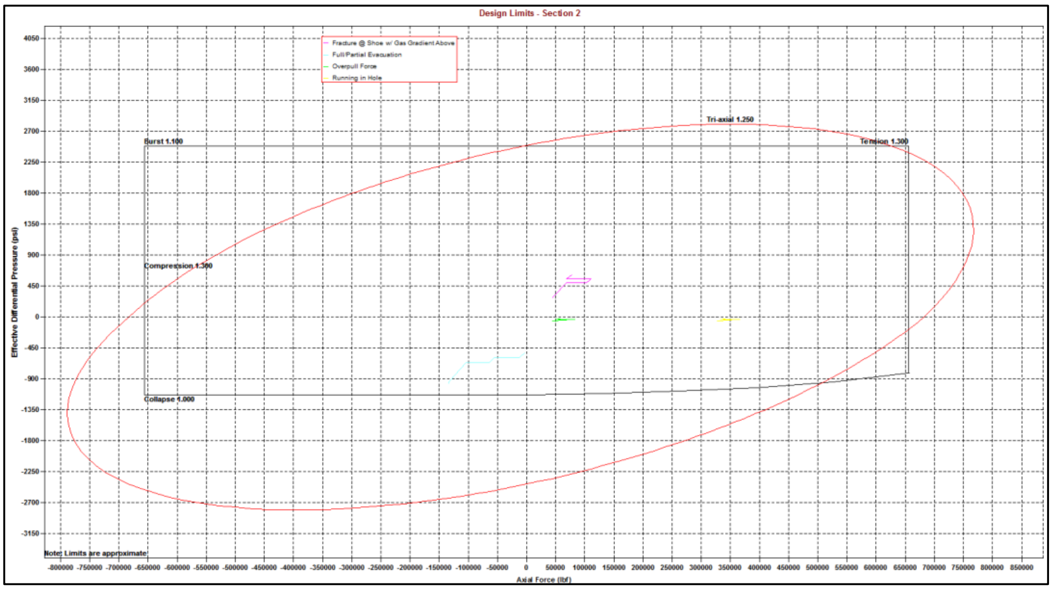

Figure 74: Tri-axial check for the surface section

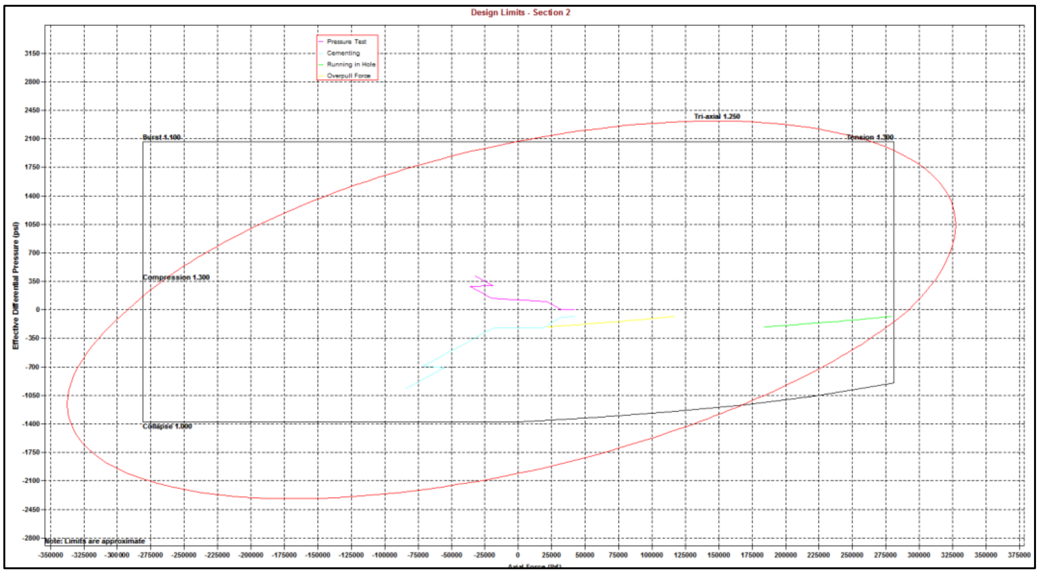

Figure 75: Tri-axial check for the production section

Torque and Drag Analysis

The torque and drag analysis is of utter importance to make sure the different sections can be drilled accurately. The software calculates tension limits, sinusoidal and helical buckling during tripping operations and during drilling. **Figure 76** to **Figure 77** show the tension plot for all drilled sections.

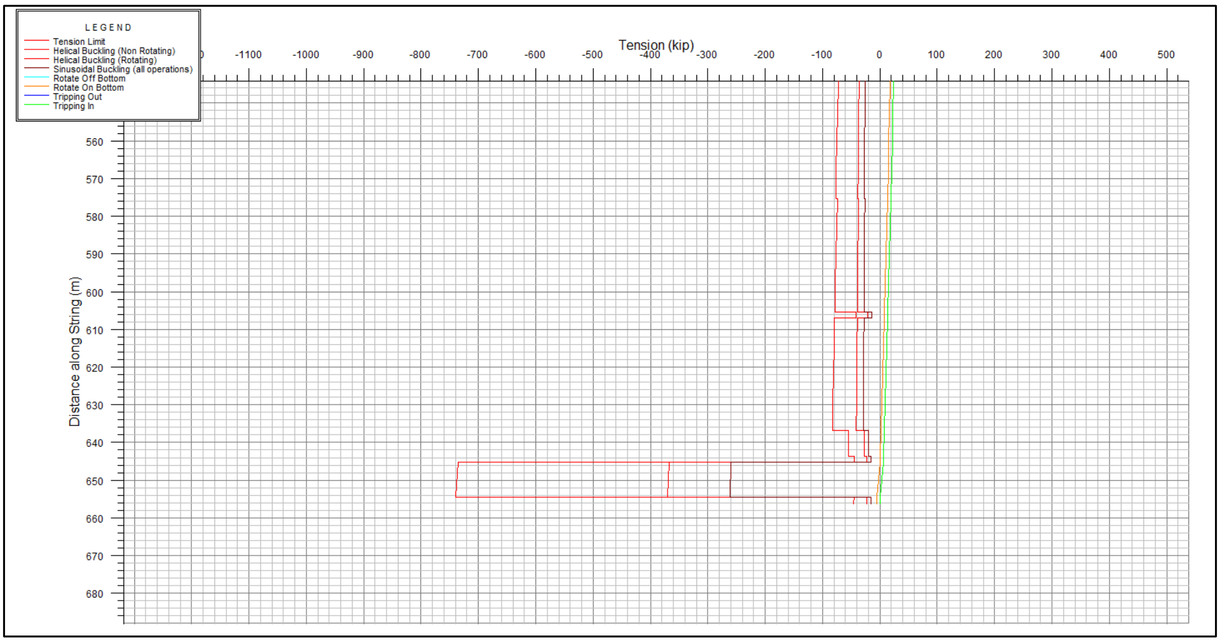

Figure 76: Tension plot for the surface section

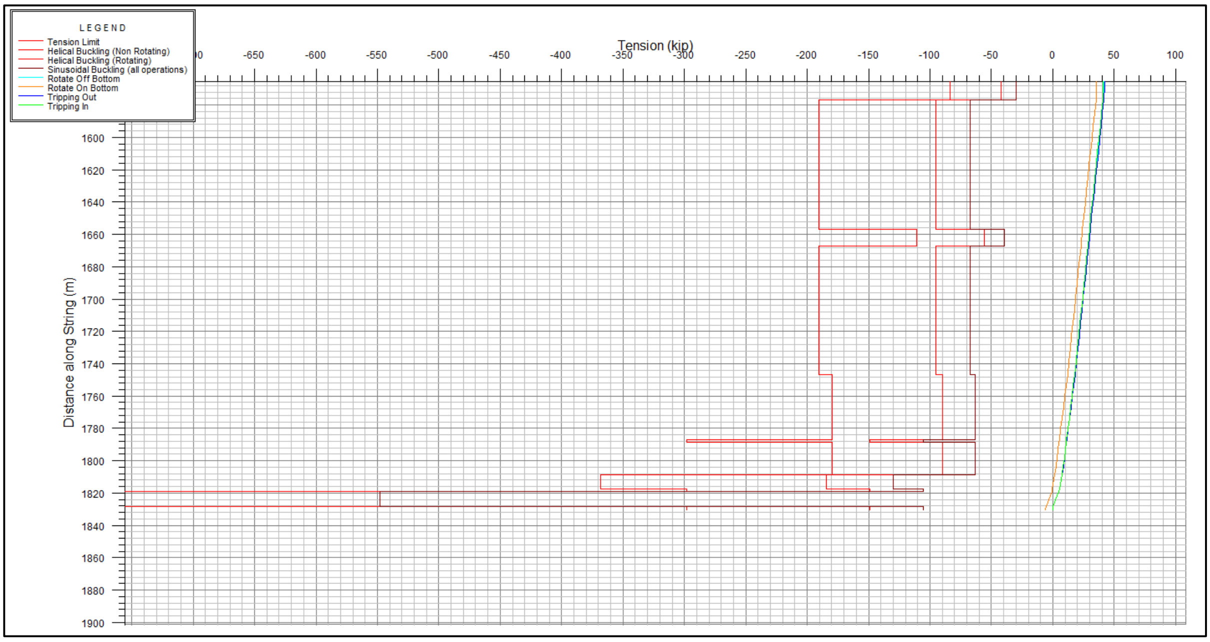

Figure 77: Tension plot for the production section

Hydraulics

Surface Section

The chosen mud for the first section is an oil based mud (OBM) with a specific gravity of 1,2. The pump flow rate is 1020 gpm and the hydraulic energy (HSI) yields a value of 2 .This is a reasonable value, since it should be between 2 and 5.

The following **Figure 78** shows the plot of the mud weight window and including the curve for the equivalent circulating density (ECD).

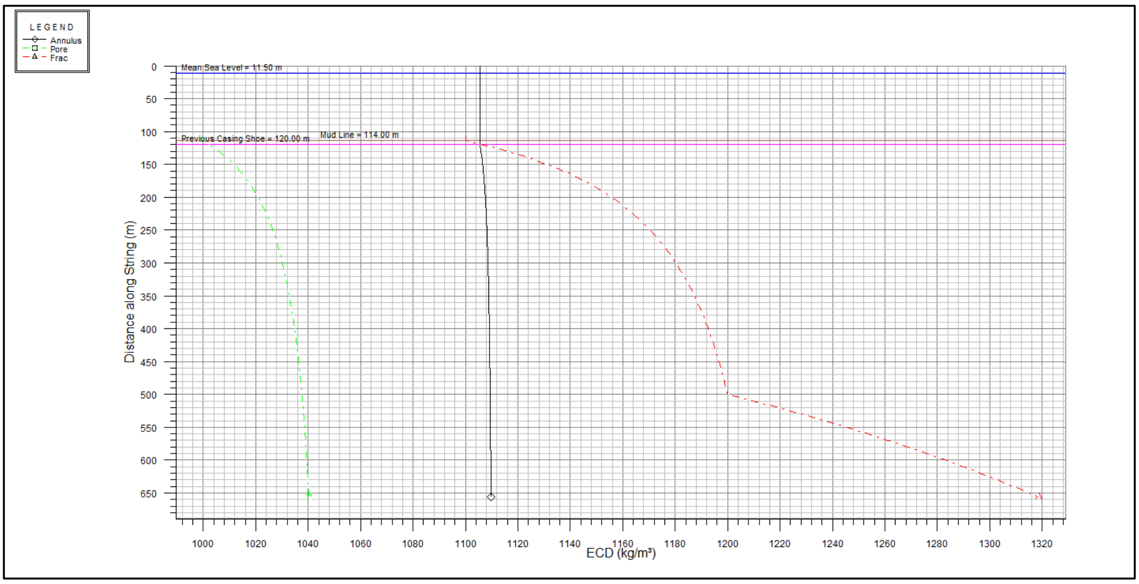

Figure 78: ECD vs depth for the surface section

Figure 79 includes a pie chart that gives an idea about the pressure losses in the drill string. Around 20% of the losses arise from the bit. The other larger source of pressure losses is the drill collars with a value of 20%.

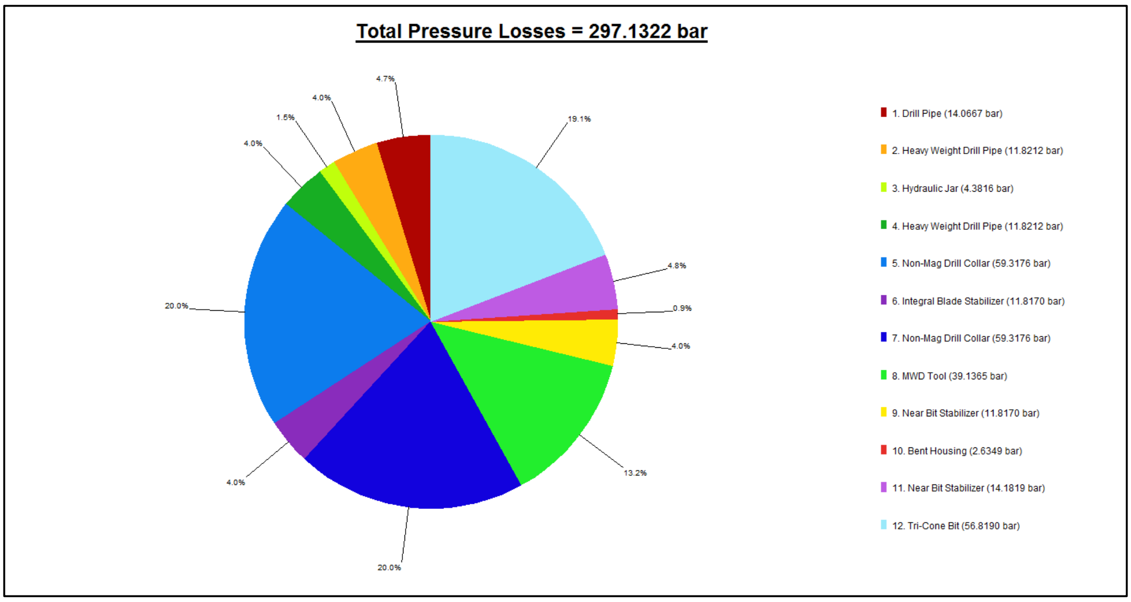

Figure 79: Pressure losses in the drill string

Figure 80 is the so called operational plot that proves no cutting beds can be formed under the designed conditions.

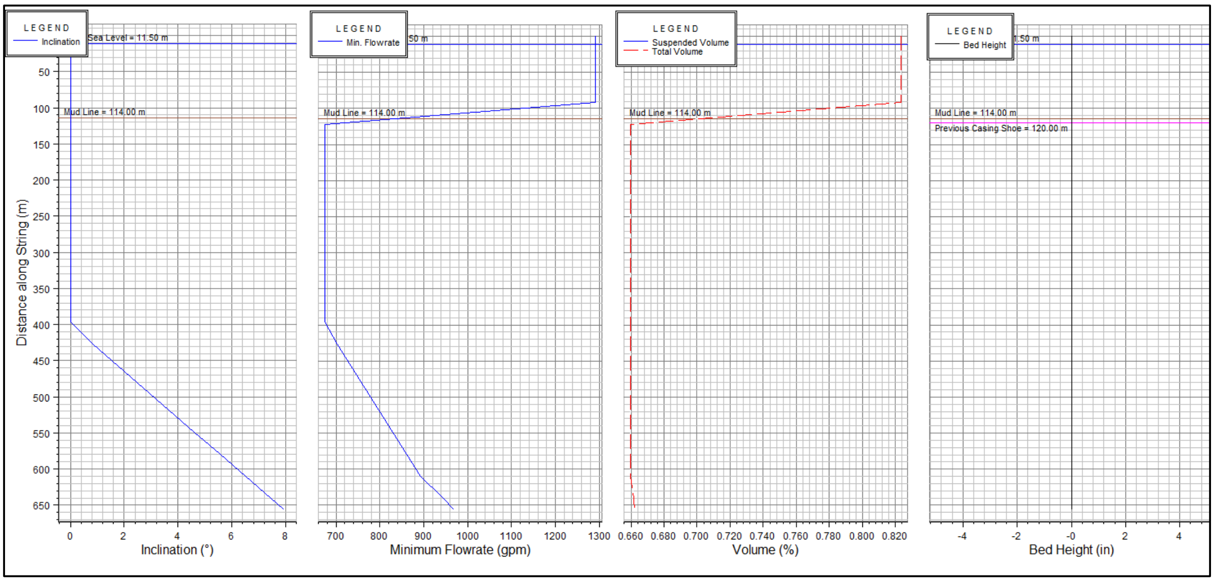

Figure 80: Operational plot for the surface section

Production Section
The chosen mud for the first section is an oil based mud (OBM) with a specific gravity of 1,4. The pump flow rate is 825 gpm and the hydraulic energy (HSI) yielded value of 3.5 .This is a reasonable value, since it should be between 2 and 5.

The following **Figure 81** shows the plot of the mud weight window and including the curve for the equivalent circulating density (ECD).

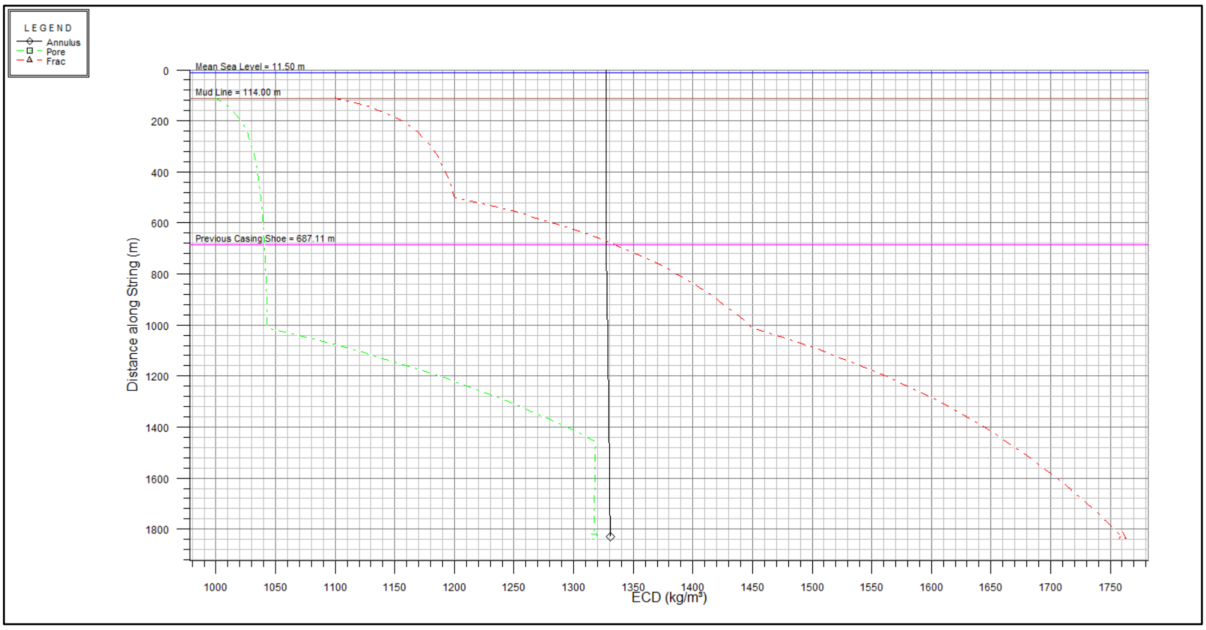

Figure 81: ECD vs depth for the production section

Figure 82 includes a pie chart that gives an idea about the pressure losses in the drill string. Over 15% of the losses arise from the bit. The other larger source of pressure losses is the drill collars with a value of 28.5%.

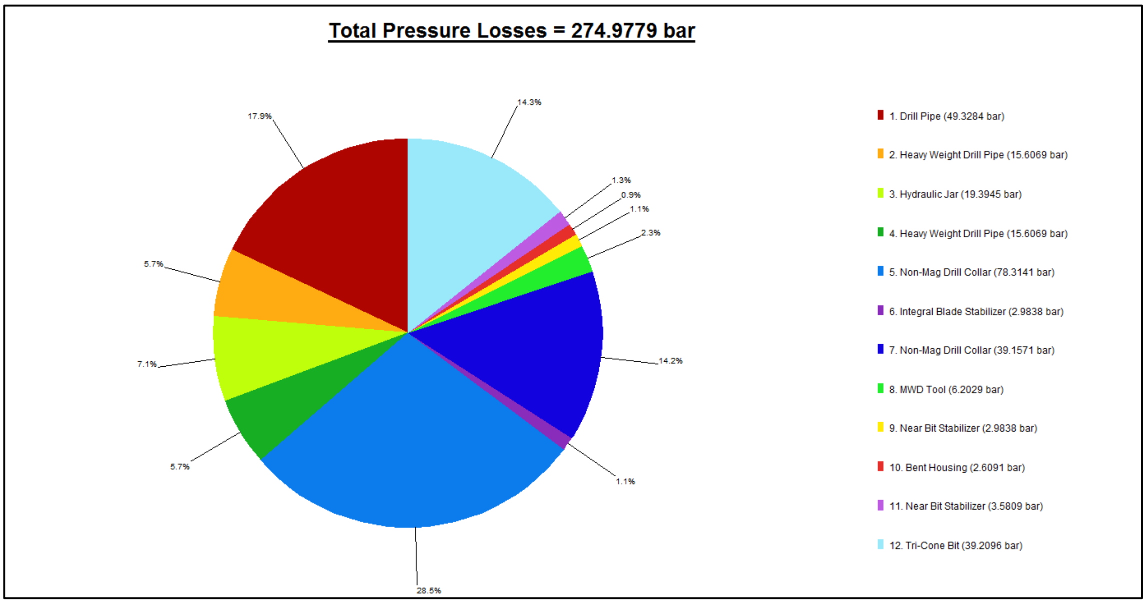

Figure 82: Pressure losses in the drill string

Figure 83 is the so called operational plot that proves no cutting beds can be formed under the designed conditions.

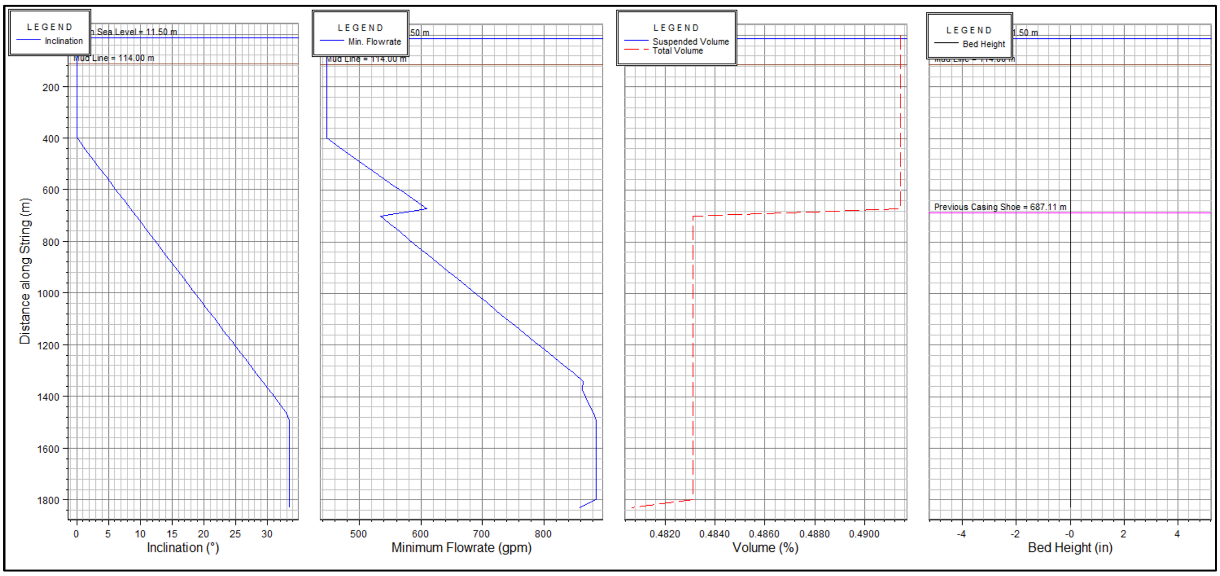

Figure 83: Operational plot for the production section