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# Abstract

The industry is moving forward to drilling in harder and more abrasive formations. This challenging environment poses a challenge upon bit technologies and rate of penetration (ROP). The aim of this thesis is to gain a better understanding on what variables influence ROP in conditions experiencing higher temperatures and pressures.

Rate of penetration can be viewed as a driver for drilling costs and the duration of an operation. Therefore, a proposed ROP prediction model has been developed throughout this thesis via analysing historical bit records and mathematical statistical modelling.

The preliminary results of this proposed model indicates a prediction range that falls within the field measured ROP value when trialled on existing fields and a synthetic field. As a consequence of limited data available, more correlations and investigations are required before concluding the model suitable for all drilling conditions.

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**Nomenclature**

|  |  |
| --- | --- |
| ANN | Artificial Neural Network |
| BHA | Bottom hole assembly |
| CCS | Confined compressive strength |
| CD | Current depth |
| DOC | Depth of cut |
| GTS | Geological Time Scale |
| HPHT | High Pressure High Temperature |
| ID | Impregnated Diamond |
| IDDP | Iceland Deep Drilling Project |
| IRIS | International Research Institute of Stavanger | |
| NPD | Norwegian Petroleum Directorate | |
| NPT | Non-productive time |
| PDC | Polycrystalline Diamond Cutter |
| ROP | Rate of Penetration |
| RPM | Revolutions per minute |
| TCI | Tungsten Carbide Inserts |
| TVD | True vertical depth |
| UCS | Unconfined compressive strength |
| WOB | Weight of bit |

# Introduction

The industry is heading towards exploring and drilling wells located in harsher environments. The associated drilling environments are inclined to possess higher temperatures, pressures and harder geological formations. Technological advancements in the industry are allowing this progression. This thesis aims to understand the application of drilling technologies in these circumstances as to develop an insight into various rates of penetration (ROP) influences.

The initial content of this report’s theoretical portion covers drilling in hard rock, its challenges and bit technology. The hardness of rocks will be categorised and investigated. The information gathered on rock hardness will be evaluated in terms of historical data on drilling performance

Technologies that will be discussed are polycrystalline diamond cutter (PDC), impregnate diamond (ID), roller cone and hybrid bits. All of these technologies pose numerous challenges within hard rock application; not limited to vibrations, bit damage and wear. The mentioned challenges influence a bit’s lifetime and ROP efficiency in different ways, which are both being evaluated.

Progressively, various fields with challenging circumstances and lithologies will be examined in depth. The established fields were chosen on characteristics based on high pressure and high temperature (HPHT), geothermal and ultra deep wells. Increasingly, geothermal fields are being developed as it is seen as a promising energy source as there are an abundance of current fields leading to reduced environmental impact and improved economics whilst meeting the energy demand. On account of this, there are more drilling challenges linked to these energy sources; such as abrasive and hard rock formations and high temperatures and pressures resulting in reduced penetration rates. Apart from the geological make-up of these fields, technologies utilised will concurrently be analysed.

An additional challenge faced by engineers in hard rock drilling is the large cost and time per foot. Furthermore, non-productive time (NPT) can be linked to various potential failures. Having an ROP prediction model can potentially support the well planning process with respect to bit choice and bit change strategies, thus ultimately reducing drilling costs.

This thesis gives an insight into the various influences there are for ROP prediction through the development of a simple model using multivariate regression. With further study and analysis, this model can be extended and refined into an ROP model that takes into consideration a multitude of factors that influences the ROP. In this instance, factors that have been used in the model were: depth, thickness and drilling time.

## Problem Formulation

The main driver of this thesis is the INNO-Drill project, which is a research project with the research institutes SINTEF and International Research Institution of Stavanger (IRIS) (Kane, 2016) in collaboration with several bit technology providers. The main goal of the project is to gain a better understanding and area of expertise in drilling in hard rock formations.

As discussed in the Introduction, the aim is to develop an insight on how ROP is influenced by various drilling parameters.

Throughout the report, the following subjects will be addressed:

* Hard rock drilling related challenges
* Common drilling technologies
* Evaluation of ROP
* ROP models

The INNO-Drill Project aims to deliver shed new light on different solutions related to deep well drilling in hard rock environments.

## Objectives

The objective of this thesis is to develop a model that takes into account the impacts of ROP in hard rock drilling. This report will start off with an overview into hard rock drilling and challenges faced in such environment followed by an assortment of drilling technologies currently available in the industry in relation to hard rock formations.

Prior to the development of the base case, various insights into already established HPHT, geothermal and ultra deep fields were studied with specific data properties of each field reviewed. Data ranging from rock hardness, drilling technology, lithology, efficiency, challenges and well design are thoroughly examined. In the following study, the primary factor of interest in hard rock drilling was rate of penetration hence; understanding which parameters directly and indirectly impacted ROP are highly desirable. The outcome of this investigation will be further used into developing a model that can be used in for ROP prediction.

Objectives achieved throughout this thesis are:

* The study of different drilling technologies
* Understand the challenges related to hard rock drilling
* Drilling parameters influence on ROP
* Developing a ROP model

## Methodology

In order to predict ROP, the evaluation of previous fields needs to be established. It will assess different drilling parameters, both stratigraphic and technical components of well design. The primary ROP influences will be gathered and quantified through the use of historical drilling performance data, which will be used to develop a simple ROP prediction model. These influences are known as independent variables, which will be used for establishing a model based on multivariate regression analysis.

Once the gathering of necessary information has been completed and a model has been established, the next step is designing a synthetic field with multiple layers and differing lithologies. The ROP model will then be used to perform a rough prediction of ROP on this synthetic field.

The following lists the assumptions used in the development of the base case discussed further into the report.

* Homogeneous lithology. There are minimal to no interbedded formations within a layer.
* The thickness of each layer was established by calculating the percentage in previously established cases.
* Values discussed are in meters, meter/hour.

# Literature Review

## Hard Rock Drilling

This section is an overview of previous research done in relations to the hard rock drilling process, defining hard rocks, and challenges associated with this drilling nature. The primary focus is to cover deep and hard rock drilling with a cross over into geothermal fields, which will be discussed in following subchapters.

Hard rock formations are defined by the hardness of the rock based on unconfined strength (UCS). UCS is known as the rock’s capacity to withstand deformation. The industry treats anything with a UCS valued above 69 MPa (10 000 psi) to be considered as hard rock. Taking into account the technologies currently available, the current value used as the technological limit of bit performance within the drilling industry is 200 MPa (30 kpsi).

### Determination

Typically, the classification of hardness, especially amongst geologist is determined using the Mohs Scale of Mineral Hardness. Essentially, it characterises the hardness of a mineral through visible scratch resistance. This is established through the ability of the harder material to scratch the softer material.

The scratch test uses the minerals against each other and easily attainable tools; fingernail (H = 2.5), copper penny (H = 3.5), knife or glass plate (H = 5.5), steel nail (H = 6.5) and Masonry Drill Bit (H = 8.5).

Table 2-1 is a classification of mineral hardness and it is key to understanding how certain lithologies may be abrasive as a result of minerals interbedded within the formation.

Abrasiveness: In this context, it is referred to a rock’s ability to induce wear on mechanical tools and apparatus. In regards to the composition of the rock, the main influence is the silicate or quartz content of the rock. This is one of the dominant determinations to a rock’s range of wear on the equipment. A higher content of silica or quartz incurs higher abrasive. The presence of conglomerates may also attribute to abrasiveness. This element coupled with poor bit design leads to low ROP, premature bit changes, which results in a shortened bit life and under gauged wellbore.

Table 2‑1 Mohs Scale of Mineral Hardness

|  |  |  |
| --- | --- | --- |
| **Mineral** | **Mohs Relative Hardness (H)** | **Scratch Test Determination** |
| Talc | 1 | Scratched with a fingernail and any mineral rated 2+ |
| Gypsum | 2 | Scratched with fingernail and mineral rated 3+ |
| Calcite | 3 | Scratched with copper penny and mineral rated 4+ |
| Fluorite | 4 | Scratched with knife/glass plate and by any mineral rated 5+ |
| Apatite | 5 | Scratched by knife and minerals rated 6+ |
| Feldspar | 6 | Scratch by steel nail and any mineral rated 7+ |
| Quartz | 7 | Scratched by Masonry Drill Bit and minerals rated 8+ |
| Topaz | 8 | Scratched by Masonry Drill Bit and minerals rated 9+ |
| Corundum | 9 | Scratched by diamond |
| Diamond | 10 | Will scratch all minerals rated between 1 – 9 |

The overall determination of a rock’s hardness is through compressive strength. The general consensus to what is constituted as hard rock is any ultimate compressive strength greater than 10 000 psi or 69 MPa; in accordance to Attewell (1976). Rock strength is a reference to the rock’s ability to resist failure while under elementary stresses; compression, tension or shear. It is categorised by its UCS values. Table 2-2 outlines the standard corresponding strength classification and UCS to the typical rock types.

Table 2‑2 Strength classification of hardness

|  |  |  |
| --- | --- | --- |
| **Strength Classification** | **UCS (MPa)** | **Typical rock types** |
| Very Weak | 10 – 20 | Weathered, weakly compacted sedimentary rocks |
| Weak | 20 – 40 | Weakly cemented sedimentary rock (schists) |
| Medium | 40 – 80 | Competent sedimentary rocks, low density coarse grained igneous rocks |
| Strong | 80 – 160 | Competent igneous rocks, some metamorphic rocks and fine grained sandstones |
| Very strong | 160 – 320 | Quartzite’s, dense fine grained igneous rocks |

When the information from Table 2-2, is merged with field examples of rocks, a clearer picture can be made between rock hardness and lithology. Given the estimated UCS ranges obtained fromThe Principles of Engineering Geology (Attewell, 1976), Figure 2-1 is a graphical representation of the values. It graphs common rock types found in field with the UCS calculated in MPa and the tabulated version can be referred to in Appendix A.

Figure 2‑1 UCS of various rocks

The strength of a rock formation plays an important role in drilling operations. It is recognised that rocks with a higher UCS value are more challenging to drill and have a great impact on ROP. Coupling the UCS value of a rock with cementation, it has been established that well cemented rocks have higher strength due to tightly compacted grains in comparison to poorly cemented rocks.

### Challenges

Regardless of the hardness of a formation, several complications can occur during drilling operations. In the following portion, problems commonly associated with drilling in hard rock will be covered briefly. The issues mentioned also overlap into factors that influence ROP directly or indirectly, which will be discussed in further detail in Chapter 2.4: Rate of Penetration Influences.

* Vibration/Abrasion
* Heterogeneous formations
* Bit wear
* Under gauged well bore
* Cutting removal

#### Vibrations

Vibrations are problematic in hard rock drilling as it causes potential damage to the bit and equipment, which reduces its lifetime. There are three types of vibrations that bits and BHA are susceptible to:

* Axial
* Lateral
* Torsional

Axial vibrations: Commonly referred to as bit bounce. It is the vertical motion of the bit whilst drilling. The high force impact between the formation and bit damages the down-hole equipment. It increases the damage on cutters and bearings. While it can be found in all types of bits, roller cones are more vulnerable to this vibration in comparison to shear bits.

A reduction in WOB, increase in RPM, bit design and use of a shock absorber can aid in mitigating axial vibrations.

Lateral vibrations: The bending of the lower part of the drill string and BHA, colliding with the borehole wall. As this impact causes the bit to move laterally, the damage is limited by the diameter of the wellbore. Ergo, a larger diameter will induce a higher impact force. In addition, high rotational speeds induce this vibration while WOB decreases and reduces penetration rates. However, this is not the main source of vibration damage in hard rock drilling.

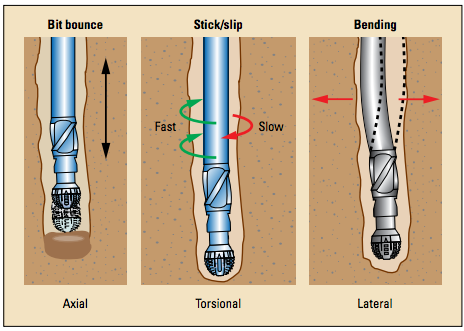


Figure 2‑2 Vibration types ("Drillstring Vibrations and Vibration Modeling," 2010)

Torsional vibrations: Stick and slip vibrations. This vibration is particularly challenging in PDC bits due to its shearing motion, especially when drilling in hard rock formations. Stick occurs when the drill string is twisted and there is almost no oscillating speed. On the other hand, slip is when the drill string’s oscillating speed is several times more than the imposed rotary speed. In essence, this form of vibration damage causes a twist in the drill string.

Depending on the situation, an increase in weight is needed to overcome torsional force in order to engage the PDC bit. However, the reactive torque may be unable to overpower the additional WOB immediately causing the bit’s speed to either reduce or stop as torque is restored throughout the drill string. Once the required torque has been achieved, the bit violently rotates, causing severe damage to the bit. While it has been investigated that this vibration does not directly negatively impact the bit, it is the fluctuation between WOB, torque and shock loads that cause tooth breakage, reduction in bearing and seal life. This vibration is highly prominent in hard rock formation drilling ("Drillstring Vibrations and Vibration Modeling," 2010).

#### Heterogeneous Formation

In comparison to soft rock drilling, hard rock drilling poses certain challenges. Contrasting both scenarios; technology and cost are some of the issues taken into consideration that can be vastly different. The primary root can be attributed to the imbalance of formation pressure induced by interbedded formations (Dykstra, Schneider, & Mota, 2011).

Over pressurised shale beds interbedded between normal pressure sand and carbonate layers causes a contrast in the pressures arising drilling instability. This formation heterogeneity is particularly problematic when the alternating layers of hard and soft rocks are within close proximity to one another. Due to the nature of these high strength and interbedded formations, sudden load changes to the bit and drill string contributes to damages and apparatus wear. Due to the nature of heterogeneous formations, down hole equipment are susceptible to vibrations leading to short and slower bit runs (Saif, 1982).

#### Bit Wear

Cutter inserts are gradually worn down throughout the drilling process, which is common when drilling in hard rock formations. As mentioned, vibrations and impact damage with the formation cause bit wear. The wearing of the bits is continued until a bit trip needs to be conducted. It is possible to continue drilling with damage inserts by increasing the WOB but this will exponentially increase the wear rate of the bit. If tattered bits are used beyond its limit, it can lead to an under gauged hole.

While bit changing trips have the potentially to be more time consuming, it could be a better decision; which is what the ROP prediction model (discussed in chapter 3.2) is developed for.

#### Under gauged well bore

Throughout this section, under gauged has been mentioned multiple times. This is a result of bit wear. After prolong wear on the bit, the length of the inserts shorten leading to a smaller well bore diameter than initially planned. This can cause problems when trying to pull the drill string out of the hole causing a potential stuck pipe.

Stuck pipe is the blocking of the BHA caused by the formation. It is possible to loosen the pipe through various methods; in some cases, this may not be successful. The worst scenario would be side tracking. To prevent situations like this, the bit should be replaced when bit wear has become too drastic and a use of an under reamer can mitigate the situation.

#### Cutting removal

Yet another issue faced by drillers during hard rock operations is the removal of cuttings. During this procedure, the cuttings commonly associated with hard rock formations have a smaller diameter. The use of a TCI cutter generates finer cuttings. If cutting transport does not efficiently removed these cuttings, will clog up the wellbore causing other problems; ergo a stuck pipe (Santos, Placido, Oliveira, & Gamboa, 2000).

## Bit Technology

The action where a bit is used to cut through the Earth’s crust, producing a pathway to resources is known better known as the drilling process. In this process, a driving mechanism originating from the surface drives the drill bit through the crust. As a mean to provide better steerability, a BHA is attached above the bit to be used as a driver.

Rocks can be broken in order to create a well by several different methods. The primary method that will be taken into consideration in this report is the Mechanical Breaking method. Through this method, the intended rock formation is exposed to mechanical or kinetic energy. The source of this energy is transferred from the bit to the formations, which induces a stress on the rock. This introduction of stress generates fractures and thus breaks the rocks.

Various technologies are available, each for a different purpose. The following chapter will be discussing various bit technologies available currently in the hard rock drilling process related to the mechanical breaking method.

For a rock breaking process to be performed as part of the drilling method, several considerations need to be noted. There are three areas of concerns:

1. Mechanical energy transferred from the bit to the rock, generates fractures and crushes the rock and thus enabling hole cleaning.
2. Secondary effects of rock and bit impact. Bit wear, drill string dynamics.
3. Cuttings removed from borehole. Effective cutting transport to prevent clogging and increase penetration rates.

In this scope, there are four methods of mechanically breaking down a formation, which can be categorised as the following:

* Shearing/grinding bit (via rotation)

Usually considered PDC and ID bits. These bits use a shearing motion or scraping motion to drill through the formation. PDC bits have fix cutters with no moving parts and require less WOB. When used in the context of soft to medium formations, PDC bits have the ability to drill faster for longer. However, in the application of hard rocks, there are issues associated to using this bit. ID bits are commonly used in abrasive environments as it has higher resistance.

* Crushing bit (via rotation)

Occasionally referred to as crushing bit, rotating bits (also known as roller cone bits), break the rocks as teeth successively come into contact with unbroken areas of the formation. With every rotation, a new cone comes into contact, thus crushing the rock underneath.

* Percussive bit (via hammering motion)

This uses impact, collision or vibration shock in order to create a wellbore. It uses the repetitive motion of a piston applying an impulse to the bit instead of WOB to load the rocks into compression. This impact may yield high penetration rates. However this isn’t the most developed method for hard rock applications.

* Rotary-percussive bit (via both rotation and hammering)

Lastly, these bits are developed with a combination of crushing and shearing motions, commonly referred to as hybrid bits. They are used to improve drilling mechanics and provide dynamic stability within the bit in a given formation.

### Polycrystalline Diamond (PDC bits)

Bits with a thin layer of polycrystalline diamond material supported by a tungsten-carbide substrate or steel matrix body is commonly referred to as a drag bit or PDC bit. An assortment of individual cutters line the body of the bit that is grouped on discontinuous blades (Detournay & Defourny, 1992). Due to the extreme hardness of the tungsten-carbide matrix body, the material is resistant to abrasions and erosions. However, the same cannot be said for the steel matrix body. In this case, the material is ductile, tough and capable of withstanding a higher impact loading but it is not as resistant in terms of abrasive wear.

As the bit does not consist of any moving parts, it works by crushing the rocks in a shearing motion. Subsequently, the bit is able to operate at higher rotational speeds and lower WOB in comparison to roller cone bits. In addition, with the lack of moving parts, the need to consider temperature bearings, seals and lubricants are minimised. This is an advantage associated with these cutter types when drilling in high temperature environments such as a geothermal drill (Energy, 2010).



Figure 2‑3 PDC bit (Martin & Jacobsen, 2002)

When studying the mechanics of rocks, rock formations are weaker while in tension. The shearing motion of the bit causes a tensile failure in the rocks, which in turn produces a higher penetration rate. In typical drilling conditions, this is a more efficient mode of rock breaking compared to other methods (Energy, 2010). It has been made popular within the industry thanks to its long bit life and ability to maintain a high ROP. Despite undergoing continuous development to improve resistance to abrasive and impact wear, due to its current limited resistance, it is the bit of choice when drilling into only soft to medium rock formations (Detournay & Defourny, 1992).

As the focus of this study is in geothermal and hard rock applications, it can be noted that PDC bits are unconventional in these environments. There are a couple of reasons behind this. As previously stated, its limited resistance to wear, cutter deterioration, high costs and mitigated risks associated to the environment. The large impact wear for the bit is attributed to the dysfunctional vibrations that occur as a result of drilling in hard rock formations (Energy, 2010). Considering that the cutters are designed with a smaller diameter, this causes stability issues and technical obstacles that contribute to significant wear. These stability issues impact ROP performance as well. By working on bit stabilisation, there is a possible to enhance durability and improve ROP, which will result in the reduction of diamond degradation and energy efficiency respectively (Mensa-Wilmot, Soza, & Hudson, 2003).

The design of cutters can reduce cutter deterioration caused by impact damage, durability and efficiency. Along with technological advancements and studies performed by Sandia Laboratories and Amoco Research Centre, significant design modifications can be implemented to enable use in hard rock drilling applications (Clayton, Chen, & Lefort, 2005)

The significance in damages cause by impact and abrasion on the bit causes performance limitations and highly inconsistent operations within the hard rock application scope (Hareland, Nygaard, Yan, & Wise, 2009)

### Impregnated Diamond Bits

This is another example of shearing bits however; it uses a grinding motion rather than a cutting motion to break the rock formation. Impregnated Diamond (ID) bits are made of synthetic diamonds that are sintered to a metal bonding powder with the intention to be used for drilling into hard or abrasive rock formations. With the integration of either natural or synthetic diamond within the matrix, ID bits have a higher durability. This bit is versatile with its intended use as it has the ability to drill in a variety of formations; abrasive low strength sedimentary formations in typical drilling conditions to the competent ultra-hard igneous and metamorphic rocks found in geothermal conditions. In this bit, blunt cutters have been replaced by sharp diamonds that are embedded within the matrix body (Mostofi, Franca, & Richard, 2013).

It is suitable for drilling in harsher conditions compared to formations that would be accustomed for PDC bits. It is able to achieve this as its high-speed ploughing action damages the cementation between inter-rock grains. However, with this rock breaking method, the drilling process slower due to the low depth of cut per revolution.

Another disadvantage associated with this bit is its significantly low energy efficiency when contrasted against both roller cone and PDC bits. To meet an adequate ROP, the rotary speeds of the ID bits need to be high.

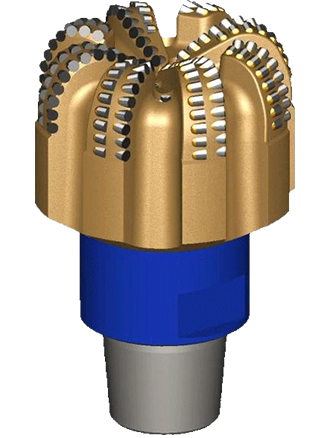


Figure 2‑4 ID bit

In relations to ID bits, drillability is known as the relationship between the thrust load and specific energy or rate of penetration. Specific energy is noted to be the energy required to drill per unit volume of rock and the rate of penetration is the average of the drilling rate with few centimeters of drilling. Both of these are also related to rock properties, such as hardness, strength and abrasiveness (Mostofi et al., 2013).

### Roller Cone Bits

This bit is designed to crush rocks under impact. Due to this crushing action, a high WOB is required to penetrate the rock formation and it is associated with relatively low rotational speeds. The roller cone bit is the bit of choice for drillers when dealing with deep, hard rock formations on account for its ability to penetrate abrasive and brittle rock.

Drilling with a roller cone bit is achieved by the energy transferral from the rotation of the drilling string to the cones causing them to rotate with a little skidding. There are different design considerations that need to be taken into account when using roller cone bits for soft and hard formations. In order to be used in hard rock applications, the following characteristics need to be present in the bit:

1. Close tooth spacing
2. Short and rounded teeth
3. Low penetration and cuttings generation
4. Low cleaning requirements (flow rate)

Ideally, the bit should have a combination of large journal angle, no offset and minimum variation in cone profile.



Figure 2‑5 Roller cone bit (Martin & Jacobsen, 2002)

If the secondary effects are considered, there are several bit wear and failure issues.

As established in the Section 2.2.1 – PDC bits, bits consisting of moving parts are more susceptible to wear, failure and damage in high temperature environments, heavy loading and vibrations. The roller cone’s entire bit design is made up of moving parts in the form of bearings, seals and lubricants. These internal components may degrade due to high temperatures posing an issue in geothermal drilling. To combat this, there has been a development of temperature resistant elastomers and grease to be used in HTHP drilling (Orazzini et al., 2012).

While roller cones are inclined to experience torsional and lateral vibrations, it is more prone to axial vibrations, which causes the most damage to the teeth. Crushing and grinding action can result in high impact loads and abrasion from drilling in hard formations more.

In the technological development of roller cone bits, the most advance material that has been used is the tungsten carbide insert (TCI) bits. The selection of TCI is based on the properties and location of these inserts in relations to the bit. Inner row inserts tend to have a lower rotational speed about the cone and bit axes have the tendency to scrape rather than roll. For this reason, softer but tougher insert grades are chosen in this application. The outer rows consist of harder, more abrasive wear resistance tungsten carbide grade. The bit-rock interaction for roller cone bits is a complicated process and challenging to model.

### Percussive drill bits

This method of drilling was initially used in the mining industry. With recent developments in technology, modifications have been done to be applicable within the oil and gas industry. Percussive drilling uses a crushing motion by means of repetitive impact, collision or vibration shock in order to break the rocks. The drill string is continuously rotated, reducing the risk of a stuck bit, improvements in cutting transport and to ensure the bit collides with an unbroken segment of rock. A piston strikes the rear of the bit, creating a shock wave of energy transfer through the bit and into the formation. This method of rock breaking disposes the need for a steady weight so less WOB is required when targeting the same ROP. To protect the bit from excessive wear, a shock absorber may be added to the BHA.

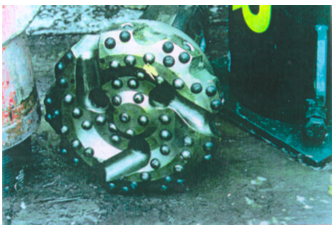


Figure 2‑6 Percussive Bit (Santos, Placido, Oliveira, & Gamboa, 2000)

As stated in the journal by (Santos et al., 2000), its utilisation decreased as its effectiveness was questionable. There are different types of percussive drill bits available in the industry today. With recent technological advancements, hydraulic hammer drills have been developed to operate in higher operational pressures as well as drill into deep, hard and abrasive formations.

Pneumatic hammer drills are currently commercially available. It has been announced that pneumatic hammers can be applicable for wells up to the depths of 4600 m in the hard rock environment of the Middle East (Vieira, Lagrandeur, & Sheets, 2011). This hammer drill can be appropriate for use in formations where there is an absent of drilling problems commonly related to pneumatic drilling.

### Hybrid bits

#### Kymera Hybrid bit

There have been an incline in technological advancements related to drill bits. Hybrid bits have been designed to fuse advantages of two different bits with one another allowing drilling operations to take place in harsher and deeper wells.

A hybrid bit developed by Baker Hughes, Kymera, has been designed with both crushing and shearing actions taken into account. It can either been seen as a bit with the standard properties of a roller cone bit with shearing capabilities or a shearing bit with crushing capabilities. When drilling in hard and abrasive formations, the PDC bit is susceptible to harmful vibrations causing damage to the bit and roller cone bit speeds are too low.

For the individual roller cone and PDC bits, torque on bit and ROPs are intermediate. In the case of the Kymera bit, higher power inputs and penetration rates are possible, achieving fewer vibrations ergo bit damage (Pessier & Damschen, 2011).



Figure 2‑7 Kymera Bit ("Drill Bits Catalog," 2013)

#### Hybrid bit: Tarim Basin

In the Tarim Basin, located in the Autonomous region of China, there have been new developments in the design of hybrid bit design to be used in ultra deep and hard rock conditions. When focusing solely on conventional PDC bits with fixed cutter design, it’s noted that the bit struggles and incurs severe damages whilst drilling in hard and interbedded formations. Additional trips are required to replace PDC bits with ID or roller cone bits, inducing higher drilling and operation costs. The current challenge faced by the modern industry is maintaining a low cost per foot when dealing with harsher conditions. A solution to this was to improve existing bit designs. The focal point in these design improvements was to develop a bit that would be durable enough to drill to a desired interval with the best possible penetration rate (Nicholl, Garcia, Barocio, Sha, & Jian, 2013).

In ultra deep and hard formations, the challenge is drilling through the presence of conglomerates. This formation is particularly damaging to fix cutters due to its high impact and abrasive nature. Along with this, heterogeneous formations with interbedded and challenging lithologies is not typically drilled using solely PDC bits or fix cutter bits to the total depth. During the bit trails, new drill bit technology developed a fusion between two current fixed cutter materials. This would allow for greater versatility for a wider range of lithologies and address the above-mentioned concerns related to formations. The new bits have been designed to be structurally durable with included material enhancements and improved cutter arrangements extending overall durability.

With the abrupt changes in formation types, typical PDC cutters are heavily impacted and damage causing mechanical failures. The improved bit design benefits by using a dual cutting structure. An engineered mix of impregnated materials is incorporated as part of PDC blades, achieving an increase in bit life and extended run lengths. This fusion bit in turn creates qualities not previously possessed by traditional fix cutter bits. Its dual function tolerates faster drilling through softer formations whilst maximising durability in harder formations.



Figure 2‑8 Tarim Hybrid Bit (Nicholl, Garcia, Barocio, Sha, & Jian ,2013)

### Factors impacting bit lifetime

As covered briefly in the beginning of this chapter, there are multiple factors that impact the lifetime of a bit. Some of these factors are:

1. Rock hardness/abrasiveness
2. Vibrations
3. Temperature
4. PDC cutter design

A bit’s life can be shortened in the presence of high silica, quartz or conglomerate content within the lithological formation. The heterogeneity of these formations increases abrasiveness, thus incurring difficulty to drill. Due to the complexity of interbedded layers of over pressured shale beds and normalised pressured sand and carbonate layers lead to abrupt load changes to the drill bit and drill string. These sudden load alterations causes various unwanted vibrations upon the bit.

#### Roller Cone bit

As a consequence of alternating heterogeneous layers, undesirable vibrations occur. When drilling with roller cone bits, the prominent vibration that the bit is vulnerable to is axial vibration. Due to the downward impact motion of the bit into the formation brought upon by the cutter rotation, the high impact force causes serious damage on the bit. This high impact force induces damages to not only the bit but also the down hole equipment, especially cutters and bearings. With the extreme cutter wear, the bit is unable to efficiently penetrate the formation exponentially increasing bit wear and damage.

In high temperature environments, heavy loading and vibrations, the roller cone has a disadvantage due to its moving parts. Bearings, seals and lubricants are unable to withstand high temperate environments faced amid deep and geothermal drilling. These internal components have a tendency to degrade as a result. This degradation leads to a reduced bit life, as it would not be able to function optimally. While there are developments in the form of temperature resistant elastomers and grease that can be used in HTHP drilling, bottom hole temperatures can reach over 300°C posing potential risk on using a bit with moving parts (Orazzini et al., 2012).

#### PDC bit

In terms of PDC bits, the vibrational impact that has a major influence on bit life is torsional vibration. The result of the twisting motion is detrimental to the internal components of the bit. When using a PDC bit to drill in hard rock, this is the parameter that needs to be taken into account.

In addition, the main decider on the bit component in regards to bit lifetime is cutter wear. Regardless of the extreme hardness of the matrix body, the cutters do not comprise of materials with the ability to withstand abrasive wear over a prolong period. In PDC, most of the impact wear is attributed to cutter deterioration. Continual improvements to cutter design have the potential to reduce cutter wear. However, attention needs to be given to the diameters of the cutters. A smaller diameter would increase stability issues that can cause lateral vibrations and significant wear, reducing the lifetime of the bit and drill string. Not only does wear occur, but also ROP performance is impacted. Working on bit stabilisation can possibly enhance durability and improve ROP. A combination of these can develop in a reduction of diamond degradation and energy efficiency respectively (Mensa-Wilmot et al., 2003). All these parameters incorporated may increase the lifetime of PDC bits.

Unlike roller cone bits, the PDC bit has minimal moving parts; lessening the concern to ensure the bit is able to withstand and remain function in high temperate environments; prolonging bit life.

In 1944, laboratory tests were conducted and it was established that solely the drill collars should apply WOB. If it was applied directly to the bit, the drill pipe would in compression, sharply reducing the lifetime of the drill pipe causing more trips to the surface to be replaced. There was an indication that WOB on a compressed drill pipe did not conclude that the weight is applied at the bottom (Johnston, 1947). With regards to WOB, if the WOB and rotary speed is too high, it can reduce bit life despite the increase in ROP. To achieve the optimum ROP and bit life, the combination of rotary speed and WOB is significant (Graham & Muench, 1959). The combination of all these factors has the potential of reducing rig time and drilling costs.

## Established fields

This segment provides a concise examination of various well designs and drilling equipment used throughout the operations of the following fields. Also included is a lithological and stratigraphical overview of the fields and challenges associated with hard rock drilling. The fields chosen were based on well depth and rock formations present. A mixture of ultra deep, hard rock formation and geothermal fields were chosen for this section of the study to be compared with and used to develop the ROP model.

### Iceland Deep Drilling Project

The Iceland Deep Drilling Project (IDDP) is a government incentive program aimed at harnessing geothermal energy in favour of reducing environmental impact and to improve economics. While there are multiple exploration wells drilled in the area, under the Project, two out of three proposed wells have been drilled; IDDP-1 and IDDP-2.

The purpose of exploring these wells is to investigate how practical it would be to utilise supercritical fluids as an energy source. These geothermal fields have supercritical conditions, which exceed the critical point for fresh water: 374 °C and 22.12 MPa. The supercritical conditions increase with the increase of water salinity. The hydrous fluid systems are able to exist at these supercritical conditions due to the underlying natural hydrothermal system that are within the volcanic complexes. This gives the expectations that well temperatures can reach over 600°C (Pálsson et al., 2014) .

Through the use of drill cutting analysis and geophysical logs, mineralogy and lithology were concluded. The primary lithologies encountered by engineers were Holocene lavas and various basalt deposits from the volcanic environment in the underlying region. The basalt deposits contained a mixture of pillow and both fine and coarse grained basalts.

#### IDDP-1

In the subsequent section, the first of the wells under the project, IDDP-1, will be discussed in further detail. The well is located in the Krafla Geothermal Field and was drilled by the National Power Company of Iceland, Landsvirkjun.

The total vertical depth drilled was 2101 m, instead of the designed 4500 m due to the presence of magma body, preventing further drilling. From the initial starting point to the depth of 1362 m, basaltic lava and hyaloclastic formations were primarily present. Between the depths of 1362 to the point of lava intrusion (2101 m), the formation composed of dyke complexes.

#### Stratigraphy

IDDP-1 is located within the Krafla Geothermal Field on the Krafla central volcano in northeastern Iceland. Consequentially, the geothermal field has been divided into four sub-fields of which the IDDP-1 well is located in the area known as Leirbotnar. The Krafla volcano is an active volcano with fissure eruptions forming Holocene. With the continual volcanic activity, the geothermal system regularly receives a renewed heat supply and it has been known that this area has been affiliated with a magma chamber underneath. Krafla rock stratigraphy comprises largely of basaltic lavas and hyaloclastic ridges, similar to the composition of volcanic and plutonic rocks in such an environment (Mortensen, Egilson, Gautason, Árnadóttir, & Guðmundsson, 2014).

The stratigraphy of the well was analysed through the collection of cutting samples at an interval of 2 m during the operations. In Table 2-3, the simplified stratigraphy of the well is presented as written in accordance to the report by (Mortensen et al., 2014). There are extremely high levels of constituting intrusive rocks in the field at very shallow depths as compared to previously drilled Icelandic geothermal fields. This could be a reflection of the underlying magma chamber during the Krafla Fires, the most recent volcanic episode in 1984.

Table 2‑3 Stratigraphy of IDDP-1

|  |  |  |  |
| --- | --- | --- | --- |
| **Upper 1362m - Basaltic Lava + Hyaloclastite FM** | | | |
| **Range (m)** | | **Thickness (m)** | **Lithology - simplified** |
| 4 | 42 | 38 | Holocene lava + breccia |
| 42 | 240 | 198 | Alt. basaltic hyaloclastite |
| 240 | 872 | 632 | Basaltic Lava (med - coarse grained basalt) |
| 872 | 952 | 80 | Hyaloclastite (fine - med grain Basaltic Tuff) |
| 952 | 1362 | 410 | Basaltic + Basaltic Lava |
| **Lower 1362m - Dyke complex until 2104m where rhyolitic lava intrusion** | | | |
| 1362 | 1700 | 338 | Basaltic Dyke Complex |
| 1700 | 2000 | 300 | Basaltic Dyked + Breccia |
| 2000 | 2070 | 70 | Basaltic Dyke + dolerites |
| 2070 | 2101 | 31 | No cuttings revealed |
| 2101 | 2104 | 3 | Magma |

#### Initial well design

Previously, 200 high temperature wells have been drilled within the volcanic rift zone to the depths ranging between 2 to 3 km, reaching bottom hole temperatures of up to 300°C. The well designed used were standard designs, comprising of either “regular diameter” or “large diameter” types. (Pálsson et al., 2014)

The IDDP-1 well was designed to produce from supercritical reservoirs between the expected depths of 3500 – 4500 m. Taking into consideration the extreme conditions expected for the well, two addition intermediate casings were included in the initial designs. As a result, five casings, a slotted liner and seven corings were anticipated in the design. Table 2-4 is a tabular representation of the design inclusive of technologies that would have been used.

Table 2‑4 Initial Well Design IDDP-1

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Casing** | **Bit** | **Depth** | **Casing Type** | **Mud** |
| Surface | 26” tricone | 0 – 100m |  | Bentonite mud |
| Intermediate I | 24.5” tricone | 100 – 300m | 162 lb/ft K55, Tenaris ER Threads | Bentonite mud |
| Intermediate II | 18 5/8” tricone | 300 – 800m | 114 lb/ft K55, BTC Threads | Bentonite mud |
| Anchor | 16.5” tricone | 800 – 2400m | 88.2 lb/ft T95, Tenaris/Hydril 563 Threads & 72 lb/ft K55, Tenaris/Hydril 563 Threads | Bentonite mud – potentially water |
| Production | 12.25” tricone | 2400 – 3500m | 53.5 lb/ft K55, Tenaris/Hydril 563 Threads | Bentonite mud – potentially water |
| Slotted liner | 8.5” tricone | 3500 – 4500m | 26 lb/ft K55, BTC Threads | Water |

#### Actual well design

This well experienced several difficulties during the drilling process; not limited to getting stuck and intrusion of magma at 2096 m. As a consequence of these difficulties, the BHA was changed approximately 14 times due to bit wear, fishing and multiple sidetracks.

As stated, the primary lithology is high-UCS basalt. To penetrate this formation, tricone roller cone bits were used for the entirety of the well, which was already approved in the initial well design. As expected, due to the stratigraphy, the average ROP would be relatively low. However, it was unexpected to experience a severely low penetration rate of an average of 2.5 m/h.

Table 2-5 illustrates the conditions and technologies that were used throughout the progress. It can be noted that there are significant differences between both well designs generated by the unexpected and premature intrusion of magma. (Pálsson et al., 2014)

Table 2‑5 Actual Well Design IDDP-1

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Casing** | **Bit** | **Depth** | **Diameter** | **Casing** |
| Surface | 26” tricone pilot bit | 0 – 87m | 32 ½” | X56 |
| Intermediate I | 26.5” tricone milled tooth bit | 87 – 254m | 24 ½” | K55 |
| Intermediate II | 23” roller cone | 254 – 785m | 18 5/8” | K55 |
| Anchor | 16.5” tricone | 785 – 1935m | 13 5/8” | 13 3/8” | T95 | K55 |
| Production | 12.25” tricone | 1935 – 1949m | 9 5/8” | K55 |
| Peak C Flex RPL P-110 | 8.5” tricone |  | 10.4” | SC 09 004 |
| Slotted liner |  | 1949 – 2072m | 9 5/8” | K55 |

**Surface Casing:**

The entire operation for this section took a total of nine days and had a diameter of 32”. A ø26” tricone pilot bit with a 36” under reamer was used to drill in addition to bentonite-based mud as the drilling fluid.

**Intermediate I Casing:**

The first part was drilled using a ø26.5” Hughes Christensen tricone milled tooth bit with water based mud, however a mud motor was not used. Due to the hard formations present, an average ROP of 2.5 m/h was measured and no circulation losses were detected. This portion was drilled to a depth of 275 m however was cased with a ø24.5 casing at 260 m as a consequence of wellbore problems. The duration of this operation was six days.

**Intermediate II Casing:**

As the formation was still hard, ø23” Hughes Christensen roller cone bit was used in conjunction with bentonite mud. To keep the hole vertical, a low WOB was used, which progressed the drilling process slowly. At the end of this section, the well was at a depth of 788 m and was cased at 784 m with a diameter of 18 3/5”. Completing this job took a total of twelve days.

**Anchor Casing:**

This section of the drilling process encountered a variety of issues, as a result taking an approximate two months to be completed. During this time, three fishing operations for the BHA and a sidetrack were carried out. The BHA consisted of:

* Ø16.5” roller cone tricone bit
* Ø9.5” mud motor with a sleeve
* Two ø16.5” stabilisers
* Anderdrift tool
* Ø9.5” and ø8” drill collar
* Shock sub
* Jar
* Heavy weight drill pipes (HWDP)

During the establishment of this casing, 5 major events occurred.

1. The float sub twisted apart in the BHA and a fishing operation happened at 1194 m.
2. A POOH was decided when the ROP was varying between 3 to 5 m/h and gradually decreased. Parts of the BHA were under-gauged and not functioning properly so it had to be replaced.
3. Extreme losses were recorded and a cement job was conducted in the loss zones. The bit was severely damaged after being in rotation for only 47 m; all the carbides in the outer rows were broken off.
4. The ninth BHA was RIH with a successful run. The fresh bit surpassed one million revolutions prior to POOH for a bit change. The continuation of drilling produced slow ROP due to the formation hardness.
5. Another fishing operation needed to be carried out, which was successful at 2074 m.

After the continuation of the second fishing operation, torque fluctuated in the well, eventually breaking the BHA again needing a third fishing operation. However, it was unsuccessful after 6 days of NPT and a sidetrack was decided. Conditions within the well were more complicated than anticipated, with an unstable formation and hole cleaning difficulties. All these events lead to a modification in well design. The anchor casing was finally set at 2000 m (instead of the targeted 2400 m) and with an unstable wellbore, the casing was made up of two different sections with varying thicknesses and materials.

**Production Casing:**

A decision was made to use a ø12.25” drill bit in a ø16.5” hole. High viscous pills with relatively low ROP and pumping rate was used prior to increasing the pumping rate and rotate the drill string axially (up and down). This process was repeated every 3 m until the depth of 2005 m was reached. During this procedure, several corings were obtained and it was discovered multiple times that the bit were completely worn. At the depth of 2103 m, the drill string was stuck and another fishing operation needed to be done. The stuck drill pipe could have been caused to the collapse of cement. This operation was deemed unsuccessfully and the second sidetrack was conducted. Basalt cuttings were observed with a temperature of 340°C. Towards the completion of this well, at 2096 m, the ROP was doubled from 2m/h prior to drilling into magma, signifying the end of the drilling operations (Pálsson et al., 2014).

The actual well design, with the first attempts at drilling to depth and the inclusion of two additional side tracks is represented in Figure 9 by (Pálsson et al., 2014)

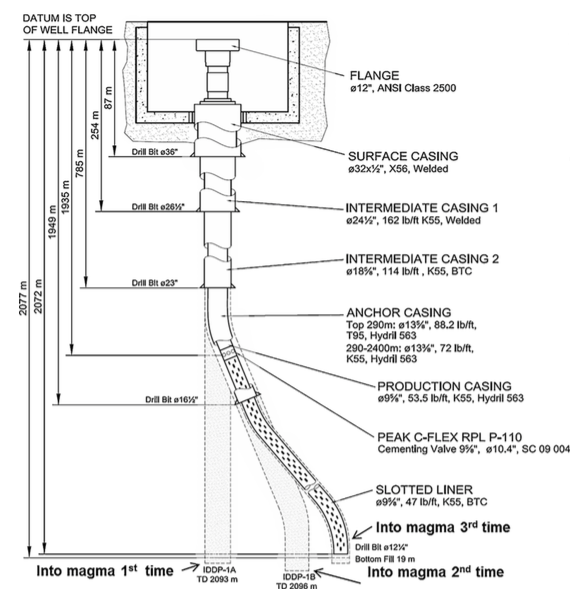


Figure 2‑9 IDDP-1 "As Built" (Pálsson et al., 2014)

#### IDDP-2

Due to the economic crisis in Iceland, modifications to the initial plans were done for the remaining two proposed wells. HS Orka Energy Company picked up the IDDP-2 well with considerations in drilling it in the Reykjanes Field, as part of its power plant expansion. In addition to this, the principle goal was to improve the overall geothermal economics through the drilling of productive wells. For this field, the measured temperature at the bottom of the well was 427°C with pressures of 340 bars. The drilling operation for this well took a total of 168 days (Friðleifsson et al., 2014).

#### Stratigraphy

The geological system of IDDP-2 resembles that of the mid-ocean ridges black smoker hydrothermal system, where by the highest recorded temperature is 464°C. In the Reykjanes Field, there has been approximately 16-production wells drill ranging to the depths of 2 – 2.5 km. The record temperature in this field was 345°C, measured at the bottom of production well RN-17B.

As mentioned, the site is a submarine geothermal system, indicating that the geological progression is a constant accumulation of volcanic strata within a submarine environment (Friðleifsson et al., 2014).

The predominant lithology of the well is pillow basalt with phreatic tuffs and dyke complex intervals due to the volcanic strata. The dyke complexes occur interbedded with the pillow basalt in intervals of 100 – 200 m in thickness. Similarly to IDDP-1, the volcanic activity operates as a heat source to the geothermal system. Commonly in lithologies such as this, permeability would be poor, however with the frequency of earthquakes, the permeability of the formation is good and maintained as such (Guðmundur Ómar Friðleifsson, 2017).

Table 2‑6 Stratigraphy IDDP-2

|  |  |  |  |
| --- | --- | --- | --- |
| **Depth Range (m)** | | **Thickness (m)** | **Lithology** |
| Surface | 60 | 60 | Holocene Lava flow series |
| 60 | 400 | 360 | Sub-glacial/submarine hyaloclastite |
| 400 | 1100 | 700 | Phreatic tuffs with shallow marine fossil ferrous |
| 1100 | 1400 | 300 | Sub aerial lavas (Pleistocene age) |
| 1400 | 3000 | 1600 | Pillow Basalt formation |

### Larderello

The world’s first geothermal complex, Larderello, is located in Southern Tuscany, Italy. The field sits upon an area of high volcanic activity, hosting its reserves in Mesozoic Carbonatic formations with a metamorphic basement. The exploration and production of this area was driven by the concept of using high temperature geothermal wells to generate electricity, with over 800 wells drilled. The complex has been drilled to depths ranging from 500 to 3000 m (an average of 2000 m), experiencing temperatures varying between 200 – 350°C. There are five defined lithologies within the complex; namely Volcanites, Ligurids, Tuscan Nappe, Tectonic Wedge Complex sitting upon a metamorphic basement (Giovanni, 2005).

#### Stratigraphy

In reference to geological ages of the rock formation in this setting, there are four: Lower Miocene, Eocene to Lower Cretaceous, Triassic and Paleozoic. The stratigraphical make up of the Larderello field is indicated through three tectonostratigraphic elements. The shallowest of these was established during the Late Miocene to Pliocene Epoch, consisting of continental to marine sediments. The middle element is the Ligurian Complex composed of remnants of a Jurassic oceanic basement. The rock types usual to this age are mixture shales, limestones and sandstones. Finally, the deepest of the elements is the Tuscan Unit (Tuscan Nappe), which is related to the Late Triassic to Early Miocene sedimentary. The make up of Tuscan Nappe is carbonate and quartizitic rock with extremely high UCS due to its nature.

As mentioned previously, the entirety of the geothermal field sits atop a metamorphic basement, constituted of two units; Upper Monticiano-Roccastrada Unit and the lower Gneiss Complex. The former of these complexes has a primary disposition of quartzite, phyllite and mica schist, all known to extremely hard to penetrate. The latter lower Gneiss Complex has a foundation of gneiss, another formation with high UCS values (Fausto Batini, 2003).

Table 2‑7 Larderello Lithology

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Range (m)** | | **Thickness (m)** | **Structure** | **Age** | **Corresponding rock** | **UCS (MPa)** |
| 0 | 280 | 280 | K- alkaline Volcanites | Lower Miocene | Neogene Sed |  |
| 280 | 910 | 630 | Ligurids | Eocene - Lower Cretaceous | Shales, Limestone (+marly LM), Sandstones | 103 - 120 |
| 910 | 1500 | 590 | Tuscan Nappe - terrigenous (marine sed) | Upper Trias | Marine Sed | 120 |
| 1500 | 2000 | 500 | Tuscan Nappe - carbonate | Quartzitic, Evaporitic, Carbonate | 275 |
| 2000 | 2280 | 280 | Tectonic Wedge Complex |
| 2280 | 3000 | 720 | Paleozoic metamorphic "basement" | Paleozoic FM | Mica schists, Phyllites | 199.5 |
| 3000 |  |  | Magmatic body | Gneiss |

### Tarim Basin

The Tarim Basin inhabits an area of approximately 906 500 km2 in the Xinjiang Uyghur Autonomous Region of the north west of China. It is known to have large reserves and multiple fields. The Tarim Basin is known for its ultra deep wells, ranging at an average depth of between 6000 – 7000 m, commonly associated with carbonate rock reservoirs. In some areas, the carbonate rocks have been up to a cumulative thickness of over 2000 m. Over the last many years of development through logging data over 10 drilling wells, large quantities of oil and gas (primarily natural gas) have been detected in this area (Huang et al., 2017).

As there are various sectors of this large basin, this information specifically is derived for the Xinken oil Field. The pay zone is sat in the Ordovician age, particularly the Middle Ordovician Yinjianfang to Middle Lower Ordovician Yingshan Formation, which is at a depth of 6000 – 7000m. In the Ordovician carbonate pay zone, differently developed grain stones, micrites and limestones are the make up of the lithology.

#### Stratigraphy

With over 20 wells drilled during the exploration for oil and gas, it was identified that the lithologies was from the Paleozoic Era consisting of carbonate rocks. Carbonate rocks were developed in various formations, notably the Lower-Middle Ordovician Yingshan Formation (dominated by limestone and dolomites) and Middle Ordovician Yijianfang Formation (clastic rock prevalence). These two notable formations are the oil-bearing layers hence it will be discussed further (Song et al., 2013).

Taking into the consideration that this Basin’s pay zone comprises of carbonate rocks, the permeability and porosity of this matrix is poor. The gas reservoirs were situated in limestone and dolomite. This basin’s cap rock lithology, referred to as the Tumuxiuke Formation, is primarily tight marls and mudstones, which acts as an excellent and stable reservoir seal. The overall consensus for geological conditions is considered good.

The two essential formations of this field are referred as the Yingshan and Yijianfang formation. The lithology of the Yinghsan formation is characterised by dominantly sparite calcarenites, sandy micrites and micrites. The former formation (Yijianfang) has layers of oolitc limestones and gravel limestones deposited with micrites. Through core samples extracted, the average porosity was 1.39% with an average permeability of 0.34 x 10&-3 microm^2.

With the information provided in the report by Song et al. (2013), it’s established that the formations in this region were developed between the geological ranges of Paleozoic – Mesozoic Era to the late Cenozoic. A more accurate lithological profile of the field is tabulated, Table 2-8, extracting data from the geological histogram in the report.

Table 2‑8 Stratigraphy Tarim

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Approximation from logs in Appendix | | | |  |
|  | **Depth Interval (m)** | | **Thickness (m)** | **Lithology** |  |
| CARBONATE RESERVOIR | 6675 | 6720 | 45 | Mudstone |  |
| 6720 | 6730 | 10 | Calcarenite |  |
| 6730 | 6750 | 20 | Limestone |  |
| 6750 | 6755 | 5 | Marl + Mudstone |  |
| 6755 | 6760 | 5 | Limestone |  |
| 6760 | 6815 | 55 | Marl |  |
| 6815 | 6835 | 20 | Wack stone | Yijianfang FM |
| 6835 | 7000 | 165 | Bioclastic | Yingshan FM |

#### PDC technology.

It has been noted that drilling the production section (ø6-5/8”) of the Tarim Basin is challenging. Starting at a depth of 7000 m, there are very hard and abrasive formations at 300 m intervals. The formation has recorded bottom hole temperatures of 148°C and a mud density of 1.9 sg is used while drilling.

The Bashijiqike formation is a geological unit formed during the Cretaceous Period with quartizitic fine sandstone (comprising 35% quartz) and silificated claystone with conglomeratic sandstone stringers at both upper and lower sections. Due to the abrasiveness of the formation, low ROP with short bit runs are used. The application of roller cone bits and down hole tools with movable parts are limited and opportunities to use it are scarce.

The drill string design for this section has always been a simple rotary BHA consisting of (Botton et al., 2012):

* A bit. The usual bits are locally sourced PDC bits with a 6 bladed matrix. The diameters of the cutters range from ø8 mm to ø16 mm.
* 468 m of 5” spiral drilling collar
* 2565 m of 4” drill pipe
* 5” drill pipe to the surface

### Ceuta Field

The Ceuta Field is a Venezuelan field located in the western side of the country. It is based in the South East corner of the Maracaibo Basin. It produces light to medium grade oil with its pay zone formed in the Eocene age at an average depth of 4940 m.

As previously noted, the applications of PDC bits have been limited to low strength, soft and non-abrasive formations. In the use of hard rock, PDC cutters chip away and fractures due to the impact loading and the heat produced by the shearing motion of the bit, making it unfavourable. Additionally, these bits tend to have shorter runs and extreme wear to the nose and gauge area. For this field, the cutter composition has been optimised to undertake harder formations and extend its application range (Vargas, 1992).

#### Stratigraphy

Sitting at an average depth of 4940 m, the production formation was developed in the Paleogene Period and has been coined Misoa. Misoa has been divided into two sections; Medium Eocene and Lower Eocene seen in Table 2-9.

Table 2‑9 Ceuta Stratigraphy

|  |  |  |  |
| --- | --- | --- | --- |
| **Stratum** | **Epoch** | **Section** | **Lithology** |
| Cenozoic Era 🡪 Paleogene Period 🡪 Eocene Epoch | Medium Eocene | Upper B Section | Shale caps, limolitics, carbonaceous |
| Lower B Section | Sand with sub angular grains |
| Lower Eocene | Upper C Section | Limolitic shales |
| Lower C Section | White and grey sands interbedded dark layers |

* Medium Eocene

Upper B Section: This section is comprised of a mixture of coarse shale caps, limolitics and carbonaceous with layers of hard cuarcitic sand.

Lower B Section: Sand with fine sub angular grains is the make up of this layer. Shale is also interbedded in this portion of the formation.

* Lower Eocene

Upper C Section: Limolitic shales are formed here with white sand.

Lower C Section: White and grey sands with fine grains lay here. Similarly to the Lower B Section, there are interbedded grey to dark shale layers, which are extremely abrasive.

#### Operational conditions

To drill the Eocene Epoch of this field, ø8-3/8” and ø8.5” bits were used. It had an average interval of 1372 m. Traditionally; the formation in this region is drilled with tricone insert bits. The average ROP in the upper sections are 3 m/h (10 ft/h). However, the ROP decreases in the lower sections due to the high sand fraction and ranges between 1.2 – 1.5 m/h (4 – 5 ft/h) on average. High WOB and low RPMs are usually experienced during the operations as well.

The mud weight for the production hole ranges between 1.22 gr/cc used in the Upper B Section to 1.44 gr/cc in the Lower C Sections.

### Vega Field

This field is a gas and condensate field located in the northern sector of the North Sea. The total water depth of this field is 370 m and the reservoirs are located in Middle Jurassic sandstone at a depth of approximately 3500 m. The field has a low permeability and is considered to be a HPHT field. The final TVD of this field is 4344 m and a bottom hole temperature of 152°C (*Well 35/8-1 Completion Report*, 1981)

The wellbore’s geological make up starts off with Pliocene aged rocks before hitting Cretaceous age rocks at a depth of approximately 2111 m with a claystone lithology. This formation stretches until a depth of 3280 m before Jurassic aged formations are drilled through with a primary make up of sandstone for a 500 m thickness. Between 3787 m and the final depth of 4344 m, the lithology is sandstone with interbedded shale. Throughout the shallow section of the field, the ROP is relatively high before drilling into the Jurassic formations where the ROP ranges between 0.72 and 4 m/h.

Table 2‑10 Vega Field

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Age** | **Lithology** | **UCS** | **Depth Interval (m)** | | **thickness (m)** |
| Pleistocene | boulder clay | 137,5 | 402,336 | 440,436 | 38,1 |
| Pliocene | clay/sand | 128,75 | 441,35 | 568,15 | 126,8 |
| Miocene | Sand | 120 | 577,27 | 890 | 312,73 |
| Eocene | Sand | 120 | 986,94 | 1614,22 | 627,28 |
| Upp Cretaceous | Claystone | 137,5 | 1614,22 | 3117,8 | 1503,58 |
| Low Cretaceous | Shales | 103,25 | 3117,805 | 3280,26 | 162,455 |
| Mid Jurassic | Brent SST | 120 | 3526,53 | 3708,81 | 182,28 |
| Early Jurassic | SST/Shale | 111,625 | 3708,805 | 4184,29 | 475,485 |
| Triassic | SST/Claystone | 128,75 | 4184,3 | 4343,71 | 159,41 |

### Valemon Field

This gas and condensate field located west of the Kvitebjørn field sits at a water depth of 135 m. The reservoirs are in the Lower Jurassic sandstone and Middle Jurassic sandstone at a depth of 4000 m. The high pressures and temperatures experienced by the reservoirs make this a HPHT field. Wellbore 34/10-35 is an appraisal well with a TVD of 4304 m and a bottom hole temperature reaching 156°C.

The geological make up of this field ranges from the Holocene/Miocene period from 220 to 1000 m (with a mixture make up of claystone and sandstone) with the Cretaceous bulk of dolomite and limestone up to a depth of 3780 m. The remaining depths are shale with interbedded siltstone and sandstone intervals. The calculated ROP for this field was relatively high for the shallow Holocene/Miocene formations with low penetration rates once Cretaceous rocks were encountered all the way down to the Jurassic formations (G. Gabrielsen, O. Hunnes, G. Tungesvik, & Østby, 1992).

Table 2‑11 Valemon Field

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Age** | **Lithology** | **UCS** | **Depth interval (m)** | | **Thickness (m)** |
| Holocene- Miocene | Clay/SST | 128,75 | 222 | 722 | 500 |
| Oligocene- Low Eocene | SST | 120 | 722 | 1565 | 843 |
|  | Dol/LMS | 102,5 | 1565 | 2136 | 571 |
| Upp Cretaceous | Dol/LMS | 102,5 | 2136 | 3615 | 1479 |
| Low Cretaceous | Claystone | 137,5 | 3615 | 3780 | 55 |
| Upp Jurassic | Siltstone/LMS | 120 | 3780 | 3883 | 103 |
| Mid Jurassic | Shale/Siltstone | 120,375 | 3883 | 3939 | 48 |
| Low Jurassic | Shale | 103,25 | 3939 | 3948,5 | 5,5 |
| SST | 120 | 3948,5 | 4018 | 19,5 |
| Sandy Shale | 103,25 | 4018 | 4078 | 28 |
| LMS/SST | 111,25 | 4078 | 4189 | 111 |
| Shale | 103,25 | 4189 | 4250 | 61 |

### Embla Field

The Embla field, located in the southern part of the Norwegian sector of the North Sea, is a producing HPHT well. The depth of wellbore 2/7-25S reached a total of 5177m with a TVD of 4560 m and a bottom hole temperature of 155°C. The overall lithologies of the rock formations were pre-Jurassic rocks. The primary formation in this area was deemed to be Permian/Devonian sandstones. The formations between 780 to 5000 m were a mixture of claystone and limestone however from depths of 5000 and below, abrasive quartzite was encountered. The general ROP of this wellbore was generally low once the drill bit encountered depths of 3500 m. The measured ROP ranged no higher than 2.4 m/h whilst in the shallower formations a higher ROP was maintained between 7/9 to a maximum of 33.5 m/h (*Well 2/7-25S Completion Report*, 1991)

Table 2‑12 Embla Field

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Lithology** | **UCS** | **Depth Interval (m)** | | **Thickness (m)** |
|  | | 98,7552 | 289,56 | 190,8048 |
| Claystone/ sst | 128,75 | 289,56 | 780,288 | 490,728 |
| Claystone | 137,5 | 783,336 | 1645,3104 | 861,9744 |
|  | | | | |
| Claystone | 137,5 | 3485,9976 | 3493,008 | 7,0104 |
| Chalk | 102,5 | 3551,2248 | 4108,704 | 557,4792 |
| LMS | 102,5 | 4108,704 | 4556,76 | 448,056 |
| Marl | 103,25 | 4560,4176 | 4710,0744 | 149,6568 |
| Clst |  | 4775,6064 | 4782,312 | 6,7056 |
| claystone | 137,5 | 4782,312 | 4801,2096 | 18,8976 |
| lms | 102,5 | 4801,2096 | 4842,9672 | 41,7576 |
| Claystone/ sand | 128,75 | 4842,9672 | 4938,0648 | 95,0976 |
| Claystone | 137,5 | 4962,7536 | 5102,352 | 139,5984 |
| Quartzite | 275 | 5112,4104 | 5159,6544 | 47,244 |
| Claystone | 137,5 | 5173,98 | 5177,028 | 3,048 |

## Rate of Penetration (ROP) Influences

To further understand ROP, factors directly or indirectly influencing penetration rates needs to be established. There are a handful of ways in which factors influencing penetration rate can be categorised. One such was, as proposed by Fear (1999) was to arrange the factors by environmental and controllable.

Table 2‑13 Fear (1999) propose factor categorisation

|  |  |
| --- | --- |
| **Environmental Factors** | **Controllable Factors** |
| Formation type | Bit wear state |
| Formation properties | Bit design |
| Mud type | Weight on bit |
| Mud density | Bit rotary speed |
| Other mud properties | Flow rate |
| Overbalance/bottom hole mud pressure | Bit hydraulic horsepower |
| Bit size | Motor/turbine geometry |
|  | Bit nozzle arrangement |

In this thesis, the proposed classifications for the influences simplify the factors into principle groupings. These factors have been classified into two distinct groups:

* Fixed
* Variable

The categorisations were decided based on the ability to anticipated and taken into consideration during the well design and planning phase. Fixed Factors are pre-existing conditions of the field and formation, which are unable to be altered. Variable Factors are the technical outcomes based on these fixed factors, thus have the ability to be altered at any point during the drill program.

In the following section, an influence diagram has been developed, Figure 2-10. Both classifications influencing ROP are explored in detail. Each factor classification is colour-coordinated, providing a visual representation of either fixed (orange) or variable (blue) categorisation.

### Influence Diagram ROP

Formation type and properties from Table 2-14 have been deduced to Rock Hardness and Formation pore Pressure, both of which are fixed factors. The some of factors listed in Table 2-14 has remained as is, while others have been reduced. The final factors categorised under variable are WOB, mud properties, wear on bit, rotary speed and lastly, drill bit type.

Figure 2‑10 Influence Diagram

Next, each of these factors will be discussed in relations to their category.

#### Fixed Factors

Fixed factors are defined as pre-existing conditions of the formation. The main two conditions that are taken into consideration in this case are Rock Hardness and Formation Pore Pressure. These two parameters categorises the type of drilling conditions engineers will be dealing with. Majority of the technical decisions are heavily dependent on these.

##### Rock Hardness

As covered in Section 2.1: Hard Rock Drilling, the hardness of a rock is determined by he UCS value. To be deemed as hard rock, the UCS value needs to be over 69 MPa. It is known that rocks with UCS values equal or more than this presents more challenges. In addition, the minerals contained within the lithology, causing abrasiveness is another contributing factor to formation hardness that needs to be taken into consideration. High traces of silica, quartz or conglomerates incur higher levels of abrasion. When these elements are coupled with cementation, it has been established that well cemented rocks have higher strength due to its tightly compacted grains.

Drilling in hard rock formation provides its own unique challenges. The drilling program is unable to carry out operations utilising high ROP, as it would generate severe bit wear and vibrations. If the ROP of a drill bit increases regardless, this would cause extreme cutter wear and a severe shortness in bit life.

##### Formation pressure

As the drilling proceeds deeper, the lithostatic pressure of the formation increases due to the overbearing formations and overbalance pressures influences ROP (Fear, 1999). This increase in formation pressure would resultantly reduce the ROP as the rocks. This is a similar trend to noticeably drilling deeper into deep permeable rocks. It takes more force to break down the rock formations. With this increase in formation pressure, the bottom hole temperature increases as a result, causing bit damage and wear.

#### Variable Factors

##### Rotary Speed (RPM)

In a study conducted by Brantly and Clayton (1939), it was established that there was a definite trend between RPM and ROP. The study concluded a positive linear relationship between these two variables. It was also determined that the study drilled through formations of the same strength. RPM and ROP are proportional to one another, an increase in one parameter leads to an increase in the other.

In the report by Botton et al. (2012), an investigation on bit performance was conducted using a PDC bit. Included was the bit performance for two wells drilled through the Bashijiqike Formation (Tarim Basin, China). Upon analysis of the data provided in the report, it was observed that data from Well A exhibited a generally decreasing RPM trend before hitting plateau with the increase of ROP. If the outliners are removed and only a comparison between rocks with the same UCS value (7500 MPa) is performed, the trend observed is an increasing ROP reduces RPM. On the other hand, data from Well B exhibited no definite trend.

This contradiction in the trends could be attributed to the depths drilled as Tarim Basin is known as an ultra deep well.

Figure 2‑11 RPM vs. ROP (Tarim)

##### Weight on bit (WOB)

The relationship between WOB and ROP as defined by Mensa-Wilmot et al. (2003), is a PDC bit’s mechanical efficiency only when the variables of rock hardness, RPM and hydraulic influences are kept constant. A study conducted by Mensa-Wilmot was carried out to experiment on the ROP response of two ø8.5” PDC bits through the identification of different rock failure mechanisms. In the hard rock scenario, the failure mechanism observed was strongly dictated by bit type in contrast to soft formations where the failure mechanism was governed by shearing mode. It was deemed by this study that a drill bit was mechanically efficient with a lowered WOB to remove rock cuttings, inferring a higher ROP used.

On the contrary, in the Autonomous Region of China, there has been evidence that drilling with an increased WOB causes a decrease in ROP as seen in Figure 2-12, using information adapted from Table 7-2 and 7-3 (Appendix B) used Botton et al. (2012)’s report.

Figure 2‑12 WOB vs. ROP (Tarim)

When studying the WOB’s significance on ROP in Well A, the general downward trend of decreasing WOB is a result of higher penetration rate. There is an exponential relationship between the two factors as seen in this well example; a 10 kN decrease in WOB causes double to triple increase in ROP.

With regards to Well B, there is no definite trend. However, if the outliner is removed, there is a similar trend as noticed in Well A – increasing ROP with decreasing WOB.

##### Type of drill bit

###### PDC bit

PDC cutter deterioration is strongly dependent on heat. The rock breaking methods experienced by these bits (shearing and grinding) produce varying levels of heat within the cutter and down hole components. Grinding is highly inefficient and is associated with the reduction in ROP and high heat levels. On the opposite side of the spectrum is the shearing motion, elevating ROP levels and lowering heat generation in the cutter (Mensa-Wilmot et al., 2003).

In order to be more effective in hard rock environments, the key is to delay cutter deterioration. To delay cutter deterioration, the WOB must be applied through only the drill collars. If the drill pipe is run under compression, the drill pipe’s life will be reduced sharply. Despite a high-recorded value for WOB during compressed drilling, it does not imply that the WOB is applied at the bottom. During the study, an increase in WOB resulted in a reduction of rotation hours to drill the well. In most cases, the increase in weight corresponded to an increase footage per bit. To reduce drill string failures and increase bit bearing life, lower rotary speeds needs to be achieved (Johnston, 1947).

###### ID bit

In a study performed by ExxonMobil Development Co., DOC is dependent on RPM, WOB and flow rate. In turn, ROP is dependent on RPM, as result indirectly dependent on flow rate. Through the study of DOC in an ID bit, there is a direct correlation between this parameter and WOB. It can be established that a higher WOB produces an increase in DOC (Roehrlich & Belohlavek, 2006).

##### Bit wear

A reduction in penetration rates causes an increase in vibrations. This leads to an increment in bit wear and damage. The continual decrease in ROP causes a reduction in efficiency. Increased bit wear and vibration damage to the BHA incurs more fishing and tripping operations. This ultimately results in more NPT and higher costs.

##### Mud properties

The mud properties decided by the engineers need to fit between the fracture and pore pressures. As the drilling is deepened, the allowance window between these two pressures decreases. In order to overcome the pore pressure, a higher density mud is needed. However the property of the mud has an influence on the cleaning abilities of the well bore as one of its functions is a cutting transport fluid. If mud exhibits poor cutting transport qualities, the well bore will be poorly cleaned and resulting in lower than expected penetration rates. This is a result of the bits need to drill through the unbroken formation and the cuttings suspended at the bottom of the borehole.

## Rate of Penetration Prediction Models

A key parameter in optimising the drilling process is predicting the potential ROP of a wellbore. The benefits prediction ROP has is the potential to reduce cost and time, which are huge factors when undergoing a drilling operation. There are currently a few well-known models available. In this section the Bourgoyne & Young Model and Artificial Neural Network (ANN) will be briefly covered.

While these two models are currently available to be used, the method that will be used throughout the remainder of this thesis will be discussed in Chapter 3: Methodology. The method uses a mathematical statistical approach. The ANN system uses a program developed by Schlumberger that is currently unavailable to the open market without permission from the company. By using a statistical approach can historical data from neighbouring wells help predict the ROP if similar lithologies and rock strengths are considered.

### Bourgoyne & Young Model

In 1974, Bourgoyne & Young proposed a model for the prediction of ROP using historical data of neighbouring wells. This proposed model utilises eight functions to design the effects of the most important drilling variables (Rahimzadeh, Mostofi, Hashemi, & Salahshoor, 2010).

In this model, the main (10) parameters that had an influence on ROP were as follows:

* Formation strength
* Bit type
* Mud type
* Solid content
* Compaction
* Overbalance
* WOB
* Rotary speed (RPM)
* Bit wear
* Bit Hydraulics

The general formula for the ROP prediction:

Equation 1 – General ROP prediction formula

a1 through to a8 are constant coefficients related to the factors of its corresponding equation. The determination of these coefficients are achieved through genetic algorithm (Rahimzadeh et al., 2010). Equation 2 is a representation of the effects of the parameters not included in the model; formation strength, bit type, mud type and solid content.

Equation 2

The following equations each signify different factors taken into account for the model.

Compaction effects:

Equation 3

Effect of overbalance on ROP:

Equation 4

Taking into consideration WOB:

Equation 5

RPM taken into account:

Equation 6

Effects of tooth wear:

Equation 7

Bit hydraulics on ROP:

Equation 8

The constant coefficients need to be evaluated prior to performing any ROP prediction. The most successful method of determining these constants is through genetic algorithm. This method of determining the constant coefficients has an impact on how accurate the resulting model is. However, the downside for this ROP model is that the equation is developed for each formation individually. Each of the coefficient constants needs to be evaluated individually and if the well data does not have a specific data, the accuracy of the model reduces. In addition, the severity of multi-collinearity influences each ROP parameter and causing uncertainties within the model (Rahimzadeh et al., 2010).

### Artificial Neural Network (ANN)

The ANN system is inspired by biological neurons. It learns by collecting data samples and analysing the relationships between the input and output functions if it is present. The system has the ability to generalise the data based on the knowledge presented. The model is seen as a method to simplify a complicated process. With an abundance of data and parameters readily available, the system is continuously adapted (Amer, Dahab, & El-Sayed, 2017).

ROP prediction models have always been based on historically gathered data, which produce mixed results. By utilising ANN, the offset is analysed. As discussed in Section 2.4: ROP influences, the independent variables are largely the same. These inputs aid in calculating a ROP estimation with two desired outputs (the given ROP and predicted). The error is determined by the differences between these desired outputs. This is repeatedly sent back to the neuron in order to reduce the error. Until the error is minimal, the iteration will continue, thereby correcting itself in based on the given data. Similar to other prediction models, if some variables are unavailable, there will be an error in prediction. It uses correlation to extrapolate the needed data.

The ANN system has been built using information from wells using the software program by Schlumberger, Drillbit Optimisation System (DBOS). DBOS identifies various physical properties of the formation and a correlation between the results and drilling environments are linked (Moran, Ibrahim, Purwanto, & Osmond, 2010).

# Methodology

In the following chapter is an overview on the process on how the ROP model has been developed.

In order to develop a useable ROP prediction model to analyse other fields, data gathering has to be carried out first. In this instance, historical drilling records has been used in the development of ROP modelling as quantitative values are provided from the previous fields studied. Following the data extraction, a multivariate regression model is used to create a simplistic but effective predictive equation using the input provided. The multivariate regression model uses a statistical approach in determining a prediction model.

The simplified steps on building a multi variant model:

* 1. Generate a list of independent and dependent variables
  2. Data collection
  3. Check relationship between independent variables and dependent variable via scatterplots and correlations
  4. Check the relationship between all independent variables amongst each other
  5. Simple linear regression with each independent and dependent pair.
  6. Use non redundant independent variables in analysis to find the best fitting model
  7. Use ideal to make a predictive dependent variable model

Figure 3‑1 ROP independent model

To develop this statistical based model, the first priority is to generate a list of independent and dependent variables. Referring to the ROP influence diagram (Figure 2-10), the dependent variable would be ROP and other variables are listed as independent.

Data sets of historical well data were collected with as much of the independent and dependent parameters available. The following step is to check the relationship between each independent variable against the dependent variable through scatterplots and correlations. Scatterplots provide a visual correlation guide. Once a visual representation of the data sets has been graphed, a trend line can be added with the R-squared value determined. The key determination is the R-squared value (coefficient of determination). The higher the R-squared value indicates a correlation between the variables and how well the model fits into the data set. Alternatively, the Pearson Correlation function is a quantitative way to check for linearity and would be presented as Table 3-1.

1 would symbolise a perfect correlation while 0 has no correlation and if there is a negative value, it implies the opposite response.

Table 3‑1 Collinearity check

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | X1 | X2 | X3 | X4 | X5 |
| X2 |  |  |  |  |  |
| X3 |  |  |  |  |  |
| X4 |  |  |  |  |  |
| X5 |  |  |  |  |  |
| Y |  |  |  |  |  |

Not only is each independent variable and dependent variable going to be checked on each other for linearity, each independent variable will be checked upon each other to ensure there is no multi-collinearity as this has the chance of impacting the model.

Ideally, there should be a high correlation between each independent variable and dependent variable. This indicates an influence relationship. On the other hand, the correlation value between each independent variable should be as low as possible if not, it would suggest multicollinearity and possibly making one of the independent variables redundant and negatively impacting the model.

Once collinearity has been established, StatPlus (an Excel Analysis Toolpak add-on software) is used to determine a multivariate regression statistical model. Initially, a regression model per independent variable versus dependent variable is plotted for each field. Following this, an additional independent variable is added in for an analysis until all the independent variables has been included in the model. All of the R, R-squared, R-squared adjusted and p-values are recorded down to be compared. The best model is decided with the highest R-squared value and the appropriate variables covered in the model.

The purpose of regression models is to predict Y on the basis of X. X is referred to as the predictor or independent variable, while Y is the dependent or response variable. In the simplified version of the model, assuming a linear relation between X and Y, it can be denoted as:

Equation 9

For the predicted value of Y, the following equation is denoted with Ŷ deemed as the residual:

Equation 10

As there are multiple variables that need to be taken into account for this model, multiple linear regressions needs to be applied. Y is the continuous dependent variable using X as the independent variables. Y is a normal distribution with mean:

Equation 11

Where all beta values are estimated using the data but more specifically, value is the intercept and , values are regression coefficients. The constant coefficients in front of each independent variable in the equation are the mean increase of Y when Xi increases, while all other variables are kept at a constant.

As this is a prediction model, there is a potential for an error on either side of the equation (plus and minus). A few steps obtain this value:

* Note the residual d.f. value from the ANOVA calculation table on StatPlus
* Assuming 0.95 percentile, find the corresponding value on the statistics t-distribution table.
* Using the t-distribution value, multiplied by the error value that is represented by S on the linear regression table on StatPlus.
* Plus or minus this error equation from the multivariant regression equation to obtain potential range of values.

# Results & Discussion

## ROP prediction model – Numerical Results

The information used for the calculations were obtained from the fields studied in Chapter 2.3 Established Fields and can be refer in Appendix B and C.

Throughout the development of this model, data for the Tarim Basin was extracted from Botton et al. (2012) and Vargas (1992) was the reference source for the Ceuta Field. The independent variables were determined by means of correlation table, utilising the Pearson Correlation function. As mentioned in Chapter 3: Methodology, independent variables used in a multivariant regression equation should have a low correlation with one another.

Table 4-1 is a tabular collection of the Pearson Correlation Results for the Tarim Basin data while Table 4-2 is for the Ceuta Field data. Refer to Appendix D for the scatterplots of the data.

Table 4‑1 Pearson Correlation (Tarim Basin)

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **Mud weight** | **Time** | **Depth** | **WOB** | **Thickness** | **Flow rate** |
|  |  | **x1** | **x2** | **x3** | **x4** | **x5** | **x6** |
| **Time** | **x2** | - |  |  |  |  |  |
| **Depth** | **x3** | 0.653980629 | 0.584404069 |  |  |  |  |
| **WOB** | **x4** | -0.033741961 | 0.483676089 | 0.968549887 |  |  |  |
| **Thickness** | **x5** | -0.44177008 | 0.805903048 | 0.236216529 | 0.285330158 |  |  |
| **Flow rate** | **x6** | -0.222486917 | -0.438193217 | -0.079946859 | 0.087485049 | -0.295252635 |  |
| **ROP** | **y** | -0.469548807 | -0.301525736 | -0.436341374 | -0.368919112 | 0.086174731 | 0.0474715 |

With a strong correlation value of 0.9685 between WOB and depth in the Tarim Basin, either one of these parameters should not be used in the equation. By using both parameters, the accuracy of the model may decrease. It was decided to remove WOB as the Ceuta Field does not have any WOB data available.

Table 4‑2 Pearson Correlation (Ceuta Field)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  | **Time** | **Depth** | **Thickness** |
|  |  | **x1** | **x2** | **x3** |
| **Depth** | **x2** | 0.083408084 |  |  |
| **Thickness** | **x3** | 0.601904526 | -0.266278684 |  |
| **ROP** | **y** | -0.15978719 | -0.387250185 | 0.322375462 |

Judging by Table 4-2, there may be a potential correlation between the time and thickness parameters. However, as the linearity correlation is medium, it will still be included in the model.

To develop an equation that would be able to predict ROP for both Tarim and Ceuta data sets, the input variables need to be available in both data groups. In the beginning, two models were established separately for each field. In these two given situations, the independent variables that were taken into consideration were depth, thickness and drill time.

The first equation that was deduced (Tarim Equation) utilises input parameters from the Tarim data set. Equation 12 was the resulting equation obtained from StatPlus:

Equation 12 Tarim Equation

With an error of

Equation 12 is fed back into the Ceuta Field resulting in Figure 4-1, where by the predicted ROP value is an average of 23% lower than the measured ROP. However, the trend of the estimated ROP model observed is similar to the field penetration rates.

While this model may not have achieved value ranges closer to the measured ROP, it is ideal to under predict ROP. If a well were predicted to have a lower penetration rate, the cost and time estimated would be higher. This would allow a buffer for time and cost estimations for any uncertainties to arise.

Figure 4‑1 Ceuta Field using Tarim Equation

The same methodology that is used to derive the Tarim Equation was used to obtain an equation based off of the Ceuta data. Equation 13 (Ceuta Equation) was the multivariate regression equation using solely data gathered from the Ceuta fields:

Equation 13 Ceuta Equation

Error of this equation is

Equation 13 uses the input data from the Tarim Basin achieving Figure 4-2. Contrary to the Tarim Equation, the error ranges for the Ceuta Equation barely encompasses the measured penetration rate. This could potentially be a result of the severely low penetration field rates measured and the Ceuta Equation is unable to reproduce significantly low ranges.

Figure 4‑2 Tarim Basin Data using Ceuta Equation

Another likelihood for the result is that the data used to create the Ceuta Equation does not comprise of data obtained from ultra deep depths, which is experienced in the Tarim Field (depths of up to 7400 m). This lack of deeper data does not allow the Ceuta Equation to handle the Tarim data.

To combat either ultra deep depths and significantly low ROP ranges, both field data from the Ceuta Field and Tarim Basin were combined together. By tabulating these records into a singular table, would allow for a wider range of analysis to be carried out. Referred to as the T&C Equation, Equation 14 is the resulting multivariant regression model.

Equation 14 T&C Equation

Error of this equation is

Once again, Equation 14 was fed back into the given data for both fields, separately to test out the proposed ROP prediction model, visually represented in Figure 4-3. Apart from a couple of outliners in the Ceuta Field at depths 3993 m and 4543 m, the general predicted ROP remained quite similar and within range. On the other hand, when observing the feedback into Tarim Basin, there were intervals of under and over prediction by the model. However, when the error range is taken into consideration, the given ROP was within the predicted boundaries.

Figure 4-3 is visual representation of the data and its corresponding predicted ROP using Equation 14. Table 4-3 is a tabulation of the R, R-squared, adjusted R-squared and predicted R-squared value for each of the equation as generated by the StatPlus model. The R-squared value is a statistical measure on how close data fits to the proposed regression line, the higher the value, the closer the fit. With regards to Table 4-3, it can be suggested that T&C Equation is the most suitable model for ROP prediction as it has the highest R-squared value amongst the three proposed equations.

Table 4‑3 Statistical values

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Equation** | | |
|  | **Tarim** | **Ceuta** | **T&C** |
| **R** | 0.5083 | 0.57731 | 0.60274 |
| **R-Squared** | 0.25837 | 0.33329 | 0.36329 |
| **Adj R-Squared** | 0.13477 | 0.29625 | 0.33816 |
| **Predicted R-Squared** | -0.01331 | 0.20694 | 0.28994 |
| **Error (S)** | 0.39765 | 1.84247 | 1.6716 |

Figure 4‑3 Tarim and Ceuta Data using the T&C Equation

The Tarim, Ceuta and T&C equations were then implemented into the three Norwegian HPHT fields previously mentioned to evaluate the proposed equations. The purpose of this is to test the equations on different fields that did not have any influence in the regression model.

#### Vega Field

The information used for the Vega field was obtained from two neighbouring wellbores, one of a shallower depth (430 – 3280 m) and a deeper well (3587 – 4343 m).

For the shallower well, the equation which best fits the data was the Ceuta Equation. However, majority of the calculated ROP were higher than the given ROP. As previously mentioned, over predicting the ROP value is not an ideal situation. The next best fitting ROP predictor model was the T&C Equation. While the Tarim Equation did under predict for the entirety of the well, the severity of its under prediction would lead to a higher degree of inaccuracy, which is undesirable.

Observing the deeper Vega wellbore, both Ceuta and T&C equations severely over predicted the ROP, whilst the Tarim equation was the only to under predict. Judging by this, neither of these equations was suitable in this section of the field as a prediction model.

Figure 4‑4 Vega Field

#### Valemon Field

While all the data inputs were from the same wellbore, Figure 4-5 has been separated into Shallow and Deep Valemon Field for easier analysis of the prediction model.

Between the 222 – 1090 m intervals, all of the models severely under predicted the ROP, with the Ceuta and T&C Equations estimating at a closer range than the Tarim Equation. The deeper half of the Valemon Field (3100 m and below), seems to have a better trend between predicted and actual ROP, apart from a few outliners with sudden increases in penetration rate. As a general observation, the Ceuta Equation has slightly over estimated the value ranges with T&C establishing a more constant trend line. Considering the entirety of this well (both shallow and deep aspects), the best equation to predict ROP is the T&C Equation. This equation would assist in giving the most reliable ROP, which can therefore be used in cost and time estimates.

Figure 4‑5 Valemon Field

Figure 4‑6 Embla Field

#### Embla Field

Following this was the implementation of the equations into the Embla Field data. Similarly to the Valemon Field, the shallower portion of the well recorded higher than predicted penetration rates with Ceuta Equation closest to the actual data. In addition, there was a variation in the pattern, an increase in the recorded ROP brought about a decrease in all predictions and vice versa.

Regardless, for the deeper portion of the well, all predicted ROP values hovered roundabouts the field measured value. The Ceuta Equation over projected for majority of the values, whilst Tarim Equation had the opposite issue by under estimating. While the T&C Equation still had some varying difference, it had a mixture of over and under valuing deeming this as the most suitable for this field.

Equation 15 NPD Equation

Equation 15 was a derivation from all the data provided by the Norwegian HPHT fields; Vega, Valemon and Embla. With the information taken from the Norwegian Petroleum Directory (NPD), valuable information related to the fields were used to develop a multivariate regression model. In these models, rock hardness (UCS), depth, thickness and time, were used to develop an equation for the fields. However, for some of these intervals, information was missing hence a formula could not be finalised with much accuracy.

Equation 15 could only be tested against the present NPD data and the Tarim Basin as both had the availability for all the information. When tested against its only data, it had similar trends and calculated a similar predicted ROP. However, when tested against the Tarim Basin, the estimated ROP was nowhere near the measured ROP values. It produced a severely negative result. This lack of corresponding data compared to the T&C Equation eliminates the NPD Equation as a proposed ROP prediction model. This is despite producing a significantly higher R-squared value.

Table 4‑4 Statistical Values for NPD and T&C Equation

|  |  |  |
| --- | --- | --- |
|  | **NPD** | **T&C** |
| **R** | 0.83395 | 0.60274 |
| **R-Squared** | 0.6955 | 0.36329 |
| **Adj R-Squared** | 0.68145 | 0.33816 |
| **Predicted R-Squared** | -0.5257 | 0.28994 |
| **Error (S)** | 6.48 | 1.6716 |

Figure 7 NPD and Tarim Field using NPD Equation

## Bit life

Historical data gathering has been used in the past when considering the lithology and drilling parameters of surrounding wells to be deemed as similar. It predicts the conditions encountered and a well plan is designed accordingly. To extrapolate data from wells of similar rock hardness and depth, this methodology could be used to estimate the expected ROP and in turn potentially determine bit life.

Notably, the Tarim Basin and Ceuta Field are the focal points of this chapter as there are abundant data in relations to the desirable parameters. As both penetration rates and time are given in the raw data, it can be used to note the distributions of these factors, which in turn may predict bit life. In the analysis of the records, it should be distinguished that for each of the intervals, a new bit was used.

To better understand the probability of ROP and time occurring, a probabilistic P10/P50/P90 framework can be approached. In order to determine this, the Percentile Function built into Excel can be used with the entirety of the desired data as an input function.

Table 4‑5 Percentile Tarim ROP

|  |  |  |
| --- | --- | --- |
|  | **PERCENTILE (ROP m/h)** | |
| **P10** | | 0.279617245 |
| **P50** | | 0.44 |
| **P90** | | 1.208333334 |

As tabulated in Table 4-5, the median ROP that occurred in the Tarim Basin only 0.44 m/h, with 0.28 m/h and 1.21 m/h in the 10th and 90th percentile range, respectively.

While the Tarim Basin experiences multiple stratigraphies, its primarily lithological make up is mudstone and siltstone. The average UCS for this rock type is estimated at 52 MPa (7500 psi), slightly below the UCS Hard Rock Value of 69 MPa. However, this does not take into account the pressure and temperature influences on the formation. Considering the ultra deep wells, the lithostatic pressures can cause the formations to increase in UCS strength.

Figure 4‑8 Tarim Basin ROP Histogram

These physical parameter attributes to the significantly low expected ROP. Figure 4-8, a histogram representation of the data, further supports the notion that when a bit is exposed to severely low ROP, there is a increased need to replace it.

Table 4‑6 Percentile Ceuta ROP

|  |  |
| --- | --- |
|  | **PERCENTILE (ROP m/h)** |
| **P10** | 0.789432 |
| **P50** | 2.17932 |
| **P90** | 3.93192 |

As previously mentioned, the dominating lithology in the Ceuta well is shale and carbonate rocks, giving an estimated UCS value of approximately 102 MPa, according to the classification in Chapter 2. This field experiences significantly higher rock strengths compared to the Tarim Basin, however it yields generally higher ROP values. This could be attributed to the lithology and the depth difference between these data collection points, as the maximum depth for Ceuta Field was just over 4800 m rivalling Tarim’s 6770 m.

As per Table 4-6, the proven penetration rate in the Ceuta Field is thrice that of the proven Tarim Basin. Regardless, the overall predicted ROP values experienced in this field is still relatively low and does require regular bit change.

Figure 4‑9 Ceuta ROP Histogram

When analysing the data presented in the company documents of the Norwegian HPHT fields, it can be deduced that depths shallower than 1000 m reuses an average of 2.66 bits. 3 for the Embla field, 3 for Valemon field and 2 in the Vega field. All of the repeatedly used bits were primarily in the Clay/Sandstone intervals, with an expected UCS value of between 120 – 128.75 MPa.

For the remaining of the depths, different bits were used. This is observed by the serial number recorded in the Bit/Mill Records of the various documentations. For each of the fields, the sections, which reused the same bit has been colour coordinated.

Table 4‑7 Vega Reused Bit Data

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Vega** | | | | | |
| **Lithology** | **UCS** | **Depth (m)** | **Thickness (m)** | **Time (h)** | **ROP (m/h)** |
| Clay | 137.5 | 440.436 | 38.1 | 6.5 | 5.861538462 |
| Clay/sand | 128.75 | 568.1472 | 126.7968 | 11 | 11.52698182 |
| 545.8968 | 95.7072 | 11 | 8.700654545 |
| 890.016 | 312.7248 | 13.5 | 23.1648 |
| Sand | 120 | 890.016 | 308.7624 | 23 | 13.42445217 |

The average ROP for the first reused bit (orange) was 7.3 m/h, which drilled through an average approximated UCS hardness of 133.125 MPa. The second bit (blue) drilled through clay/sand and sand intervals resulting in a slightly low UCS of 124.4 MPa with an average penetration rate of 18 m/h. The difference in the ROP could be a result of the rock hardness; lower UCS increases the ROP.

Table 4‑8 Valemon Reused Bit Data

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Valemon** | | | | | |
| **Lithology** | **UCS** | **Depth (m)** | **Thickness (m)** | **Time (h)** | **ROP (m/h)** |
| Clay/SST | 128.75 | 222 | 63 | 7.4 | 8.513513514 |
| 223 | 64 | 7.4 | 8.648648649 |
| 224 | 1 | 2.6 | 0.384615385 |
| 227 | 4 | 2.6 | 1.538461538 |
| 552 | 299 | 6.9 | 43.33333333 |
| 720 | 496 | 12.1 | 40.99173554 |
| 722 | 498 | 12.1 | 41.15702479 |
| SST | 120 | 1090 | 863 | 24.2 | 35.66115702 |

The first two bits drilled through the same lithology (clay and sandstone) with a UCS of 128.75 MPa. Despite this, the average ROP between the two were twice; first bit (orange) yielding 8.5 m/h and the second (blue) averaging 15 m/h. In align with a lower UCS resulting in a higher ROP, the third bit (purple) yielded 39 m/h when drilling through 125 MPa formations.

Table 4‑9 Embla Reused Bit Data

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Embla** | | | | | |
| **Lithology** | **UCS** | **Depth (m)** | **Thickness (m)** | **Time (h)** | **ROP (m/h)** |
|  |  | 209.3976 | 110.6424 | 14 | 7.903028571 |
|  |  | 213.36 | 3.9624 | 2 | 1.9812 |
|  |  | 226.1616 | 12.8016 | 1 | 12.8016 |
|  |  | 289.56 | 76.2 | 7 | 10.88571429 |
| Claystone/ SST | 128.75 | 534.924 | 245.364 | 10 | 24.5364 |
| 780.288 | 245.364 | 7 | 35.052 |
| Chalk | 102.5 | 4108.704 | 27.432 | 5 | 5.4864 |
| LMS | 4120.5912 | 11.8872 | 11 | 1.080654545 |
| 4399.4832 | 26.5176 | 11 | 2.410690909 |

The shallow lithologies of the Embla Field were not disclosed. Nonetheless, the first bit (orange) averaged a ROP of 6.9 m/h. The second bit (blue) experienced over thrice that with 24 m/h.

At an interval of a relatively softer formation (102.5 MPa), there was a bit reused at the depth of over 4100 m. In this limestone lithology, the bit handled an average of 3 m/h. This reiterates the possibility of that bit drilled in HPHT and deep formations has to be changed regularly despite maintaining an extremely low ROP value.

In conclusion to this section, it can be determined during a shallow section of a well (shallower than 1000 m), a bit can have a prolonged life when the predicted ROP is measured greater than 7 m/h as determined by the existing well data from the NPD fields. However, for intervals exceeding the 1000 m depth, bit life is exponentially shortened due to the abrasive lithologies and high UCS values.

## Baseline Establishment

In the development of this baseline, data was extrapolated from previously established fields; both geothermal and HPHT fields. It has been adapted from a combination of the Iceland Deep Drilling Project (both IDDP-1 and IDDP-2), the Larderello Geothermal Field in Italy, Ceuta Field in Venezuela, various Norwegian HPHT wells and the Tarim Oil Basin within the Autonomous China Region.

The purpose of creating this base case was to develop a reference field with changeable variables to be compared to existing and future fields. The following section of the report will be detailing lithological and technological factors of each layer. The synthetic field consists of six layers, each with varying geological rock ages and corresponding rock types consistent with hardness and thickness in the studied cases.

### Geological Timescale

It should be noted that the foundation when designing the base case was establishing rock type, hardness and depth dependent on the geological rock ages with accordance to the Geological Time Scale. The GTS is a system used by geologists and Earth scientists to chronological date stratigraphy against time. In this system, there are four Eras that are broken down into different periods, epoch and ages. Figure 4-10 is a simplified representation of how each of the categorisations are related to one another. The field development primarily takes into account the Era, Period and in some instances the Epoch.

In this base case, the primary Eras that will be focused on are the Cenozoic, Mesozoic and Paelozoic Eras. The description of the field will be described from the shallowest and consequently to the deepest layer.

Figure 4‑10 Geological timescale

As the GTS used by geologists is complicated, Table 14 is a representation of a simplified GTS that has been used to adapt the rock ages.

Table 4‑10 Simplified GTS of Synthetic Field

|  |  |  |
| --- | --- | --- |
| **Era** | **Period** | **Epoch** |
| Cenozoic | Neogene | Miocene |
| Paleogene | Eocene |
| Mesozoic | Triassic |
| Paleozoic | Permian |

### Layer description

The following is an in depth description of each of the layers of the synthetic case used to evaluate the low ROP decision case that uses an excel spreadsheet. As noted in the previous simplified GTS Table 4-10, rock ages were not specified and in some periods, there were no differentiation between Epochs. The thickness of each layer was valued by evaluating the thickness of previously studied base fields and then calculating its relation to the entirety of the total vertical depth as a percentage determined the thicknesses of each lithological layer.

The following is an in depth description of each of the layers within the base case. Creating this base field assumes lithological uniformity with minimum interbedded layers of other lithologies. The thickness of each layer was calculated by using the average percentage of the total vertical depth of the established fields.

Table 4-11 is a tabular representation of the base case with corresponding rock types, hardness and thickness.

Table 4‑11 Tabular Representation of Base Case

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Layer** | **Geological Era** | **Geological Epoch** | **Rock Type** | **Hardness** | **Thickness** |
| 1 | Cenozoic/ Neogene | Miocene | Sandstone | 120 MPa | 300 |
| 2 | Cenozoic/ Paleogene | Eocene | Shales, limestone | 102.5 MPa | 700 |
| 3 | Mesozoic | Cretaceous/ Jurassic | Mudstone | 103.25 MPa | 600 |
| 4 | Mesozoic | Triassic | Carbonate | 275 MPa | 400 |
| 5 | Paleozoic | Permian | Basalt | 227.5 MPa | 600 |
| 6 | Paleozoic | Ordovician | Bioclastic | 102.5 MPa | 185 |

For the Mesozoic Era, it was the Triassic Period with no differentiation between the Epochs.

Lastly, as this field will be considered a deep well, the rock age dwelled into the Paleozoic Era with the deepest lithologies developed from the Permian and Ordovician period. From the previously mentioned deep fields (in the field example sections), this is how the geological ages were decided as a base line.

Layer 1 (dark blue)

The shallowest layer of this Synthetic Field is a geological unit established during the Cenozoic Era specifically during the Neogene Period. In reference to the already established fields, this lithology would have been formed during the Miocene Epoch, thus resulting in the formation of sandstone for its corresponding rock type consistent with the rock ages. In accordance with the average UCS range discussed in Chapter 2.1: Hard Rock Determination, the approximate hardness of this layer is 120 MPa, which is considered hard.

The thickness of this layer was derived through a percentage of comparable fields studied. An approximation of 10% of the entire lithological thickness was formed in the Miocene Epoch resulting in a valued thickness of 300 m, sitting at a depth between surface and 300 m.

Layer 2 (red)

Following the chronological order of the geological timescale, the next layer would have been formed in the same era but in the period prior, Paleogene Period. The predominating rock type found in the Eocene Epoch was a mixture of shale cap rock with interbedded intervals of limestones. The field of reference for this layer was specifically the Larderello, with a thickness of over 20% of the entirety of the field. In this case, it was designed to have a thickness of 25% of the field, producing a thickness of 700 m; bringing the depth range of this geological unit between 300 and 1000 m.

In reference to the Ligurian Complex of the Larderello Geothermal Field, this Eocene unit would comprise of shales and limestones with the estimated UCS value between 69 MPa (10 000 psi) and 103 MPa (15 000 psi).

Layer 3 (green)

With a thickness of 600 m, this geological unit from the Mesozoic Era is composed of mudstone. Mudstone and shale are both made of ancient mud, with the primary difference being the size and way the rocks are broken up into when external pressure is introduced. For this reason, the UCS expectancy for mudstone can be categorised under shale, which is 103.25 MPa.

The geological epoch for this layer is between the Cretaceous and Jurassic Epoch extending between the depths of 1000 to 1600 m

Layer 4 (purple)

The next lithological layer with a thickness of 400 m is located in the depths of 900 and 1300m. It originated from the Mesozoic Era with a specification in the Triassic Period with no definite Epoch. The rock that corresponds to this geological timescale is primarily carbonate and quartizitic, in correspondence to the previously studied fields.

As defining the UCS value of carbonate poses its challenges, extrapolation of data is needed. Taking into consideration that the fundamental composition of this formation and quartizitic occurred under the same conditions, the UCS value will be in a similar approximate range. Hence, at the depth with the given pressure and temperature, the approximated UCS of the formation is a staggering 275 MPa (almost 40 000 psi). However, due to its carbonate nature, this layer has reduced permeability and porosity to the tightly compacted grains.

Layer 5 (light blue)

Hard rock lithology tends to be formed at great depths. As a result, the next two layers were formed several million years ago in the Paleozoic Era. Basalt rock formations are a common deposited at these depths and conditions in the Permian Period. The thickness of this layer is 600m, similarly to the previous layers, it was calculated through a percentage of the entirety of the total vertical depth. As the formation is set quite deep in the well, there is a high UCS of 227.5 MPa. Basalt is a hard and abrasive rock formation so a lot of care should be taken when drilling.

Layer 6 (orange)

As mentioned previously, due to the conditions needed for hard rock lithology, the final layer is still within the Paleozoic Era but in the Ordovician Period. The deepest field analysed in this report within the Tarim Basin has the Ordovician Period Rock formations as the deepest layer, hence why it was the final potential reserve bearing layer. Bioclastic rock formations are commonly formed at these depths and due to the environmental circumstances surrounding the era. Due to the surrounding environment this layer was deposited in, bioclastic is a type of limestone formation. To estimate the expected hardness of bioclastic, the value for limestone can be used – 102.5 MPa. This however, does not take into account the lithostatic pressures on the formation at such depths. The total thickness of this layer is 185m, which is 7 % of the overall depth.

Figure 4‑11 Lithological Diagram

### Implementing ROP Prediction Model

As the baseline has been discussed in the previous section, the next step is to use the ROP prediction model in practical analysis here. In order to obtain variables to be used as an input in the prediction model, historical data gathering from previous fields was needed. The input data that was used in this Synthetic Case can be found in Appendix E.

The input variables that were used for this case were the depths, thickness of each interval and the time taken to drill. The each of the six layers is designed to use the established fields to act as neighbouring wells extracting existing data into the model. By doing so, it would be able to test the T&C Equation to determine if a random combination of well data could yield a predicted ROP that is within range of the calculated.

Figure 4‑12 ROP Prediction on Synthetic Case

As mentioned in Section 4.2: Bit Life, it was determined that when the ROP was greater than 7 m/h at a depth shallower than 1000 m, the bit has a potential to be reused. Between the depth intervals 545 to 1050 m, the predicted ROP ranged between 8 and 9 m/h. By that notation, by under predicting the ROP, costs and time would be over predicted. This would allow a buffer that could be used in the deeper sections of the well. The predicted ROP for the model has been under predicted until the depth of 1000 m. However, the pattern follows the measured ROP.

The ROP model as the ability to calculate within range the expected ROP value for a deep section of a well, regardless of lithology. As the lower section of the synthetic field has a make up similar to the Tarim and Ceuta Field, it could be the reasoning behind the close proximity between measured and predicted values.

## Applications

There are various applications in which this formula can be used for. As for its main function, it has the potential to be used as a ROP predictor with a higher degree of accuracy, when further developed.

Currently, as discussed in Section 4.2: Bit Life, the model can only predict at which intervals can a bit be reused. Investigating other HPHT and geothermal fields’ bit records and determining a correlation between intervals and bit lifetime can achieve this. In addition, differing between the types of bit that should be ideally used. The current ROP prediction model at presently does not differ between bit types.

Throughout the analysis of establish fields, a major problem that is dealt with by drilling engineers are vibrations caused by bit-rock interactions in the hard rock formations. To overcome or minimise the vibrations effects, anti-vibration subs or shock absorbers can be implemented as part of the BHA. In order to evaluate the effectiveness of this, bit records with the included drilling enhancements could be added into the analysis. By doing this, it could determine whether a new technology should be invested in or save costs if it does not impact ROP significantly.

In extension to this, a slow ROP equates to an increase in drilling cost. Hence the prediction of ROP is important for well-cost projection. As the cost per foot is a logarithmic function, introducing the ROP variable could develop it even further. By applying the ROP prediction model to cost function, a potential cost and time analysis of a well plan can be established.

# Conclusion

The industry is exploring opportunities that are within harsher environments and harder formations to meet the energy demands. It is not uncommon to encountered HPHT formations with high UCS values, both of which pose a challenge on the drilling operations. The primary parameter that was investigated in this thesis was the rate of penetration. This parameter has the potential to be a cost and time driver, especially in tougher conditions.

The harsh conditions has a negative impact on penetration rates as it reduces ROP significantly in rocks with a high UCS value and in deeper wells where formations can be abrasive causing bit damage and wear. Understanding bit technology is also key to optimising ROP as selecting the wrong bit can have cause vibrations on the drill string. Bit technology is an important function and is the fundamental decision maker in the well design. The geological architecture determines the bit used and this can have adverse effects on the time taken to drill the entirety of the well.

The purpose of this thesis was to evaluate ROP influences and develop a potential ROP prediction model using historical bit records of the geothermal, HPHT and ultra deep fields. Using mathematical statistical formulation developed the ROP prediction model. Several data sets were inputted into StatPlus. This was to analyse multiple multivariant regression equations to derive one that best suited an array of data.

The proposed ROP prediction model, based on the T&C Equation was adapted into a synthetic field to evaluate its accuracy and efficiency range. It was concluded that deeper section of the field fitting within the predicted range of the model and the shallower section slightly under predicted the ROP value. By under predicting the ROP value, cost and time would be slightly over estimated, creating a buffer for uncertainties. In addition to this, it can be noted that shallow sections of wells (up to 1000 m) has the potential to reuse bits, prolonging the bit life regardless of lithology that was drilled.

The prediction model has room for improvement to include other ROP influencers and for a wider range of data points. As this was based on a multivariant linear regression model, future work scopes could investigate altering the model as a polynomial regression equation. There is a potential to incorporate the types of drilling equipment used as bit wear and vibrations impact ROP.

Part of the equation’s downfall was due to the lack of information for the selected fields. Regardless, with more information readily available, the ROP prediction model can continuously be improved further with more data correlation. The proposed model can be adapted to supporting the well planning process when determining the lifetime of a bit and to potential cost estimation calculations. As ROP incurs time taken to drill, it can lead to a cost estimation to drill either an entirety of the hole or a section of the well bore.

In conclusion, the proposed ROP prediction model has the potential to predict the range of the measured ROP by utilising various neighbouring well data, especially for deeper well sections.

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# Appendix

##### Appendix A

Table 7‑1 UCS Values to calculate Figure 2-1

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **(MPa)** | | | |
|  | **low** | **high** | **delta** | **Average** |
| Granite | 40 | 290 | 250 | **165** |
| Basalt | 180 | 275 | 95 | **227.5** |
| Sandstone | 10 | 230 | 220 | **120** |
| Siltstone | 25 | 250 | 225 | **137.5** |
| Shale | 6.5 | 200 | 193.5 | **103.25** |
| Limestone | 5 | 200 | 195 | **102.5** |
| Quartzite | 200 | 350 | 150 | **275** |
| Gneiss | 151 | 248 | 97 | **199.5** |
| Schist | 7.5 | 139 | 131.5 | **73.25** |
| Slate | 95 | 250 | 155 | **172.5** |
| Marble | 48 | 230 | 182 | **139** |

##### Appendix B

Table 7‑2 Well A (Tarim Basin)

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Bit No.** | **Size** | **Class** | **Depth in (m)** | **Depth out (m)** | **Interval (m)** | **ROP (m/h)** | **WOB (kN)** | **RPM** | **Lithology** | **UCS MPa** |
| A1 | 6 5/8" | PDC | 6453 | 6509 | 56 | 1.21 | 50 | 70 | Siltstone | 137.8948965 |
| A2 | 6514.2 | 6554 | 39.8 | 1.1 | 50 | 70 | Siltstone | 137.8948965 |
| A3 | 6554 | 6584.5 | 30.5 | 0.36 | 60 | 70 | Mudstone | 51.71058619 |
| A4 | 6584 | 6612 | 28 | 0.43 | 60 | 70 | Marl | 51.71058619 |
| A5 | 6612 | 6630 | 18 | 0.39 | 60 | 70 | Marl | 51.71058619 |
| A6 | 6630 | 6663 | 33 | 0.62 | 60 | 70 | Marl | 51.71058619 |
| A7 | 6663 | 6670.9 | 7.9 | 0.28 | 80 | 75 | Marl | 51.71058619 |
| A8 | 6670.87 | 6705 | 34.13 | 0.29 | 80 | 90 | Mudstone | 51.71058619 |

Table 7‑3 Well B (Tarim Basin)

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Bit No.** | **Size** | **Class** | **Depth in (m)** | **Depth out (m)** | **Interval (m)** | **ROP (m/h)** | **WOB (kN)** | **RPM** | **Lithology** | **UCS MPa** |
| B1 | 6 5/8" | PDC | 6655.78 | 6700.7 | 44.92 | 0.45 | 70 | 75 | Mudstone | 51.710586 |
| B2 | 6700.68 | 6725.7 | 25.02 | 0.37 | 80 | 95 | Mudstone | 51.710586 |
| B3 | 6725.7 | 6765 | 39.3 | 0.39 | 80 | 75 | Limestone | 60.329017 |
| B4 | 6765 | 6769.5 | 4.5 | 0.24 | 50 | 60 | Marl (lime-rich mudstone) | 51.710586 |

Table 7‑4 Well Data (Ceuta)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Type** | **Depth (m)** | **Thickness (m)** | **Time (h)** | **ROP (m/h)** |
| SP65 | 3443,0208 | 12,8016 | 4,5 | 2,83464 |
| F2 | 3620,7192 | 177,6984 | 28,5 | 6,2484 |
| J22 | 3755,136 | 134,4168 | 39,5 | 3,41376 |
| J22 | 3815,7912 | 113,9952 | 50 | 2,286 |
| J33 | 3889,5528 | 134,4168 | 36 | 3,74904 |
| R437N | 3912,108 | 96,3168 | 33 | 2,92608 |
| J33 | 3979,164 | 89,6112 | 26,5 | 3,38328 |
| J33 | 3993,4896 | 84,4296 | 33 | 14,41704 |
| J33 | 4061,46 | 82,296 | 25,5 | 3,23088 |
| J33 | 4124,8584 | 131,3688 | 53 | 2,46888 |
| J44 | 4162,044 | 100,584 | 42,5 | 2,37744 |
| DS47H | 4174,5408 | 71,9328 | 22 | 3,26136 |
| F3 | 4282,7448 | 157,8864 | 61 | 2,5908 |
| DS49H | 4208,3736 | 50,9016 | 13 | 3,90144 |
| J44 | 4270,5528 | 108,5088 | 50 | 2,16408 |
| ATJ33 | 4283,964 | 109,4232 | 48,5 | 2,25552 |
| ATJ22 | 4297,9848 | 89,6112 | 37,5 | 2,37744 |
| J33 | 4389,12 | 146,304 | 51 | 2,86512 |
| F3 | 4428,1344 | 145,3896 | 64 | 2,286 |
| ATJ33 | 4337,6088 | 53,6448 | 20 | 2,68224 |
| ATJ22 | 4403,7504 | 105,7656 | 42 | 2,52984 |
| ATJ33 | 4402,2264 | 64,6176 | 33,5 | 1,92024 |
| J44 | 4396,4352 | 56,9976 | 38 | 1,49352 |
| J33 | 4419,6 | 30,48 | 10,5 | 2,8956 |
| C-1 | 4696,0536 | 300,8376 | 71,5 | 4,20624 |
| F5 | 4475,3784 | 78,9432 | 60 | 1,31064 |
| F3 | 4478,4264 | 76,2 | 32,5 | 2,34696 |
| TB16 | 4583,5824 | 179,832 | 153 | 1,18872 |
| W798 | 4468,6728 | 49,0728 | 36,5 | 1,34112 |
| F4 | 4545,1776 | 117,0432 | 66 | 1,76784 |
| J33 | 4543,044 | 102,7176 | 11 | 9,32688 |
| CB303 | 4530,852 | 62,1792 | 74,5 | 0,82296 |
| F5 | 4561,9416 | 86,5632 | 48 | 1,79832 |
| F3 | 4588,4592 | 110,0328 | 54 | 2,04216 |
| F3 | 4709,4648 | 166,4208 | 52,5 | 3,16992 |
| J33 | 4575,6576 | 30,48 | 30 | 1,00584 |
| F5 | 4632,96 | 71,0184 | 52,5 | 1,34112 |
| F4 | 4646,9808 | 71,3232 | 40 | 1,79832 |
| ATJ33 | 4602,48 | 18,8976 | 8 | 2,37744 |
| F3 | 4665,5736 | 77,1144 | 38 | 2,04216 |
| N798 | 4609,1856 | 6,7056 | 20,5 | 0,33528 |
| CB403 | 4635,3984 | 26,2128 | 53,4 | 0,48768 |
| N798 | 4643,628 | 8,2296 | 18,5 | 0,4572 |
| N798 | 4731,7152 | 88,0872 | 103 | 0,85344 |
| SDGH | 4654,296 | 5,7912 | 4 | 1,46304 |
| F4 | 4721,9616 | 67,6656 | 36 | 1,88976 |
| F3 | 4680,204 | 14,6304 | 18 | 0,82296 |
| J44 | 4684,4712 | 4,2672 | 17 | 0,24384 |
| F3 | 4685,0808 | 0,6096 | 6 | 0,09144 |
| TB593 | 4708,2456 | 23,1648 | 23 | 1,00584 |
| C-1 | 4750,6128 | 55,1688 | 39,6 | 1,40208 |
| F4 | 4759,1472 | 50,9016 | 30,5 | 1,6764 |
| J33 | 4760,976 | 51,5112 | 16,5 | 3,10896 |
| J44 | 4770,4248 | 48,4632 | 28 | 1,73736 |
| F4 | 4757,928 | 26,2128 | 31 | 0,85344 |
| F3 | 4807,3056 | 56,6928 | 10,5 | 5,39496 |
| AJT33 | 4828,032 | 70,104 | 32 | 2,19456 |
| F4 | 4819,8024 | 60,6552 | 34,5 | 1,76784 |

|  |  |
| --- | --- |
| WELL: VLG-3738 | WELL: VLG-3743 |
| WELL: VLG-3741 | WELL: VLG-3744 |
| WELL: VLG-3742 | WELL: VLG-3745 |

##### Appendix C

Table 7‑5 Vega Data Set

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Age** | **Lithology** | **UCS (MPa)** | **Depth (m)** | **Thickness (m)** | **Time (hr.)** | **RPM** | **Pump pressure (psi)** | **Mud Weight (WT)** | **ROP (m/h)** |
| Pleistocene | boulder clay | 137.5 | 440.436 | 38.1 | 6.5 | 100 | 1850 |  | 5.861538462 |
| Pliocene | clay/sand | 128.75 | 568.1472 | 126.7968 | 11 | 125 | 3000 |  | 11.52698182 |
| Pliocene | clay/sand | 128.75 | 545.8968 | 95.7072 | 11 | 120 | 1650 |  | 8.700654545 |
| Miocene | Sand | 128.75 | 890.016 | 312.7248 | 13.5 | 100 | 1600 |  | 23.1648 |
| Miocene | Sand | 120 | 890.016 | 308.7624 | 23 | 100 | 1600 |  | 13.42445217 |
| Eocene | Sand | 120 | 1614.2208 | 627.2784 | 35.5 | 120 | 2600 | 9.4 | 17.66981408 |
| Upp Cretaceous | Claystone | 137.5 | 2111.3496 | 497.1288 | 40 | 125 | 2950 | 9.8 | 12.42822 |
| Upp Cretaceous | Claystone | 137.5 | 2214.372 | 84.7344 | 12.5 | 110 | 2950 | 9.8 | 6.778752 |
| Upp Cretaceous | Claystone | 137.5 | 2232.9648 | 36.8808 | 6 | 110.13 | 2800 | 9.6 | 6.1468 |
| Upp Cretaceous | Claystone | 137.5 | 2672.7912 | 439.8264 | 37.5 | 125 | 3000 | 10.1 | 11.728704 |
| Upp Cretaceous | Claystone | 137.5 | 2878.2264 | 205.4352 | 30.5 | 125 | 3000 | 10.4 | 6.735580328 |
| Upp Cretaceous | Claystone | 137.5 | 2956.2552 | 78.0288 | 18.5 | 120 | 3000 | 10.8 | 4.217772973 |
| Upp Cretaceous | Claystone | 137.5 | 3117.7992 | 161.544 | 64.5 | 80 | 3000 | 11 | 2.50455814 |
| Low Cretaceous | Shales | 103.25 | 3231.7944 | 113.9952 | 28.5 | 100 | 3000 | 11 | 3.999831579 |
| Low Cretaceous | Shales | 103.25 | 3280.2576 | 48.4632 | 15.5 | 100 | 3000 | 11.2 | 3.126658065 |
| Upp Jurassic | Shale & SST | 111.625 | 3280.2576 |  |  |  |  |  |  |
| Mid Jurassic | Brent Sand | 120 | 3518.3064 | 238.0488 | 13.5 | 75 | 3000 | 11.2 | 17.63324444 |

Table 7‑6 Valemon Data Set

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **AGE** | **LITHOLOGY** | **UCS (MPa)** | **Depth (m)** | **Thickness (m)** | **Time (hr.)** | **RPM** | **Pump pressure (psi)** | **WOB (ton)** | **Flow rate (GPM)** | **ROP (m/h)** |
| Holocene- Miocene | Clay/SST | 128.75 | 222 | 63 | 7.4 | 100 | 1044.2736 | 5 | 1034 | 8.513513514 |
| Holocene- Miocene | Clay/SST | 128.75 | 223 | 64 | 7.4 | 100 | 1044.2736 | 5 | 1034 | 8.648648649 |
| Holocene- Miocene | Clay/SST | 128.75 | 224 | 1 | 2.6 | 60 | 1203.8154 | 10 | 880 | 0.384615385 |
| Holocene- Miocene | Clay/SST | 128.75 | 227 | 4 | 2.6 | 60 | 1203.8154 | 10 | 880 | 1.538461538 |
| Holocene- Miocene | Clay/SST | 128.75 | 552 | 299 | 6.9 | 120 | 2465.646 | 7 | 968 | 43.33333333 |
| Holocene- Miocene | Clay/SST | 128.75 | 720 | 496 | 12.1 | 130 | 2610.684 | 10 | 990 | 40.99173554 |
| Holocene- Miocene | Clay/SST | 128.75 | 720 | 496 | 12.1 | 130 | 2610.684 | 10 | 990 | 40.99173554 |
| Holocene- Miocene | Clay/SST | 128.75 | 722 | 498 | 12.1 | 130 | 2610.684 | 10 | 990 | 41.15702479 |
| Oligocene- Low Eocene | SST | 120 | 1090 | 863 | 24.2 | 140 | 1958.013 | 7 | 564.3 | 35.66115702 |
| Oligocene- Low Eocene | Dol/LMS | 102.5 | 1091 | 571 | 11.4 | 160 | 3045.798 | 11 | 990 | 50.0877193 |
|  |  |  |  |  |  |  |  |  |  |  |
| Upp Cretaceous | Dol/LMS | 102.5 | 2570 | 1479 | 68.8 | 180 | 4351.14 | 30 | 814 | 21.49709302 |
| Upp Cretaceous | Dol/LMS | 102.5 | 2975 | 405 | 47.1 | 180 | 4351.14 | 41 | 748 | 8.598726115 |
| Upp Cretaceous | Dol/LMS | 102.5 | 3102 | 127 | 21.3 | 140 | 4351.14 | 38 | 704 | 5.962441315 |
| Upp Cretaceous | Dol/LMS | 102.5 | 3116 | 14 | 5.5 | 140 | 4351.14 | 30 | 704 | 2.545454545 |
| Upp Cretaceous | Dol/LMS | 102.5 | 3186 | 70 | 20.7 | 150 | 4351.14 | 35 | 693 | 3.381642512 |
| Upp Cretaceous | Dol/LMS | 102.5 | 3215 | 29 | 10.6 | 155 | 4278.621 | 31 | 676.5 | 2.735849057 |
| Upp Cretaceous | Dol/LMS | 102.5 | 3218 | 3 | 2.3 | 70 | 4162.5906 | 25 | 550 | 1.304347826 |
| Upp Cretaceous | Dol/LMS | 102.5 | 3316 | 98 | 23.2 | 140 | 4351.14 | 27 | 572 | 4.224137931 |
| Upp Cretaceous | Dol/LMS | 102.5 | 3330 | 140 | 7.2 | 150 | 971.7546 | 16 | 264 | 19.44444444 |
| Upp Cretaceous | Dol/LMS | 102.5 | 3339 | 23 | 5.2 | 120 | 4394.6514 | 27 | 565.4 | 4.423076923 |
| Upp Cretaceous | Dol/LMS | 102.5 | 3496 | 180 | 35.8 | 140 | 4423.659 | 28 | 567.6 | 5.027932961 |
| Upp Cretaceous | Dol/LMS | 102.5 | 3527 | 31 | 17.8 | 200 | 4351.14 | 26 | 523.6 | 1.741573034 |
| Upp Cretaceous | Dol/LMS | 102.5 | 3534 | 7 | 2.8 | 200 | 4351.14 | 25 | 528 | 2.5 |
| Upp Cretaceous | Dol/LMS | 102.5 | 3547 | 13 | 7 | 150 | 4351.14 | 22 | 528 | 1.857142857 |
| Upp Cretaceous | Dol/LMS | 102.5 | 3549 | 2 | 2.3 | 120 | 4133.583 | 30 | 616 | 0.869565217 |
| Upp Cretaceous | Dol/LMS | 102.5 | 3595 | 46 | 22.3 | 220 | 4206.102 | 25 | 473 | 2.062780269 |
| Upp Cretaceous | Dol/LMS | 102.5 | 3615 | 20 | 11.4 | 210 | 4061.064 | 30 | 475.2 | 1.754385965 |
| Low Cretaceous | Claystone | 137.5 | 3670 | 55 | 37.1 | 225 | 4496.178 | 26 | 486.2 | 1.482479784 |
| Low Cretaceous | Claystone | 137.5 | 3700 | 30 | 11 | 138 | 4496.178 | 26 | 528 | 2.727272727 |
| Low Cretaceous | Claystone | 137.5 | 3779 | 79 | 11.6 | 227 | 4496.178 | 23 | 484 | 6.810344828 |
| Low Cretaceous | Claystone | 137.5 | 3780 | 1 | 1.3 | 116 | 2393.127 | 15 | 354.2 | 0.769230769 |
| Upp Jurassic | Siltstone/LMS | 120 | 3883 | 103 | 31.1 | 130 | 3480.912 | 13 | 332.2 | 3.311897106 |
| Mid Jurassic | Shale/Siltstone | 120.375 | 3931 | 48 | 13.4 | 110 | 275.5722 | 15 | 286 | 3.582089552 |
| Mid Jurassic | Shale/Siltstone | 120.375 | 3939 | 8 | 2.1 | 100 | 1421.3724 | 13 | 204.82 | 3.80952381 |
| Low Jurassic | Shale | 103.25 | 3944.5 | 5.5 | 2.9 | 100 | 1319.8458 | 13 | 200.2 | 1.896551724 |
| Low Jurassic | Shale | 103.25 | 3948.5 | 4 | 1.9 | 72 | 1377.861 | 13 | 200.2 | 2.105263158 |
| Low Jurassic | SST | 120 | 3968 | 19.5 | 10.5 | 122 | 1377.861 | 16 | 207.9 | 1.857142857 |
| Low Jurassic | SST | 120 | 3984 | 16 | 6.1 | 110 | 13633.572 | 15 | 20.9 | 2.62295082 |
| Low Jurassic | SST | 120 | 3994 | 10 | 2.6 | 100 | 1450.38 | 9 | 206.8 | 3.846153846 |
| Low Jurassic | SST | 120 | 4012 | 18.5 | 4.7 | 105 | 1450.38 | 8 | 206.8 | 3.936170213 |
| Low Jurassic | SST | 120 | 4018 | 5.5 | 2.3 | 110 | 1595.418 | 11 | 204.6 | 2.391304348 |
| Low Jurassic | Sandy Shale | 103.25 | 4046 | 28 | 10 | 103 | 1725.9522 | 9 | 207.9 | 2.8 |
| Low Jurassic | Sandy Shale | 103.25 | 4057 | 11.5 | 4 | 120 | 1740.456 | 16 | 209 | 2.875 |
| Low Jurassic | Sandy Shale | 103.25 | 4078 | 20.5 | 17.5 | 110 | 1450.38 | 14 | 204.6 | 1.171428571 |
| Low Jurassic | LMS/SST | 111.25 | 4189 | 111 | 30.9 | 106 | 3089.3094 | 22 | 296.12 | 3.59223301 |
| Low Jurassic | Shale | 103.25 | 4250 | 61 | 12.5 | 230 | 2987.7828 | 18 | 296.12 | 4.88 |

Table 7‑7 Embla Data Set

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Lithology** | **UCS (MPa)** | **Depth (m)** | **Thickness (m)** | **Time (hr.)** | **RPM** | **Pump pressure (psi)** | **WOB (MLB)** | **Flow rate (GPM)** | **Mud weight (ppg)** | **ROP (m/h)** |
|  |  | 209.3976 | 110.6424 | 14 | 100 |  | 10 |  | 8.8 | 7.903 |
|  |  | 213.36 | 3.9624 | 2 |  | 650 | 15 | 399 | 8.8 | 1.98 |
|  |  | 226.1616 | 12.8016 | 1 | 75 | 860 | 5 | 559 | 8.8 | 12.81 |
|  |  | 289.56 | 76.2 | 7 | 70 | 860 | 20 | 559 | 8.8 | 10.89 |
|  |  | 534.924 | 245.364 | 10 |  | 1450 | 10 | 354 | 8.8 | 24.54 |
| claystone/ sst | 128.75 | 534.924 | 245.364 | 10 | 120 | 1300 | 10 | 342 | 8.8 | 24.54 |
| claystone/ sst | 128.75 | 780.288 | 245.364 | 7 | 120 | 1300 | 20 | 342 | 8.8 | 35.05 |
| claystone/ sst | 128.75 | 775.716 | 44.196 | 2 | 90 |  | 10 |  | 8.8 | 22.1 |
| Claystone | 137.5 | 1088.7456 | 305.4096 | 16 | 230 |  | 30 |  | 11.2 | 19.09 |
| Claystone | 137.5 | 1088.7456 |  |  |  | 3500 |  | 942 | 11.2 |  |
| Claystone | 137.5 | 1645.3104 | 401.7264 | 12 | 160 | 3700 | 30 | 942 | 11.6 | 33.478 |
|  |  |  |  |  |  |  |  |  |  |  |
| Claystone | 137.5 | 3493.008 | 7.0104 | 4 | 170 | 3750 | 45 | 299 | 14.4 | 1.753 |
| Chalk | 102.5 | 3559.7592 | 8.5344 | 10 | 175 | 3600 | 45 | 309 | 14.3 | 0.8534 |
| Chalk | 102.5 | 3611.88 | 8.5344 | 10 | 240 | 3500 | 35 | 295 | 14.4 | 0.8534 |
| Chalk | 102.5 | 3627.12 | 10.0584 | 10 | 150 | 3700 | 50 | 302 | 14.3 | 1.0058 |
| Chalk | 102.5 | 4108.704 | 27.432 | 5 | 150 | 4200 | 10 | 277 | 13.7 | 5.4864 |
| LMS | 102.5 | 4120.5912 | 11.8872 | 11 | 120 | 3900 | 20 | 288 | 13.7 | 1.081 |
| LMS | 102.5 | 4399.4832 | 26.5176 | 11 | 740 | 4200 | 40 | 277 | 13.7 | 2.411 |
| LMS | 102.5 | 4541.52 |  |  | 720 | 3000 | 30 | 281 | 14 |  |
| LMS | 102.5 | 4556.76 | 1.524 | 1 | 140 | 4200 | 15 | 324 | 14 | 1.524 |
| Marl | 103.25 | 4560.4176 |  |  |  | 4000 |  | 180 | 16 |  |
| marl | 103.25 | 4710.0744 |  |  |  |  |  |  | 17.7 |  |
| Clst |  | 4782.312 | 6.7056 | 4 | 170 | 2650 | 40 |  | 17.7 | 1.676 |
| claystone | 137.5 | 4801.2096 | 18.8976 | 8 | 100 | 2400 | 30 | 270 | 17.6 | 2.36 |
| lms | 102.5 | 4842.9672 |  |  |  |  |  | 277 | 17.6 |  |
| claystone/ sst | 128.75 | 4854.8544 |  |  | 120 | 1900 | 40 |  | 17.6 |  |
| claystone/ sst | 128.75 | 4938.0648 |  |  | 140 | 2300 | 30 | 281 | 17.6 |  |
| claystone | 137.5 | 4962.7536 |  |  | 70 | 3400 | 50 | 255 | 17.6 |  |
| claystone | 137.5 | 5088.0264 | 0.6096 | 3 | 90 | 3000 | 45 | 288 | 17.6 | 0.203 |
| claystone | 137.5 | 5102.352 | 14.3256 | 14 | 100 | 2000 | 45 | 252 | 17.6 | 1.023 |
| Quartzite | 275 | 5113.9344 | 1.524 | 2 | 120 | 2200 | 30 | 230 | 17.6 | 0.762 |
| Quartzite | 275 | 5138.928 | 9.144 | 11 | 110 | 2200 | 30 | 245 | 17.6 | 0.8313 |
| Quartzite | 275 | 5138.928 |  | 6 | 90 | 4200 | 35 | 255 | 17.6 |  |
| Quartzite | 275 | 5138.928 |  |  | 800 | 3100 | 40 | 288 | 17.6 |  |
| Quartzite | 275 | 5159.6544 |  | 2 | 800 |  | 40 | 252 | 17.6 |  |
| claystone | 137.5 | 5177.028 | 3.048 | 3 | 170 |  | 30 |  | 17.6 | 1.016 |

##### Appendix D

Dependent versus independent variables (Tarim)

Figure 7‑1 Dependent versus independent variable (Tarim)

Independent versus independent variables (Tarim)

Figure 7‑2 Dependent versus independent variable (Tarim Basin)

Independent versus Dependent variables (Ceuta)

Figure 7‑3 Independent versus dependent variables (Ceuta)

##### Appendix E

Table 7‑8 Synthetic Data

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |  |  |  | **ROP (m/h)** | | | |
| **Age** | **Lithology** | **UCS (MPa)** | **Layer** | **Depth Interval (m)** | | **Interval Thickness (m)** | **Layer Thickness (m)** | **Time (h)** | **Measured** | **Predicted** | **Plus** | **Minus** |
|  |  |  | **1** | 0 | 106.68 | 106.68 | 336.9784 | 14 | 7.62 | 5.3982556 | 8.72758132 | 2.06892988 |
|  |  |  | 106.68 | 131.9784 | 25.2984 | 6.28 | 4.028407643 | 3.671829128 | 7.001154848 | 0.342503408 |
| Holocene- Miocene | Clay/SST | 128.75 | 131.9784 | 194.9784 | 63 | 7.4 | 8.513513514 | 4.508825128 | 7.838150848 | 1.179499408 |
| 194.9784 | 258.9784 | 64 | 7.4 | 8.648648649 | 4.511205128 | 7.840530848 | 1.181879408 |
| 258.9784 | 259.9784 | 1 | 2.6 | 0.384615385 | 3.151239128 | 6.480564848 | -0.178086592 |
| 259.9784 | 263.9784 | 4 | 2.6 | 1.538461538 | 3.220419128 | 6.549744848 | -0.108906592 |
| 263.9784 | 336.9784 | 73 | 6.9 | 10.57971014 | 4.709555128 | 8.038880848 | 1.380229408 |
| Pliocene | Clay/ sand | 128.75 | **2** | 336.9784 | 545.8968 | 95.7072 | 717.1944 | 11 | 8.700654545 | 5.070993256 | 8.400318976 | 1.741667536 |
| Miocene | Clay/ sand | 128.75 | 545.8968 | 649.7032 | 312.7248 | 20 | 15.63624 | 9.910030744 | 13.23935646 | 6.580705024 |
| Sand | 120 | 649.7032 | 958.4656 | 308.7624 | 23 | 13.42445217 | 9.639482752 | 12.96880847 | 6.310157032 |
| Upp Cretaceous | Claystone | 137.5 | **3** | 958.4656 | 1043.2 | 84.7344 | 585.7632 | 12.5 | 6.778752 | 4.6112524 | 7.94057812 | 1.28192668 |
| 1043.2 | 1121.2288 | 78.0288 | 18.5 | 4.217772973 | 4.276841296 | 7.606167016 | 0.947515576 |
| Low Cretaceous | 1121.2288 | 1176.2288 | 55 | 37.1 | 1.482479784 | 3.249166496 | 6.578492216 | -0.080159224 |
| 1176.2288 | 1206.2288 | 30 | 11 | 2.727272727 | 3.308964496 | 6.638290216 | -0.020361224 |
| Upp Jurassic | Siltstone/ LMS | 120 | 1206.2288 | 1309.2288 | 103 | 31.1 | 3.311897106 | 4.484356496 | 7.813682216 | 1.155030776 |
| Mid Jurassic | Shale/ Siltstone | 120.375 | 1309.2288 | 1357.2288 | 48 | 13.4 | 3.582089552 | 3.621702496 | 6.951028216 | 0.292376776 |
| 1357.2288 | 1365.2288 | 8 | 2.1 | 3.80952381 | 2.963596496 | 6.292922216 | -0.365729224 |
| Low Jurassic | SST | 120 | 1365.2288 | 1375.2288 | 10 | 2.6 | 3.846153846 | 2.994706496 | 6.324032216 | -0.334619224 |
| 1375.2288 | 1393.7288 | 18.5 | 4.7 | 3.936170213 | 3.135473496 | 6.464799216 | -0.193852224 |
| Sandy Shale | 103.25 | 1393.7288 | 1421.7288 | 28 | 10 | 2.8 | 3.216029496 | 6.545355216 | -0.113296224 |
| Sandy Shale | 103.25 | 1421.7288 | 1433.2288 | 11.5 | 4 | 2.875 | 2.975564496 | 6.304890216 | -0.353761224 |
| LMS/SST | 111.25 | 1433.2288 | 1544.2288 | 111 | 30.9 | 3.59223301 | 4.599842496 | 7.929168216 | 1.270516776 |
| Triassic | SST/ Claystone | 128.75 | **4** | 1544.2288 | 1703.6392 | 159.4104 | 315.6816 | 61 | 2.613285246 | 4.926963464 | 8.256289184 | 1.597637744 |
| Quartzite | 275 | 1703.6392 | 1705.1632 | 1.524 | 2 | 0.762 | 2.701750144 | 6.031075864 | -0.627575576 |
| 1705.1632 | 1714.3072 | 9.144 | 11 | 0.831272727 | 2.651182624 | 5.980508344 | -0.678143096 |
| 1714.3072 | 1721.0128 | 6.7056 | 2 | 3.3528 | 2.818287376 | 6.147613096 | -0.511038344 |
| Claystone | 137.5 | 1721.0128 | 1739.9104 | 18.8976 | 8 | 2.3622 | 2.947483168 | 6.276808888 | -0.381842552 |
| SST/ Claystone | 128.75 | 1739.9104 | 1859.9104 | 120 | 30 | 4 | 4.729829568 | 8.059155288 | 1.400503848 |
| Permain | Basalt | 227.5 | **5** | 1859.9104 | 2012.9104 | 153 | 586 | 61.2 | 2.5 | 4.669223568 | 7.998549288 | 1.339897848 |
| 2012.9104 | 2032.9104 | 20 | 8 | 2.5 | 2.876699568 | 6.206025288 | -0.452626152 |
| 2032.9104 | 2102.9104 | 70 | 90 | 2 | 1.963839568 | 5.293165288 | -1.365486152 |
| 2102.9104 | 2104.9104 | 2 | 3 | 0.6 | 2.555839568 | 5.885165288 | -0.773486152 |
| 2104.9104 | 2133.9104 | 29 | 7.25 | 4 | 3.073754568 | 6.403080288 | -0.255571152 |
| 2133.9104 | 2300.9104 | 167 | 80 | 2.9 | 4.429799568 | 7.759125288 | 1.100473848 |
| 2300.9104 | 2366.9104 | 66 | 116 | 0.57 | 1.128039568 | 4.457365288 | -2.201286152 |
| 2366.9104 | 2445.9104 | 79 | 134 | 0.59 | 0.954229568 | 4.283555288 | -2.375096152 |
| Ordovician | Bioclastic | 102.5 | **6** | 2445.9104 | 2470.9304 | 25.02 | 181.02 | 67.62162162 | 0.37 | 1.348850536 | 4.678176256 | -1.980475184 |
| 2470.9304 | 2510.2304 | 39.3 | 100.7692308 | 0.39 | 0.836804737 | 4.166130457 | -2.492520983 |
| 2510.2304 | 2514.7304 | 4.5 | 18.75 | 0.24 | 2.082763968 | 5.412089688 | -1.246561752 |
| 2514.7304 | 2545.9304 | 31.2 | 81.99 | 0.380534211 | 1.107534768 | 4.436860488 | -2.221790952 |
| 2545.9304 | 2553.9304 | 8 | 27.58 | 0.290065265 | 1.929738568 | 5.259064288 | -1.399587152 |
| 2553.9304 | 2582.9304 | 29 | 45 | 0.644444444 | 1.975032968 | 5.304358688 | -1.354292752 |
| 2582.9304 | 2588.9304 | 6 | 21.34 | 0.281162137 | 2.028311768 | 5.357637488 | -1.301013952 |
| 2588.9304 | 2626.9304 | 38 | 98.67 | 0.385122124 | 0.820602368 | 4.149928088 | -2.508723352 |