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Licenciado em Engenharia Geológica

Hole Cleaning Performance Monitoring During The Drilling Of Directional Wells

Dissertação para obtenção do Grau de Mestre em Engenharia Geológica (Georrecursos)

Orientador: Doutor José António de Almeida
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UNIVERSIDADE NOVA DE LISBOA

Setembro 2012

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RESUMO

Durante a perfuração de um poço, são produzidos detritos que devem ser removidos do fundo do poço para evitar constrangimentos que podem dar origem a tempo não produtivo. A maioria dos eventos relacionados com o entrave da coluna de perfuração, levando em certos casos a perda de coluna de perfuração estão relacionados com a inapropriada limpeza do poço. Existem parametros que ajudam a aumentar a eficiência da limpeza do poço e outros que ajudam a determinar as condições de limpeza do poço. A seleção apropriada dos parâmetros chaves, facilita a monitorização da evolução da limpeza do poço assim como as possíveis intervenções em caso de haver constrangimentos durante a perfuração.

O objectivo da monitorização do desempenho da limpeza do poço em tempo real e de acompanhar a eficiência da limpeza do poço e as condições de estabilidade do poço durante a perfuração. A adequada limpeza do poço, e uma das maiores preocupações durante a perfuração de um poço, principalmente em poços direcionados e horizontais.

Este trabalho tem como objetivo endereçar alguns fundamentos teóricos e práticos sobre a limpeza de poço que irão servir de princípios básicos a serem aplicados durante a perfuração de um poço. Entender de que modo os parâmetros *Flowrate*, Rotacoes Por Minuto (RPM), *Rate Of Penetration* (ROP) and *Mud Weigth* aumentam o desempenho da remoção dos detritos do fundo do poço e como os parâmetros do *Equivalent Circulate Density (ECD), Torque & Drag (T&D)* e *Volume de Detritos* vindos do fundo do poço indicam o estado de limpeza e estabilidade do poço.

Para o caso de estudo, a monitorização do desempenho da limpeza do poco, será baseada na medição em tempo real do volume de detritos removidos do fundo do poço a um determinado tempo, tendo em conta o *Flowrate, RPM* e *Mud Wigth*, projetando graficamente numa folha *Excel* os valores obtidos de modo a comparar com os valores esperados durante a perfuração. A monitorização dos parâmetros *Equivalent Circulate Density (ECD)* servirá de auxílio para determinar as condicoes de estabilidade do poco e o modelo *Torque & Drag (T&D) Data,* servirá de auxílio para determinar em que condições de limpeza se encontra o poço. O *T&D Model Software* providencia valores teóricos para o *Torque and Drag*. Este modelo usa as medições do *Hookload* para calcular os factores de fricção em torno do poço.

Palavras-chave: Limpeza de Poço; Tempo Não Produtivo; Volume de Detritos; Flowrate, Rotações Por Minuto (RPM), Rate Of Penetration (ROP); Equivalent Circulate Density (ECD); Torque and Drag (T&D)

ABSTRACT

During drilling operation, cuttings are produced downhole and must be removed to avoid issues which can lead to Non Productive Time (NPT). Most of stuck pipe and then Bottom-Hole Assembly (BHA) lost events are hole cleaned related. There are many parameters which help determine hole cleaning conditions, but a proper selection of the key parameters will facilitate monitoring hole cleaning conditions and interventions.

The aim of Hole Cleaning Monitoring is to keep track of borehole conditions including hole cleaning efficiency and wellbore stability issues during drilling operations. Adequate hole cleaning is the one of the main concerns in the underbalanced drilling operations especially for directional and horizontal wells.

This dissertation addresses some hole cleaning fundamentals which will act as the basis for recommendation practice during drilling operations. Understand how parameters such as Flowrate, Rotation per Minute (RPM), Rate of Penetration (ROP) and Mud Weight are useful to improve the hole cleaning performance and how Equivalent Circulate Density (ECD), Torque & Drag (T&D) and Cuttings Volumes coming from downhole help to indicate how clean and stable the well is.

For case study, hole cleaning performance or cuttings volume removal monitoring, will be based on real-time measurements of the cuttings volume removal from downhole at certain time, taking into account Flowrate, RPM, ROP and Drilling fluid or Mud properties, and then will be plotted and compared to the volume being drilled expected. ECD monitoring will dictate hole stability conditions and T&D and Cuttings Volume coming from downhole monitoring will dictate how clean the well is. T&D Modeling Software provide theoretical calculated T&D trends which will be plotted and compared to the real-time measurements. It will use the measured hookloads to perform a back-calculation of friction factors along the wellbore.

Keywords: Hole Cleaning; Non Productive Time (NPT); Cuttings; Flowrate, Rotation Per Minute (RPM), Rate Of Penetration (ROP); Torque and Drag (T&D); Equivalent Circulate Density (ECD)

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ABBREVIATIONS

AV: Annulus velocity

BHA: Bottom-Hole Assembly

BU: Bottoms up

CP: Conductor Pipe

DF: Drilling Fluid

DP: Drill Pipe or Drillpipe

ECD: Equivalent Circulate Density

ERD: Extended Reach Drilling

FD: Fluid Density

FRT: Free Rotate Torque

FV: Fluid Viscosity

h = Bed height

HWDC: Heavy Weight Drill Collar

LWD: Logging While Drilling

MD: Measure Depth

MWD: Measure While Drilling

NABM: Non Aquose Base Mud

NMDC: Non Magnetic Drill Collar

NPT: Non Productive Time

OBM: Oil Base Mud

OD: Outer diameter

OD: Outer Diameter

Cd: Cuttings drilled

SbA: Surface bit Area

ROP: Rate of Penetration

POOH: Pull Out of Hole

PUW: Pick Up Weight

PV: Plastic Viscosity

PWD: Pressure While Drilling

RIH: Run In Hole

ROP: Rate of Penetration

RPM: Rotation per Minute

SBM: Synthetic Based Mud

SG: Specific Gravity

SOW: Slack Off Weight

Stand: Group of at least three drill pipes or casing units approximately 10 meters long and connected to each other.

T&D: Torque and Drag.

TD: Total Depth.

TOC: Top of Cement.

TVD: True Vertical Depth.

WBM: Water Base Mud

YP: Yield Point

α = Residual bed height

β = Initial bed height

γ = Reciprocal time constant

1. INTRODUCTION

1.1 OBJECTIVES AND FRAMEWORK

The purpose of this dissertation is to fulfil the internship requirement for a Master's Decree of Geological Engineering. The internship began on March, 19th 2012 ended on September, 7th of 2012 at Total E&P in Angola. Focused on drilling techniques, in particular on good Hole Cleaning techniques and procedures when drilling, tripping and running the casing in directional drilled wells.

The dissertation also dmostrate the benefits provided by monitoring hole cleaning parameters and how hole cleaning efficient parameters improve cuttings removal and discuss what could happen in downhole and the best actions or procedures to take in case of hole cleaning issues.

1.2 ORGANIZATION

This dissertation is organized into eigth chapters:

Chapter 1 presents a brief review of the general objectives of the dissertation.

Chapter 2 outline basic concepts about drilling operations and describes general drilling operations overview.

Chapter 3 chapter describes the theoretical background for hole cleaning as well as the main parameters and their interaction and standard procedures for hole cleaning when drilling, tripping, etc.

Chapter 4 explains what parameters must be used to get a good motorization for hole cleaning.

Chapter 5 discusses the environmental issue, how drilling waste affects the environment and mitigation measures.

Chapter 6 presents the dissertation's case study including a discussion of the basic practices used on the M-10 well drilled in the case study.

Chapter 7 discuss final remarks.

Chapter 8 lists dissertation's references.

2. DRILLING OPERATION OVERVIEW

During drilling the well, the material produced by the bit when it is drilling the formation, must be removed as much as possible and taken to the surface. This process is called **hole cleaning**, a very important operation that requires careful procedures. Despite recent improvements in hole cleaning procedures, debris continues to remain in the wells, which makes operations difficult to perform during drilling.

When cuttings are not removed from the bore hole, they accumulate in the well and form a cuttings bed around the Bottom Hole Assembly (BHA). This result in pack off which are responsible for a NPT's such as stuck pipes, hole instability, etc. Even though having several parameters that influence hole cleaning, due to the complex mechanisms involved, this phenomenon is not yet fully understood.

Hence, good Extended Reach Drilling (ERD) wells performance must be planned in advance. A drilling process consists of many steps, of which the actual drilling into the geological formation and the continuous cleaning of the borehole are core sub-processes. Fig. 2.1 shows a schematic drawing of an oil well being drilled.

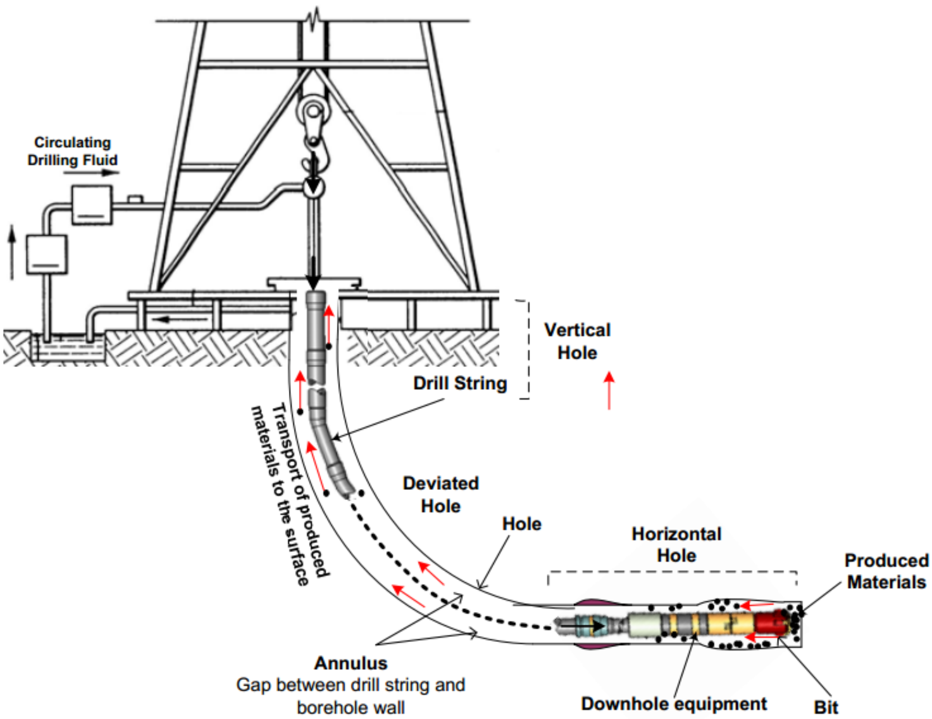

Figure 2.1: Schematic drawing of an oil well being drilled (http://www.idi.ntnu.no/~agnar/publications/iccbr09-drilling-causes. 09/2012)

2.1 DRILLSTRING DESIGN

Bit and BHA design are two of the main ERD performance factors. Drillings parameters such as angle, rotary speed limitations, flow rate limitations, directional performance, bit utility and overall hole cleaning efficiency must all be considered in the design and must be planned in advance. The following is a description of drillstring and some of its components.

Drill string is a column, or string, built with the drill pipe, bottom hole assembly tools and drill bit used to transmit rotation and circulation to the drill bit. Fig. 2.2 shows how drillstring is divided.

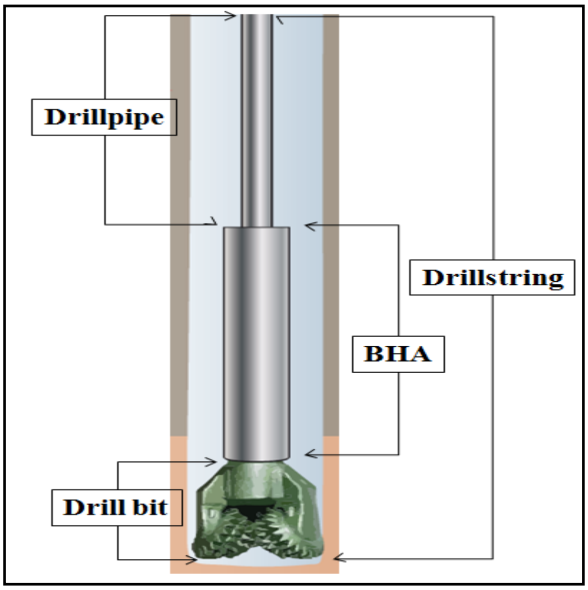

Figure 2.2: Drillstring (HERIOT WATT UNIVERSITY, 2005)

Drill Pipe (DP) is a heavy pipe is used to transmit torque from surface to the bit and allows the Drilling Fluid (DF) to circulate through in from surface to bottom of the well.

Bottom Hole Assembly (BHA) portion of the drilling string is settled by drill collars, stabilizers, down hole motor and rotary steerable system, Measured While Drilling (MWD) tools, and Logging While Drilling (LWD) tools. (HERIOT WATT UNIVERSITY, 2005)

To design a BHA, several factors such as target, formation types and drilling phases must be taken in account. All of these factors could affect mud properties. (Mims & Krepp, 2007)

- ✓ **Azimuthally Density Neutron (ADN):** an LWD tool, built with a stiff tubular collar fitted by electronic component and sensors and a gamma ray and neutron source room inside the collar which provides real time apparent neutron porosity, formation bulk density and photoelectric factor data to characterize the formation porosity and lithology.

- ✓ **Array Resistivity Compensated (ARC):** a LWD tool, built with a stiff tubular collar fitted by electronic component and sensors, which provide real time resistivity, and gamma ray and annular pressure while drilling measurements.
- ✓ **Telescope:** a MWD tool, built with a stiff tubular collar fitted by electronic component and sensors, which provides continues direction and inclination to guide geosteering while drilling.
- ✓ **Non Magnetic Drill Collar (NMDC):** a heavy stiff tubular pipe, usually located on the bottom part of the BHA which is used to provide weight and rigidity to the bit and also used to avoid and isolate magnetic interference coming from BHA steel components when survey is taken by a MWD tool.
- ✓ **Drill Collar (DC):** a heavy stiff tubular pipe, used at the bottom of BHA to provide weight and rigidity for the bit.

Figure 2.3: Drill collar

- ✓ **Heavy Weight Drill Pipe (HWDP):** works as a DC with different weight and is commonly used to reinforce drill string resistance against compressive strength.
- ✓ **Stabiliser:** used to control the deviation of the wellbore, so as to avoid the risk of unexpected deviation one or more stabilisers may be used to keep the desired trajectory.

Figure 2.4: Stabilizer

- ✓ **Hydraulic Jar:** designed to deliver impact either upward or downward in case of a stuck pipe.

Figure 2.5: Hydraulic Jar

- ✓ **Cross-over (XO):** a joint, normally used to connect two pipes of different sizes.

Figure 2.6: Cross-over

- ✓ **Bit** the cutting element at the bottom of drillstring, which is used to bore the formation.

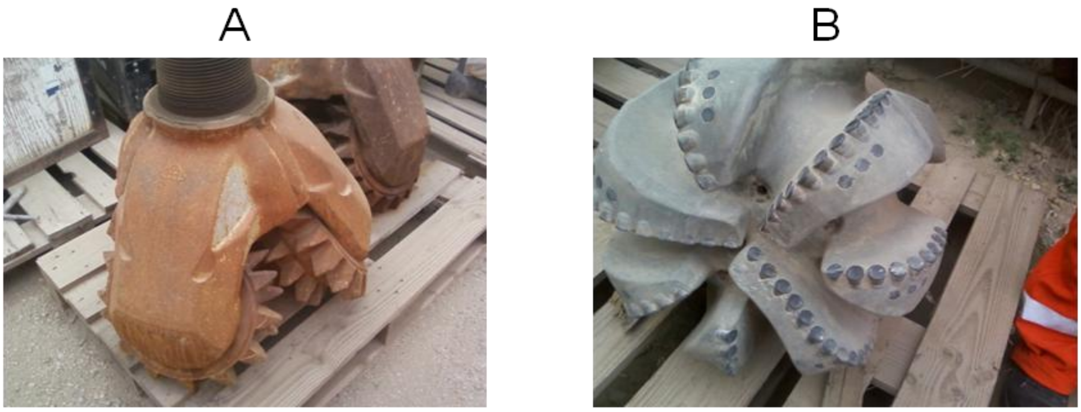

Figure 2.7: Drilling Bit. A) Tooth bit for soft formation. B) PDC Bit for hard formation

2.2 WELL DESIGN

Due to shallow hazards when the well in being drilled is not advisable drill a well in only one section. Normally hazards such as: shallow gases, depleted zones, blow-out issue, wellbore instability, are commonly occurred therefore drilling in only one section is quit hard.

2.2.1 WELL ARCHITECTURE

The architecture of the well is based on the number of different section sizes. Those sizes must go according to:

- The diameter of the last casing to be run in the hole.
- The pore and fracturation pressures of the formations to drill.
- The lithology of the formations to drill.
- The intended depth.
- The constraints (safety, environment).
- The number of reservoir crosses.

2.2.2 CASING

Casing is a diameter steel pipe used to line the hole during drilling operation.

Figure 2.8: Casing. A) Conductor Pipe. B) 14" Casing

Purpose of casings:

- To maintain the fluids inside the well.
- To maintain the formations already drilled.
- To allow drilling safely (casings should allow to circulate a kick without risks of fracturation in the open hole).
- To re-establish and maintain the seal between layers.

Casings used on drilling operations:

- **Conductor pipe (CP)**
  - ✓ To constitute a foundation for the well and maintain the soil.
  - ✓ Length: from few meters to few tenths of meters (≈65m).
- **Surface casing**
  - ✓ To support others casings and well head.
  - ✓ To protect potable water reservoir.
  - ✓ Is cemented from bottom to surface.
  - ✓ Length: a few hundred meters.
- **Intermediate or technical casing**
  - ✓ To solve pressure, lithology, depth problem.
  - ✓ Is always cemented at the shoe
  - ✓ Length: few thousand meters.
- **Production casing**
  - ✓ To protect pay zone.
  - ✓ To allow completion equipment to be put in place.

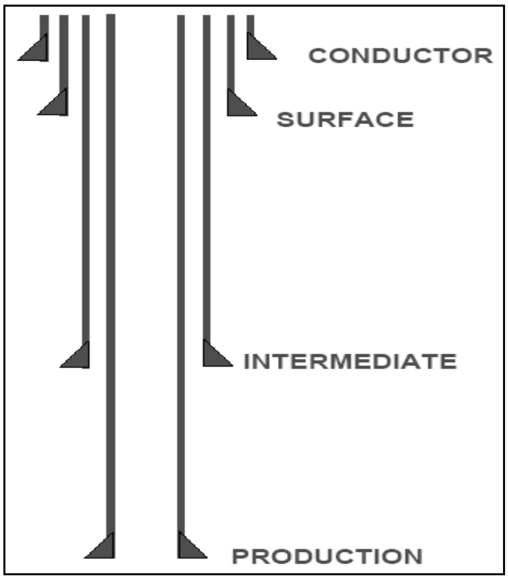

Figure 2.9: Casings used to drill a well. (From: IFP Training 2010)

2.2.3 CEMENT

The bit size is bigger than the casing size and the empty spaces must be avoided during perforation, because gas leaks may occur. Cement is used to seal these gaps. When the cement job is properly done, further drilling and production operations can be made without problems. (HERIOT WATT UNIVERSITY, 2005)

Main functions of cement

- Zonal isolation to avoid fluid emigration either from one formation to another or from formation to the surface through annulus between casing and formation.
- To support the casing string.
- To protect the casing from the corrosive fluids in the formations.

2.2.4 WELL PROFILE

The most usual types of well profile are: Vertical well, J-type well, S-type well and Horizontal well. The well profile is established before drilling, but due to some constrains or issues changes in the well profile may be required.

- **Vertical wells** are wells with a minimum deviation from the vertical. Fig. 2.10 shows an example of a vertical well.

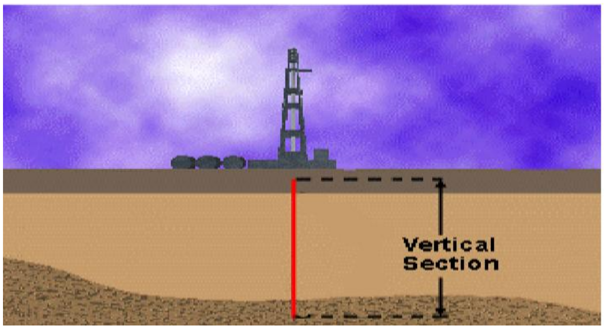

Figure 2.10: Vertical well (Schlumberger OIL Computer-Based Training 6.1)

- **J-Type wells:** this profile type has vertical, build section and tangent section. In another words these wells change from vertical intentionally as we can see in Fig. 2.11.

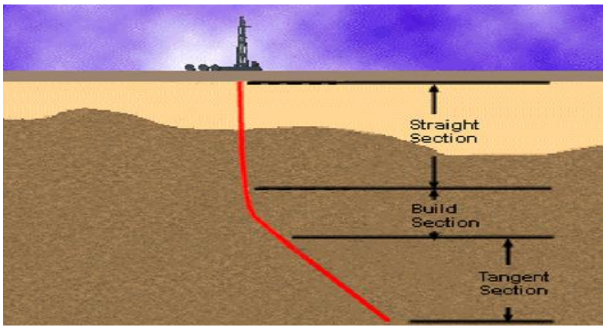

Figure 2.11: J-Type well (Schlumberger OIL Computer-Based Training 6.1)

- **S-Type wells:** this profile type has vertical, build section, a tangent section and a drop section. In another words these wells change from vertical and go back to vertical intentionally as we can see in Fig. 2.12.

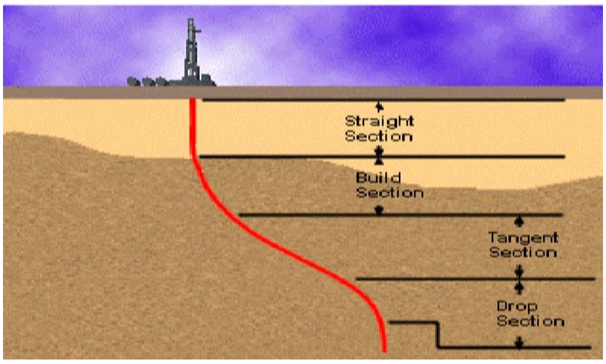

Figure 2.12: S-Type well (Schlumberger OIL Computer-Based Training 6.1)

- **Horizontal wells:** this profile type has vertical, build section, a tangent section, a second build section and a horizontal section. In another words these wells change from vertical to approximately to horizontal intentionally, as we can see in Fig. 2.13. Horizontal wells are likely used in development wells

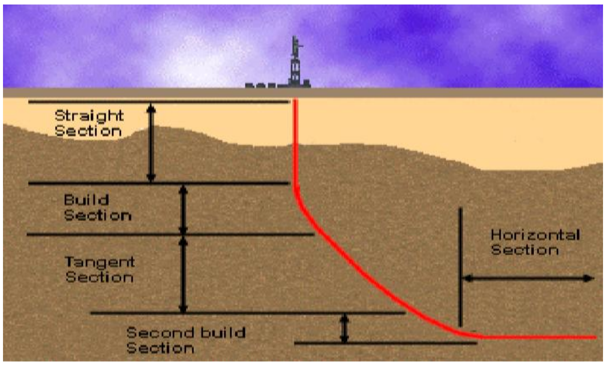

Figure 2.13: Horizontal well (Schlumberger OIL Computer-Based Training 6.1)

The following constraints can lead to changes in the well profile.

- ✓ **Fault, formation dip**: due to geological properties and cross faults could represent challenges. Sudden changes in formation properties, for instance in the presence of a normal fault where the formation can change from shale to sand or vice versa, leads to changes in the drilling fluid (DF) properties to guarantee a good wellbore stability, avoid swelling and formation invasion, etc. A S-Type well profile is likely used to cross faults.
- ✓ **Horizontal wells and multi-drains for recovery**: may call for drilling multiple entry points to cut through a reservoir at a better angle and increase the drainage area. The Horizontal well profile provides a better recovery mainly in thickness reservoirs.
- ✓ **Inaccessible locations**: do not allow to rigging up on an interest area, so the rig should be far away from the target. In this case, a deviated or directional well is needed. Any type of well profile could perform this job, depending upon the well requirements.
- ✓ **Multiple target**: may require steering the well path to include more than one target reservoir, S-Type well profile is one of profile used to perform this task.
- ✓ **Relief well**: may be applicable due to pressure downhole in order to avoid blowout. J-Type or S-type well are usually used to perform this job.
- ✓ **Salt domes**: due to slat properties (plastic and chemistry properties) is better avoid drilling through salt domes. Differential tensions may lead to a stuck BHA. Any well profile could perform this job.

- ✓ **Side track**: in case of stuck BHA where is not possible fish the tools from downhole, or when the formation behave (due to its properties) does not allow to drilling ahead. It basically consists of changing the path and drilling in another direction using the same top hole. An S-Type well profile is most appropriate in this situation.

Fig. 2.14 illustrates some of the applications of wells profiles .

Figure 2.14: Deviated well applications. (From: IFP Training 2010)

2.3 DRILLING FLUIDS (DF) SELECTION

Drilling fluid or drilling mud is one of the most important elements of drilling. The DF helps us avoid many hazards associated with drilling. Therefore, the properties of the DF must be analyzed very carefully to fulfil all the necessary requirements to have a good drilling performance. (HERIOT WATT UNIVERSITY, 2005). Follow are described the mains purpose of drilling fluid.

Purposes of DF

- **To remove and suspend cuttings:**

  It is the primary function of DF to ensure drilling efficiency. As we know rock cuttings generated by the drill bit must be removed from the wellbore as much as possible. If these cuttings are removed properly the drillstring will become stuck in the wellbore, leading to NPT. Rheological properties have a significant effect on hole cleaning.

- **To prevent formation fluids flowing into the wellbore:**

  When drilling a new formation, the first barrier for the protection of the influx is the mud. The hydrostatic pressure exerted by a DF column should be controlled so that it does not not exceed formation fracture pressure while at the same time being high enough to prevent the influx coming from the formation. In many cases increase DF weight along with some additives (such as barite) due to the lost weight while mud passes through the shakers (lost solids in shakers because of mesh size and friction during transportation) and to overbalance the formation pressure.

$$\mathbf{P_h} = \frac{\mathbf{d * TVD}}{\mathbf{10.2}} \ [\mathbf{bar}]$$

$$\mathbf{P_{Pore}} < \mathbf{P_{Hydrostatic}} < \mathbf{P_{Fracture}}$$

$\mathbf{P_h}$ = Hidrostatic Pressure

$\mathbf{d}$ = Drilling Fluid Density

$\mathbf{TVD}$ = Total Vertical Depth

Equation 2.1: Hydrostatic pressure. (From: Heriot-Watt University 2005)

- **Maintain wellbore stability:**

  Shale instability is one of the most common problems in drillings operations. Maintain wellbore stability requires a balance between mechanical and chemical factors. These two factors should combine to provide a stable wellbore until running casing and finish cement job. Shale instability may be caused by:

  - Differential Pressure between the bottom hole pressure in the borehole and pore pressure in the shales. Figure 2.15 shows the drilling fluid density window (mechanical factor).
  -

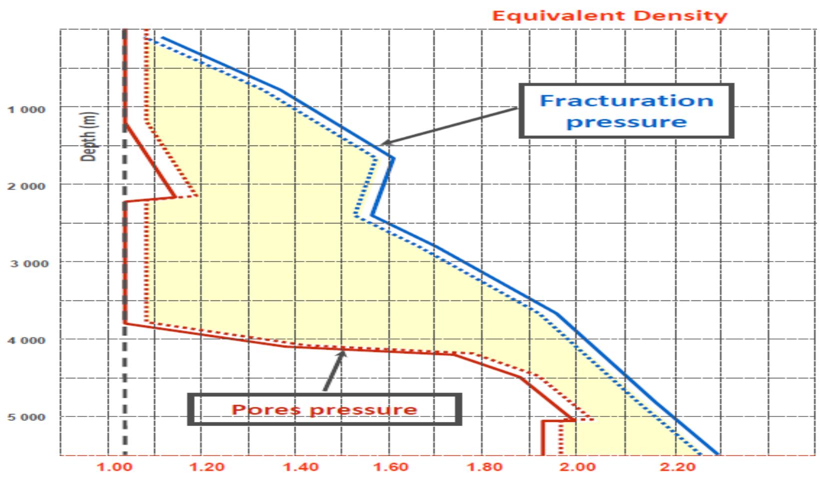

Figure 2.15: Drilling Fluid Density window and formation pressure.

- The hydration of the clay within the shale by water contained in the drilling mud filtrate cause an expansion of the clay which can lead to hole instability. The mud used in this situation should contain inhibitory agents such as calcium and potassium to reduce the ability of water to hydrate clays contained in the formation.

- **Cooling and lubricate the bit:**
  Due to the friction generated during drilling in particular with PDC, an increase in the bit temperature it will overheat and quickly wear out the bit. The circulation of DF reduces the bit temperature and helps lubricate it
- **Transmit hydraulic horse power to bit and MWD tool:**
  Hydraulic system energy can be used to maximize ROP by improving cutting removal at the bit. It also provides power for mud motors to rotate the bit and for MWD and LWD tools.

DF properties

Density: is a measure of mud weight, density which is very important to maintaining well control.

Rheology:

- **Gel Strength:** can be assumed as the strength of any internal structures formed in the mud when is static. This characteristic can keep cuttings suspended. Provide the ability of drilling fluid to keep the cuttings in suspension when mud has been static due to the connections or other reason. Provide the indication of the pressure necessary to restart the flow after stationary condition.

- **Plastic Viscosity (PV):** is a measure of resistance of liquids to flow. Despite the fact that increased viscosity has smaller effect on pressure loss and improving the transport of debris, it has a negative effect on ROP, caused by particles in the DF becoming heavier and leading to an increase in RPM to maintain the ROP. Otherwise, although cuttings settle rapidly in low-viscosity fluids and are difficult to circulate out of the well, viscosity should be maintained at as lower as possible values for optimum drilling rate performance. Once again is necessary to keep the viscosity high enough to transport the cuttings and low enough to guaranty an optimum drilling rate.

- **Yield Point (YP):** is a measure of electro–chemical attractive forces within the mud under flowing conditions.

Filtration: occurs when the mud pressure is higher than the pore pressure and mud penetrates the pores of the formation. This infiltration should be controlled to avoid damage to the formation. It can be allowed to invade the formation up to a certain distance (a few meters) to build a cake protection. Once the mud cake reaches the correct thickness, invasion slows down and stops. The filter cake building properties of mud can be measured by means of a filter press which reflects both the efficiency with which the solids in the mud are creating an impermeable filter cake and the efficiency thickness of the filter cake that will be created in the wellbore. In Fig. 2.16 we can see how mud cake is built.

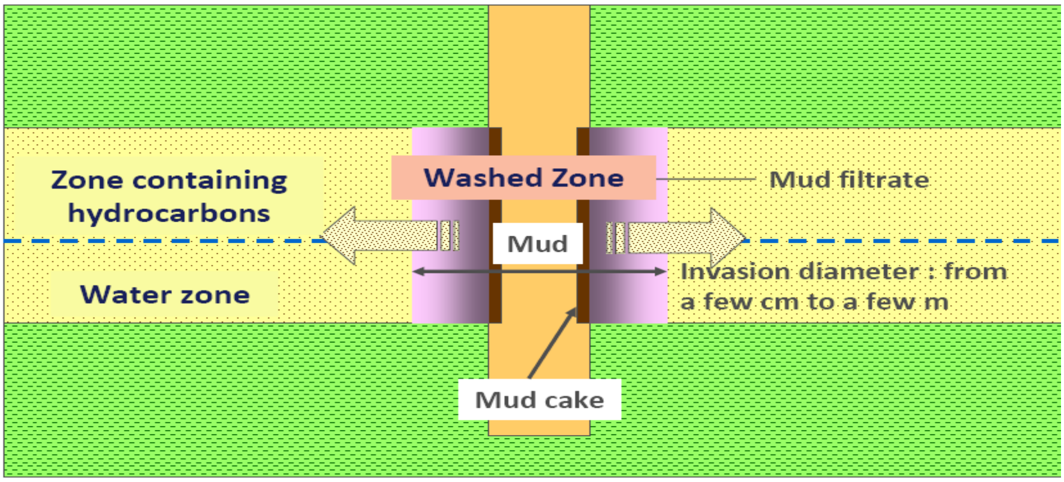

Figure 2.16: Mud filtrate. (IFP training 2010)

Sand Content: is the proportion of sand in the mud. This proportion should not be high in order to avoid mud pump damage, increase ECD and change mud density while drilling. Table 2.1 describes resumed the mud function and physical nda chemical properties.

Table 2.1: Function and Physical Properties of Drilling Fluid (HERIOT WATT UNIVERSITY, 2005)

Function	Physical/Chemical property
Transport cuttings from wellbore	YP, apparent viscosity, velocity, gel strength
Prevent formation fluid flowing into the wellbore	Density
Maintain wellbore stability	Density, reactive with clay
Cool and lubricate the bit	Density, velocity
Transmit hydraulic horsepower to bit	Velocity, density and viscosity

Main types of DF

Water Based Mud (WBM): is a type of drilling fluid used when the continuous phase of the system is water (salt water or fresh). It consists of a mixture of solids, liquids and chemicals. Some solids (clays), known as active solids react with the water and the chemicals in the mud. Those which do not react within the mud are called inactive or inert solids (barite). The system can be based on sea water.

- ✓ **Advantages**
  - In offshore applications, there is an abundance of seawater supply.
  - It is economical and environment friendly.
- ✓ **Disadvantage**
  - The water in this mud can create instability (caused largely by the hydration of clay mud containing water).

Oil Base Mud (OBM): consists of a composite of WBM, but the continuous phase is oil instead of water. In an invert oil emulsion (a mix of water with the oil in the continuous phase), mud water may increase to a large percentage of the volume, but oil is still in continuous phase. OBM does not contain free water which can react with clays in shale.

- ✓ **Advantages**
  - Provides excellent wellbore stability.
  - Less formation risk damage than WBM.
- ✓ **Disadvantages**
  - More expensive and require more careful handling than WBM.
  - Drilled cuttings contaminated by OBM can have lasting environment impact.

2.4 WELLBORE STABILITY ISSUE

Wellbore stability is critical when drilling the horizontal phase, and is critical to all assumptions of feasibility and performance on an extended reach well. Hole cleaning is significantly affected by intervals of hole enlargement or swelling.

Hole angle is one of the main reasons for wellbore stability. Generally, as the inclination increases, drilling fluid weight does not need to vary greatly because in many cases we are crossing the same formation. Otherwise, high angles result in longer intervals of troublesome formations being open, which can lead to an increase of problems related to hole stability.

Tectonic stress must be understood and managed appropriately. For a deviated well, when horizontal stresses exceed vertical stresses, it is actually safer to drill in high inclination than on the vertical. Therefore, a minimum drilling fluid weight for stability is required when drilling, relative to the horizontal stress orientation.

Time exposure is usually greatly increased for an extended reach well. Formations that are relatively at beginning in low angle wells may be quite problematic because of the increased time exposure.

ECD is pretty much significant for wellbore stability in an extended reach well. Long hole sections, or very shallow sections with small gaps, may induce a large ECD effect. When the pumps are turned on and off at various times, wellbore instability can be induced by constant flexing and relaxing of the wellbore. This must be noted, especial when using high flow rates and pipe rotation. (Mims, Krepp, 2007)

Sticking mechanism

Sticking mechanism is defined as a condition which causes forces to be transferred between the string and the wellbore at stuck point If abnormal overpull or set down is experienced, there is Sticking Mechanism acting in the well which makes it more difficult to move the string. When this happens, the first step is to identify the sticking mechanism involved, because the optimal way to deal with it varies from case to case and any mistake can make the problem worse (ABC of Stuck Pipe). There are three categories of sticking mechanism:

1. **Wellbore Geometry / Mechanical**

❖ **Undergauge hole**

Causes:

- Hard abrasive formation wears the bit gauge and results in an under gauge hole.

Occurrences:

- When the is changed and replaced by a new bit.
- Running a PDC after a tricone.
- Drilling across abrasive formations.

Rig Site Warnings:

- Pulled bit or stabilizers are under gauge.
- Occurs only when trip in hole.
- A sudden set down in weight.
- Circulation is unrestricted or slightly restricted.
- The bit get stuck before reaching the bottom.

First response:

- Jar in the opposite direction of the movement.
- Reaming.

Second response:

- Pump pills.

Preventive Actions:

- Use proper gauge protection in bits and stabilizers.
- Record tight spots while running in the hole or pulling out of the hole.
- Ream suspected tight spots sections.
- Reduce the trip in speed before the BHA enters a suspected under gauge zone.
- Always gauge all BHA components on trips in and out.
- Use spiral stabilizers, which are better than straight blade stabilizers.

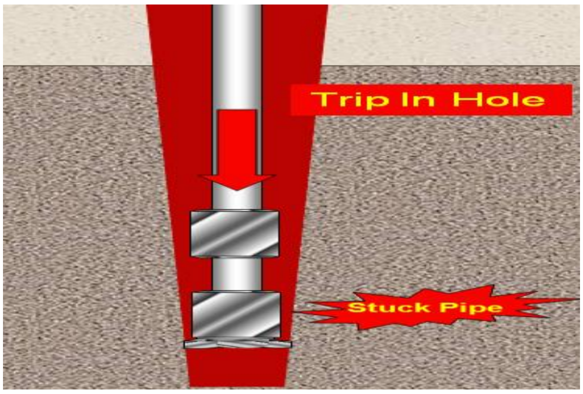

Figure 2.17: Undergauge hole. (http://www.google.com/imgres?q=undergauge+hole&um=1&hl=pt. 12/2012)

❖ **Mobile formation**

Causes:

- Due to the lower mud weight, the overburden weight squeezes the formation.

Occurrences:

- In salt or shale formation.

Rig Site Warnings:

- Over pull when picking up, takes weight when trip in hole.
- Restricted circulation with BHA at mobile formation depth.

First response:

- Jar in the opposite direction of the movement.
- Reaming.

Second response:

- Pump pills.

Preventive Actions:

- Maintain sufficient mud weight. Select carefully a mud system that will not aggravate the mobile formation.
- In order to prevent mobile salt formation washout, consider using a slightly under-saturated mud system.
- Plan regular reaming/wiper trips particularly for this section of the hole.
- Minimize as much as possible the open hole exposure time of these formations.
- Reduce trip speed before BHA enters the suspected area.

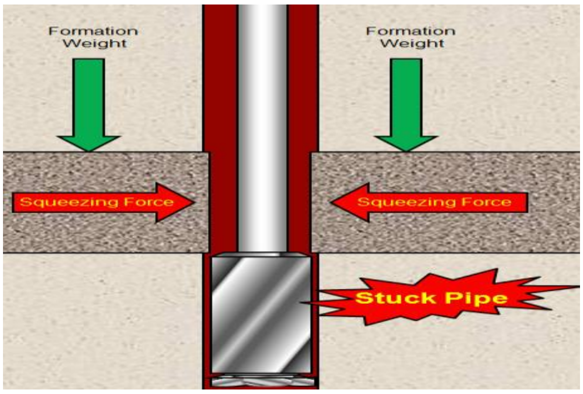

Figure 2.18: Mobile formation. (http://www.drillingformulas.com/mobile-formation-causes-stuck-pipe 09/2012)

❖ **Ledges and doglegs**

Causes:

- Ledges at interface of hard/soft formations.

Occurrences:

- Hard/soft interbedded layers.
- Faulted/fractured formations.
- Frequent angle/direction changes.

Rig Site Warnings:

- Sudden erratic over pull or set down.
- Issues are at recurring fixed depths.
- Issue does not disappear with circulation below the problem area.
- Full circulation is possible.

First response:

- Jar in the opposite direction of the movement.
- Reaming.

Second response:

- Pump pills.

Preventive Actions:

- Reduce excessive directional changes in the well bore.
- Consider reaming trips.
- Reduce the trip speeds before the BHA reaches the suspected ledge zone or dogleg.
- Avoid prolonged circulation across soft inter bedded formations.
- Reduce momentum effects when running into a tight zone.
- Do not start the building angle near the shoe.
- Optimize sliding and rotating based on Lithology.

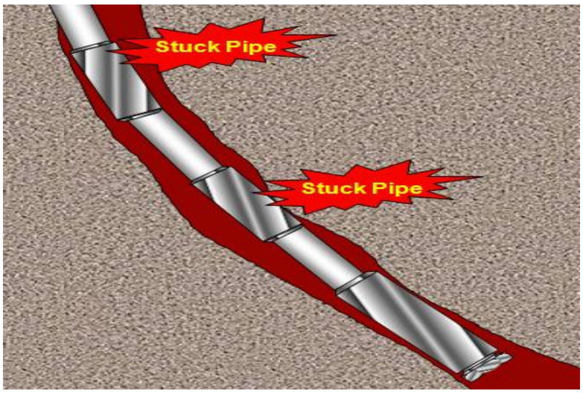

Figure 2.19: Dogleg. (http://www.drillingformulas.com/ Ledges and doglegs-causes-stuck-pipe 09/2012)

❖ **Keyseat**

Causes:

- By the drill pipe rotating against the wellbore wall at the same point and wearing a groove or "keyseat".
- Tool joints or BHA are pulled and "jammed" into the groove.

Occurrences:

- At abrupt changes in inclination or direction.
- After long drilling hours with no wiper trips in dogleg section.
- During tripping out.

Rig Site Warnings:

- Sudden over pull when the BHA reaches dogleg.
- No restriction in circulation.

- Free string movement below key seat depth possible if not, already stuck in key seat.
- Cyclic over pull at tool joints when trip in or out.

First response:

- Jar in the opposite direction of the movement.
- Reaming.

Second response:

- Pump pills.

Preventive Actions:

- Minimize side forces.
- Perform reaming and/or wiper trips if a dogleg is present.
- Consider running reamers or a key seat wiper if a key seat is likely to be a problem.

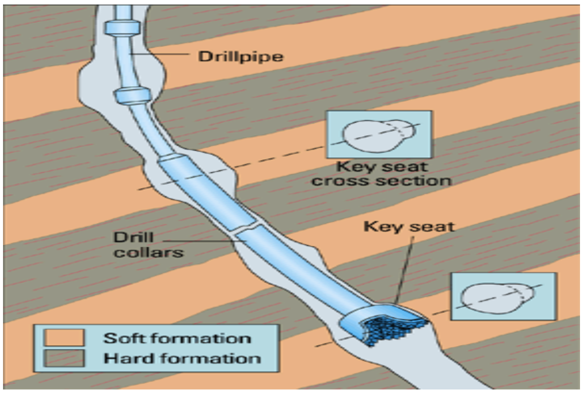

Figure 2.20: Key seat. (http://www.glossary.oilfield.slb.com 09/2012)

2. Solids Induced Packoff

❖ **Hole cleaning**

Causes:

- Insufficient rotation.
- Low AV.
- Poor mud properties.
- Lack of patience.

Occurrences:

- Big hole.
- Deviated hole (usually above 30 degrees inclination).

Rig Site warnings:

Low Angle Hole

- Overpull after connections.
- Increased Stand Pipe Pressure (SPP) / ECD.

High Angle Hole

- Sudden increase in drag (high PUW readings)
- Tight hole on trips (if tight spot moves up after circulation).

First response:

- Circulation

Second response:

- Jar in opposite direction of the movement.

Preventive action:

Low Angle Hole

- Maximize Annular Velocity (AV)
- Increase low-end rheology
- Pump Sweep.
- Match ROP to hole cleaning rate

High Angle Hole

- Maximize RPM
- Circulate a long time prior to tripping
- Match ROP to hole cleaning rate
- Maximize AV
- Optimize low-end mud rheology

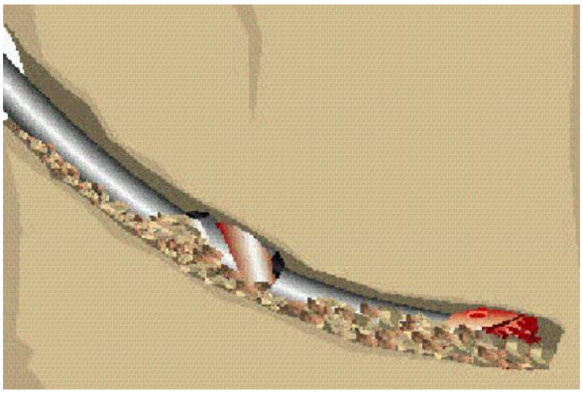

Figure 2.21: Hole Cleaning Induced Packoff (K&M Technology Group-2010)

- **Unconsolidated formation**

Causes:

- No bonding between particles.
- Little or no filter cake.
- Not enough hydrostatic pressure to support the formation.
- Sand/Gravel falls into the hole.

Occurrences:

- While drilling top hole sections.
- While drilling shallow formations (sands).

Rig Site Warnings:

- Increasing pump pressure.
- Increasing Torque and Drag.
- Overpull on connections.
- Fill on bottom.
- Shakers blinding.

First response:

- Jar in the opposite direction of the movement.
- Reaming.

Second response:

- Pump pills.

Preventive Actions:

- Design the mud to build a low permeable cake.
- Keep adequate hole cleaning (flowrate and viscosity).

- Control drill to ensure an adequate hole cleaning.
- Control drill to allow time for the filter cake to build up.
- Reaming and backreaming when needed.
- Clean out hole and fill prior to drilling ahead.
- Consider viscous pills on trips.
- Trip carefully.

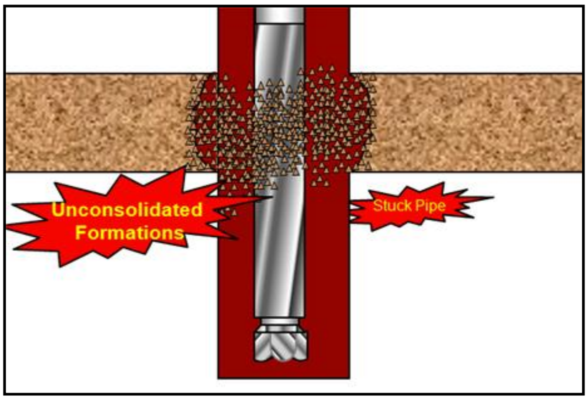

Figure 2.22: Unconsolidated formation. (K&M Technology Group-2010)

❖ **Reactive formation**:

Causes:

- Water sensitive shale /clays drilled with less inhibition than required.
- Leads to swelling, cavings, or both

Occurrences:

- Poor shale inhibition.
- Occurs much more often with WBM.
- The reaction is time dependent, depending on the mud and formation interaction.
- While drilling or more tripping.

Rig Site Warnings:

- Hydrated or mushy cavings, gumbo attacks.
- Shakers screens blind off, clay balls form.
- Increas cake thickness, PV, YP.
- Increasing pump pressure.
- Circulation is highly restricted or impossible.
- Increasing Torque and Drag.
- Occurs more often while BHA is passing the reactive formation

First response:

- Jar in the opposite direction of the movement.
- Reaming.

Second response:

- Pump pills.

Preventive Actions:

- Use an inhibited mud system. If the problem is severe, use OBM/SBM.
- Drill and case off as fast as possible.
- Perform wiper trips regularly when drilling the hole.
- Consider staged reamers some distance above the BHA to avoid wiper trips.
- Maintain mud properties within specification.
- When using WBM, monitor MBT closely. If MBT increases, this means the clay formation is reacting with the mud.

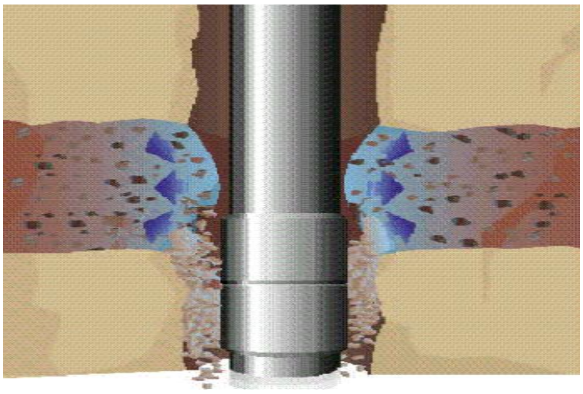

Figure 2.23: Reactive Formations. (K&M Technology Group-2010)

- **Fractured formation**

Causes:

- Rock near faults can be broken into small or large pieces, if loose it can fall into the hole and jam the drill string.

Occurrences:

- In tectonically active zones.
- Fractured limestone.

Rig Site Warnings:

- Possible losses or gains (or ballooning).
- Fault damaged cavings at shakers.
- Splintering or tabular cavings.
- Hole fill on connections.
- Instantaneous sticking occurs.

First response:

- Circulating

Second response:

- Jar in the opposite direction of the movement.

Preventive Actions:

- Limit the rotary and tripping speeds
- Monitor ECDs.

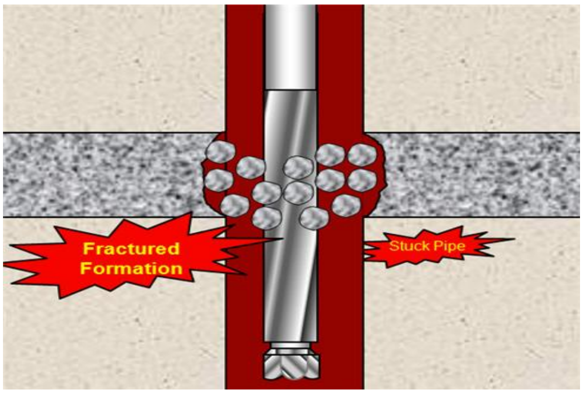

Figure 2.24: Fractured formation (K&M Technology Group-2010)

❖ Cement blocks

Causes:

- Hard cement chunks fall into the well bore and jam the drill string.

Occurrences:

- Around the casing shoe.
- Around open hole squeeze plugs.
- Around kick-off plugs.

Rig Site Warnings:

- Circulation unrestricted.
- Large Cement fragments at the shakers.
- Rotation and downward movement may occur possible.
- Erratic torque

First response:

- Circulating

Second response:

- Jar in the opposite direction of the movement.

Preventive Actions:

- Allow sufficient curing time for cement before attempting to drill out.
- Drill out the cement with enough flow rate and rotation and preferably controlled ROP.
- Ream casing shoe and open hole plugs thoroughly before drilling ahead.
- Limit casing rat hole length to reduce a source of cement blocks.
- Reduce the trip speed down before the BHA enters the casing shoe or the plug depth.

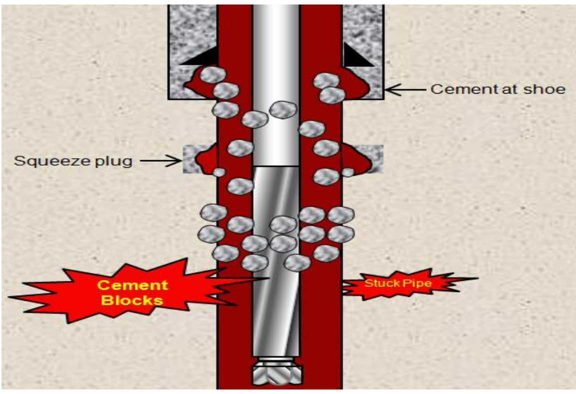

Figure 2.25: Cement blocks (K&M Technology Group-2010)

❖ **Naturally over-pressured shales**

Causes:

- Caused most often by geological phenomena such as under-compaction, naturally removed overburden and uplift.
- Fractured shales and cavings fall into the well bore.
- Using insufficient mud weight in these formations will cause the hole to become unstable and collapse.

Occurrences:

- When insufficient mud weight is used.
- Removal of ECD.
- Most frequent while tripping out (swab load).
- Possible while drilling while pumps are off.

Rig Site Warnings:

- Splintery cavings at shakers.
- Increased Torque and Drag.
- Gas levels increase.
- Circulation restricted or impossible.
- Hole fill after trips.
- An increase in ROP due to under balanced conditions

First response:

- Recirculation

Second response:

- Jar in the opposite direction of the movement.

Preventive Actions:

- Monitor shale shakers for cuttings and cavings.
- Use enough mud weight to control pore pressure.
- Use pore pressure analysis and confirm with gas readings.
- Allow sufficient overbalance to compensate for swab load.
- Pump, backream, or strip out if sufficient trip margin is not possible.

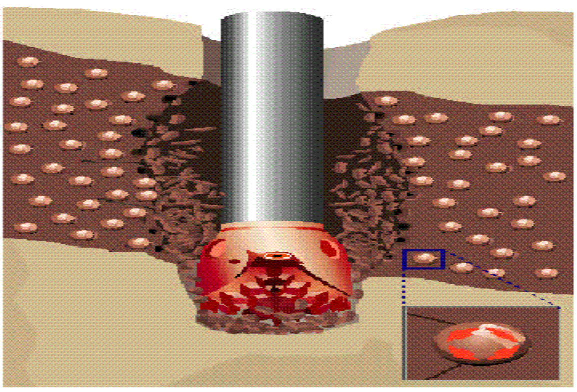

Figure 2.26: Natural over-pressure (K&M Technology Group-2010).

- **Induced over-pressured**

Causes:

- Shale pore pressure becomes “super charged”by hydrostatic or ECD overbalance.
- Shale cracks and falls into the wellbore.

Occurrences:

- After a decreasing in MW or a long exposure time with constant MW.
- In high ECD environments.
- It is likely to occur in any type of mud.
- While drilling or tripping (surge).

Rig Site Warnings:

- Cavings (splintery) at shakers.
- Cuttings / cavings show no sign of hydration.
- Ballooning effect.
- Increasing Torque and Drag.
- Circulating restricted or impossible.
- Hole fill.
- Tight hole in casing rat hole.

First response:

- Recirculation.

Second response:

- Jar in the opposite direction of the movement.

Preventive Actions:

- Control ECD properly to minimize ballooning and inducing over pressure to sensitive formations.
- Good hole cleaning practices are required if cavings occur.

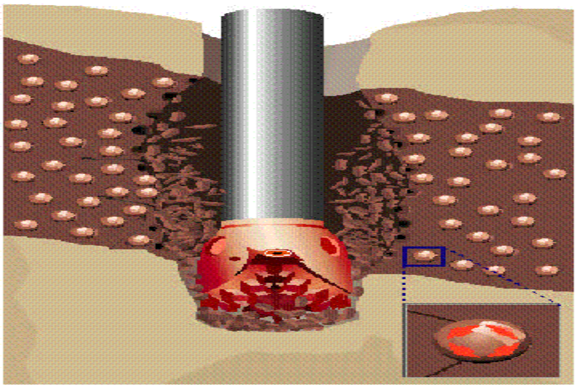

Figure 2.27: Induced over-pressure (K&M Technology Group-2010)

- **Tectonically stressed formations**

Causes:

- Natural lateral stresses are present due to the movement of the earth's crust.
- Shale fractures and falls into the wellbore.

Occurrences:

- In reverse or strike-slip stressed locations.
- In mountainous locations.
- During drilling or tripping (due to swab load).

Rig Site Warnings:

- Increase in Torque and Drag.
- Increase in Pump Pressure / ECD.
- Fill on bottom.
- Cavings at shakers.
- LWD indicators.

First response:

- Recirculation

Second response:

- Jar in the opposite direction of the movement.

Preventive Actions:

- Use geomechanical analysis and/or offset data to establish optimum inclination and azimuth.

- Well design is required to accommodate the correct mud weight (wellpath, casing points, ECD management).
- Keep mud weight and ECD (including swab load) within correct mud weight window.
- Keep the hole clean and be prepared for increased amount of cuttings and cavings.

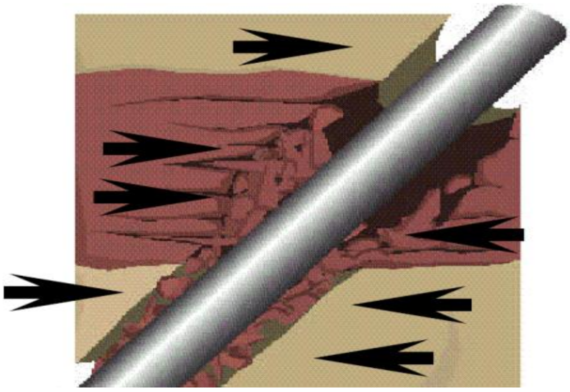

Figure 2.28: Tectonically stressed formations (K&M Technology Group-2010)

❖ **Overburden stress**

Causes:

- The overburden or vertical stress, σV, is usually a principal stress. MW is not enough to support the overburden and is not adjusted as the hole angle increases.

Occurrences:

- Mainly in deviated wells.

Rig Site Warnings:

- Angular cavings at the shakers.
- Increase in Torque and Drag.
- Increase in Pump Pressure / ECD.
- Fill on bottom.
- LWD indicators.

First response:

- Recirculation

Second response:

- Jar in the opposite direction of the movement.

Preventive Actions:

- Use geomechanical analysis and/or offset data to establish optimum inclination and azimuth.
- Design the well to accommodate the correct mud weight (wellpath, casing points, ECD management).
- Maintain mud weight (and swab load) within correct mud weight window.
- Maintain the hole clean and be prepared for an increased amount of cuttings and cavings

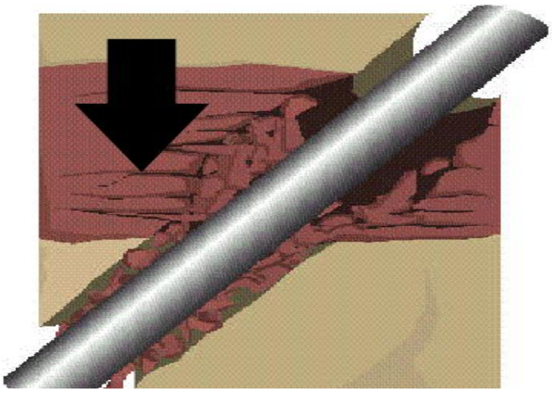

Figure 2.29: Overburden stress (K&M Technology Group-2010)

- ❖ **Junk in hole**

Causes:

- Down hole equipment failure.
- Poor housekeeping on the rig floor.
- Hole cover is not installed.

Occurrences:

- At any time.

Rig Site Warnings:

- Sudden erratic torque.
- Inability to continue drilling ahead.
- Circulation not restricted.

First response:

- Recirculation

Second response:

- Jar in the opposite direction of the movement.

Preventive Actions:

- Inspect all handling tools regularly, especially rig tongs and slips.
- Practice good housekeeping.
- Install drill pipe wiper.

Figure 2.30: Junk in hole (K&M Technology Group-2010)

❖ **Green cement and LCM**

Causes:

- Circulation attempted with the bottom of the drill string in soft cement which dehydrates the cement due to differential pressure.
- Cleaning LCM treatment with insufficient flow rate and high ROP.

Occurrences:

- When using LCM or cement (Dress cement plug).

Rig Site Warnings

- Increase in pump pressure leading to inability to circulate.
- Loss of string weight and decreasing in torque.
- Green cement in mud returns, discolored mud.

First response:

- Recirculation

Second response:

- Jar in the opposite direction of the movement.

Preventive Actions:

- Give cement enough time to set and estimate the TOC.
- Start circulation several joints above the TOC and run down slowly. The weight indicator could not be reliable to show TOC.
- Drill out cement with low WOB and high flow rate.

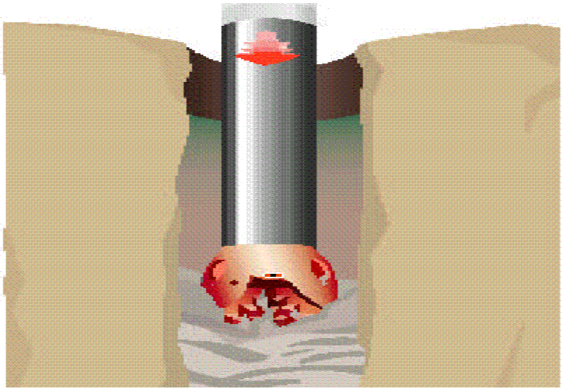

Figure 2.31: Green cement (K&M Technology Group-2010)

3. Differential Sticking

Differential sticking may occur due to mud pressure overbalance and it is influenced by drilling practices, type mud solids, permeability, bottom-hole assembly clearance, coefficient of friction and the lubricating characteristics of mud (Technical Data Book). Stationary condition should be avoided because differential sticking may occurs when the pipe is stationary during taking a directional survey, making a connection, etc. (ABC of Stuck Pipe).

Causes

- Overbalance applies a differential sticking force to the drill string contact area.
- Drill string contacts a permeable zone.
- When motion stops, static filter cake develops.

Occurrences

- With a stationary or very slow moving drill string.
- When contact exists between the drill string and the well bore.
- When an overbalance is present across a permeable formation.
- In a thick filter cake or cuttings bed.

Rig site warnings

- Increasing over pull on connections and after surveys.
- Increasing trends in static friction.
- Full unrestricted circulation.
- High overbalance (losses, MW).

Preventions

- Reduce the stationary time.
- Reduce the contact area between the wellbore and the pipe by using the minimum length drill collars needed for required bit weight.
- Manage mud properties.

In figure 2.27 we can follow the effect of differential sticking.

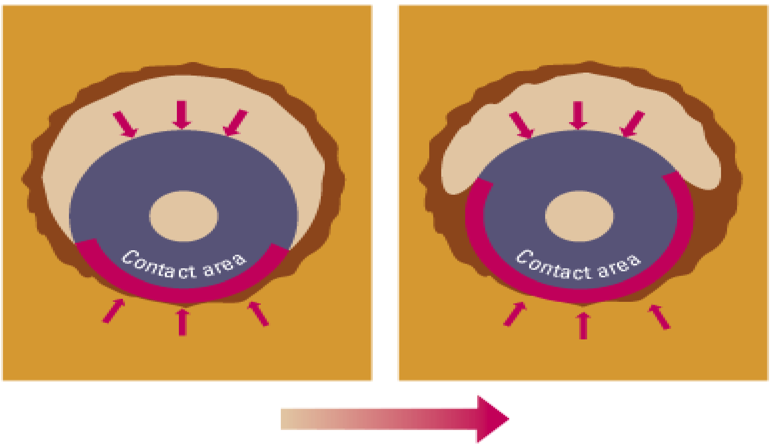

Figure 2.32 - Differential sticking (http://www.glossary.oilfield.slb.com 09/2012)

Despite all of conditions associated with deferential sticking pipe can not be eliminated, those may be reduced by following good drilling practices. Below are described what we have to do to reduce the wellbore differential sticking. (Alexandre, 2008)

Estimating Formula for Differential Sticking

Force to pull free depends on the length of pipe in contact with permeable formation, and the coefficient of friction between pipe and wall.

The estimated force required to pull free is as equation 2.2 shows. This estimate tends to be more accurate in a straight hole than in a directional well. (Technical Data Book)

$$\mathbf{Fdiff} = \mathbf{K} \times (\Delta\mathbf{P}) \times \mathbf{Area}$$

K = Sticking coefficient (0.2 water base mud)

(ΔP) = Differential pressure

Area = Contact area

Area = L (12in/ft) (πd/3)

(assume ⅓ of the drill collar circumference is buried)

Circumference = π x Diameter

Equation 2.2 - Formula for F differential Sticking. (From: Technical Data Book)

3. FUNDAMENTALS OF HOLE CLEANING

Hole cleaning is one of the biggest challenges in high deviated drilling wells. Despite all recent improvements in technologies and procedure we cannot know what is really happening in the downhole yet, even though efforts have been made to understand what is happening relative to cuttings and borehole condition when drilling, tripping and running the casing.

3.1 CUTTINGS BEHAVIOR IN DOWNHOLE

As inclination increase the difficult to bring the cuttings to surface increase as well. Hole cleaning in the vertical phase depends on the Annular Velocity (AV). In vertical wells the cuttings move around the drillpipe through flow path. On the other hand, in the high inclinations the fluid path is essential moving above drillpipe, the problem is that cuttings fall quickly to the low side of the hole, where the flow path is very slow. Figure 3.1 shows how cuttings move in low and high inclination and annulus.

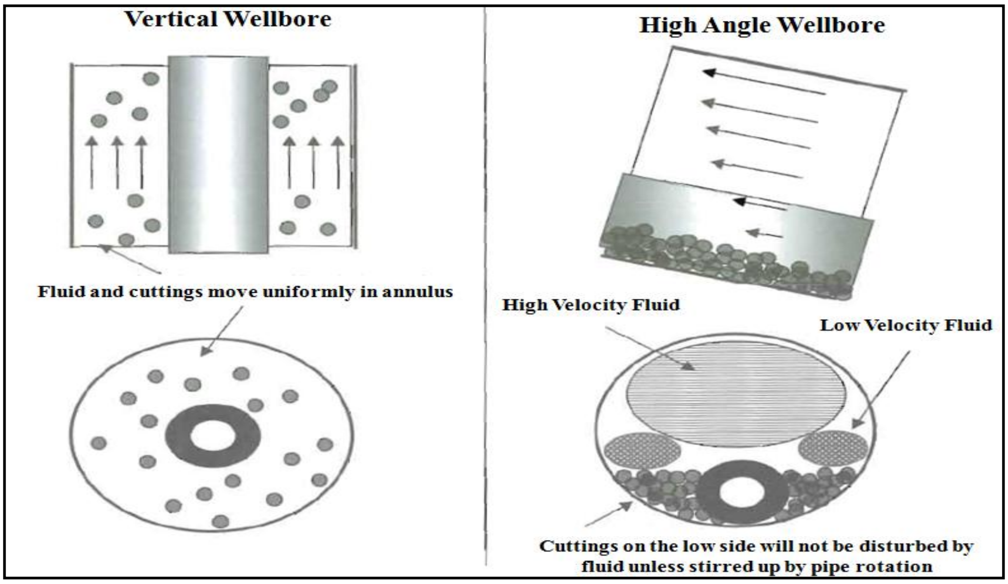

Figure 3.1: Fluid Movement in the Annulus (Drilling Design and Implementation For Extended Reach and Complex Wells)

The annular space increases after the BHA, which leads to a decrease in AV. With this decreases, the cuttings quickly fall to the low side of the well and will accumulate to form dunes. If the dunes reach a critical height it is possible to pack off the hole with cuttings once rotation starts. It is essential to prevent the dunes from reaching a critical height, and is important to take this phenomenon into account before start the rotation. Figure 3.2 show how cuttings dunes form when they leave the BHA.

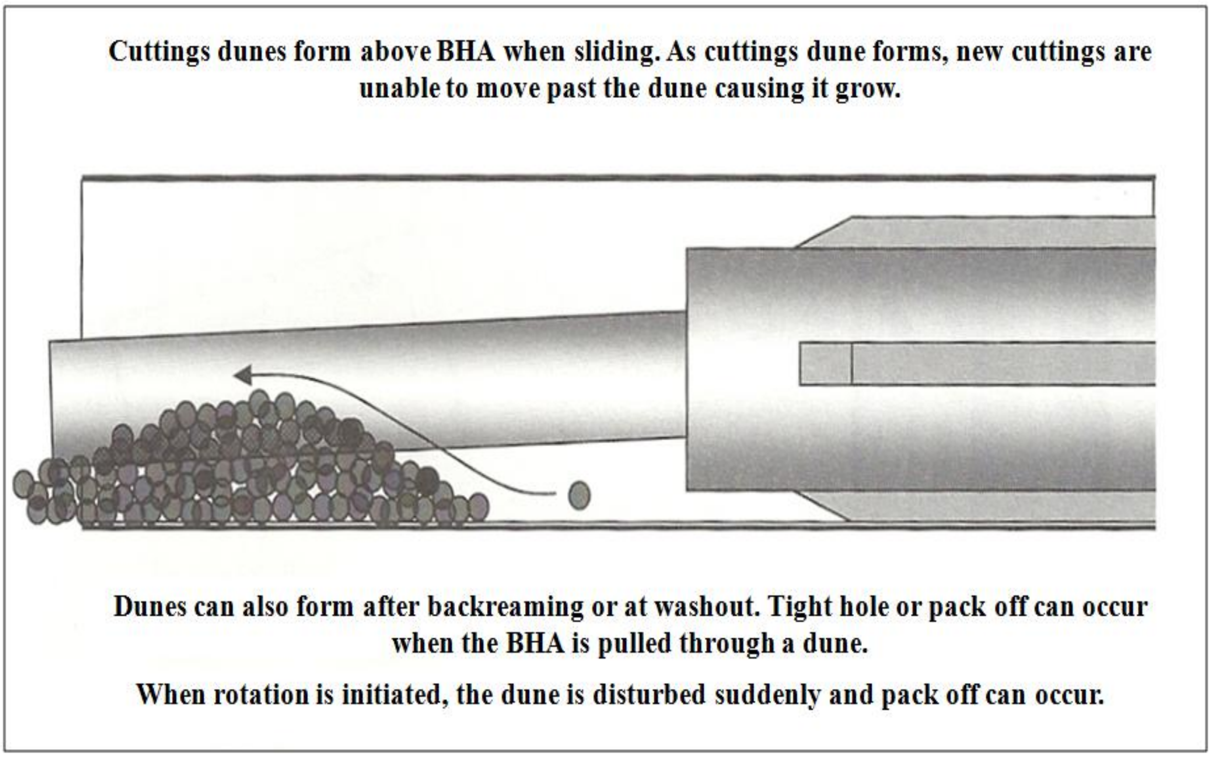

Figure 3.2: Formation of Cuttings Dunes when Sliding (Drilling Design and Implementation For Extended Reach and Complex Wells)

On slopes range from 45°-65°, cuttings transportation becomes even more critical. When the rotation and pumps are switched off for any reason these cuttings settle at the bottom of the section and gravity causes them to slide downhole. (Mims, Krepp, 2007)

3.2 CUTTINGS TRANSPORTATION

The main purpose of hole cleaning is to carry as much debris as possible from downhole to the surface. To understand clearly what is happening in the entire hole, hole can be divided in three categories based on the wellbore inclination:

Cuttings behaviour with inclination range from 0°- 45°

As we already discussed, in this inclination, cuttings are brought to surface by fighting gravity and slip velocity. Rheology properties and flow rate in annular play as an important role in cuttings transportation. Viscous and gel strength are in charge and keep cuttings suspended when the pumps are turned off. But luckily, the cuttings are not alone. The fluid is crowded with solids, therefore, in a crowded solids environment a mechanism called **hindered settling** occurs. For each cutting that drops, another is forced upwards.

Cuttings behaviour with inclination range from 45° - 65°

Here the cuttings move up the hole mostly on low side and begin to form dunes, with rotation is easily to stirred up the cuttings into the effective flow regime. The main issue in this range is that when pumps are stopped, the cuttings will fall in low side and begin to slide as an avalanche to downhole. Alteration in hole cleaning strategy must be done with respect to the vertical well section.

Cuttings behaviour with inclination range from 65° - 90°

At ranges, the cuttings fall to low side and form a long, continuous cutting bed. As we already know the great issue is that the drilling fluid will flow above the drillpipe, mechanical agitation is necessary to stir up cuttings through the effective flow area. Hole cleaning in this section is actually less critical than in inclination range 45° - 65°, but takes a lot of time (Mims, Krepp, 2007). Fig. 3-3 shows how cuttings behaviour in different inclinations.

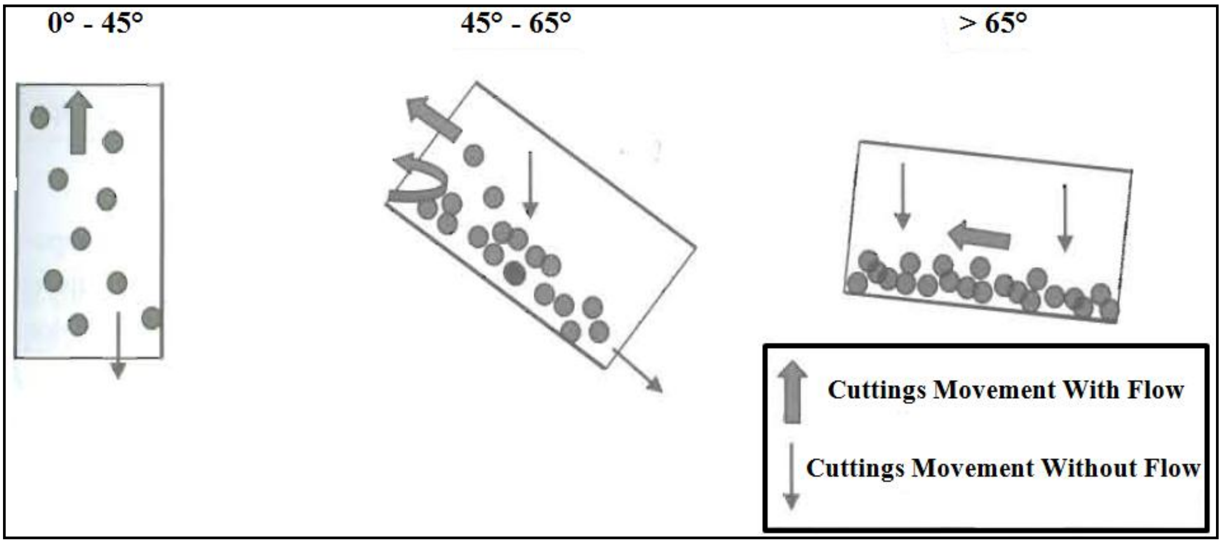

Figure 3.3: Cuttings behaviour at different ranges of inclination (Drilling Design and Implementation For Extended Reach and Complex Wells)

3.3 PARAMETERS THAT EFFECT HOLE CLEANING

There are two processes which allow us to clear a well of debris, **dispersion** and **mechanica**l. **Dispersion process** is the separation or unbundling of cuttings to make them lighter and easier to carry. This process is most commonly used in most soft formations and with no inhibitive properties, due to the fact that inhibitive properties prevent cuttings from dispersing into drilling fluid. Dispersion process is usually applied with water base mud (WBM). **Mechanical processes** have several parameters that act together to clean a well more effectively. The parameters that affect the hole cleaning performance are: drillpipe rotation, flow rate and drilling fluid rheology. (Mims, Krepp, 2007)

3.3.1 DRILLPIPE ROTATION

Rotation can improve hole cleaning even more effectively working together with other parameters. This level of enhancement due to pipe rotation is a function of the simultaneous combination of mud rheology, cuttings size, and mud flow rate. Also it was observed that the dynamic behaviour of the drillpipe (steady state vibration, unsteady sate vibration, whirling rotation, true axial rotation parallel to hole axis, etc.) plays a major role on the improvement of hole cleaning. With rotation, the cuttings resting on the lower side of the hole will stir up into the upper side, where the flow is effective (Sanchez *et al*, 1999). The Fig. 3.4 shows the effectiveness of the drillpipe rotation.

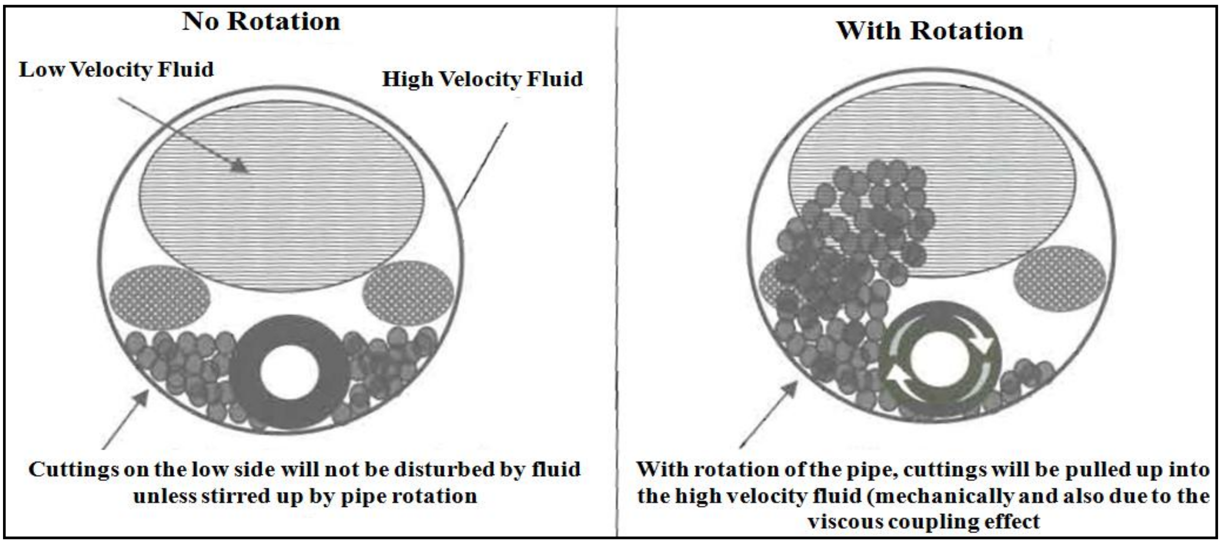

Figure 3.4:Impact of Rotation on Cuttings Beds (Drilling Design and Implementation For Extended Reach and Complex Wells)

Rotary Speed Drawback

At lower inclinations, for instance at 40°, the cuttings bed tends to start sliding down, rotating the pipe seems to help initiate it when stir up the cuttings. In general, rotation at this inclination caused more disorder than in lower angles.

3.3.2 FLOW RATE

When planning or drilling a deviated well, one of main parameters to determine is the minimum flow rate necessary to transport the cuttings and keep the well clear. When this parameter is not determined precisely, the cuttings sit at the bottom of the hole and form large beds of debris, which lead to NPT caused by such problems as high torque and drag, hole packing-off and stuck pipe. All these problems may subsequently require expensive remedial operations and thus incur substantial increases in drilling cost (Luo *et al*, 1994). Hence, if drilling mud is pumped at a high flowrate, it is more difficult for the cuttings bed to build up is easier to remove (Adari *et al*, 2000). The rate of cuttings bed erosion in the annulus with time can be given by the following non-linear exponential formula:

$$\mathbf{h} = \boldsymbol{\alpha} + \boldsymbol{\beta} \mathbf{e}^{\boldsymbol{\gamma}\mathbf{t}}$$

h = Bed height

α = Residual bed height

β = Initial bed height

γ = Reciprocal time constant

Equation 3.1: Bed height

Flow rate Regime

Cuttings removal in deviated wells occurs by a combination of two mechanisms, **saltation** and bed **sliding**. These mechanisms result from two forces that act on fluids such as lift and the drag forces that act on the cuttings bed. In laminar flow, the drag force dominates, while in turbulent flow the lift force dominates. Results show that turbulent flow is more efficient in removing the cuttings than laminar flow, because turbulent flow lifts the cuttings into the effective flow path. (Luo *et al*, 1994)

Flow rate and Mud Rheology

In turbulent flow, a lower YP causes a higher turbulent intensity and thus results in a higher lift force for transporting cuttings by saltation. In laminar flow, a higher YP corresponds to a higher fluid drag force which removes cuttings as sliding bed. So high YP muds are preferred in laminar flow for hole cleaning.

3.3.3 DRILLING FLUID PROPERTIES

Drilling Fluid Weight

DF weight influences hole cleaning through the buoyancy of drilled cuttings, as mud weight increases the cuttings weight becomes soft then drilling fluid weight and tend to float out of well making hole cleaning easier. (Tomas, 2011)

Drilling Fluid Rheology

As we already know, the mud rheology is an important factor and the most challenging is to optimize, because the viscosity must be high enough to keep the cuttings suspended and low enough to carry them as far as and as fast as possible. Fig. 3.5 shows the change in effective flow path area with viscosity changings. (Mims, Krepp, 2007)

- If DF is too thick:
  - Effective flowrate path will be more prone to channelling up the high side of the hole, making cuttings removal more difficult and slower.
  - May increase pumping pressures and ECD's to the point where flow rate has to be reduced.
- If DF is too thin:
  - There is a decrease in the ability of the cuttings transport.
    Cuttings will drop out of the fluid faster, allowing the cuttings bed to increase faster.

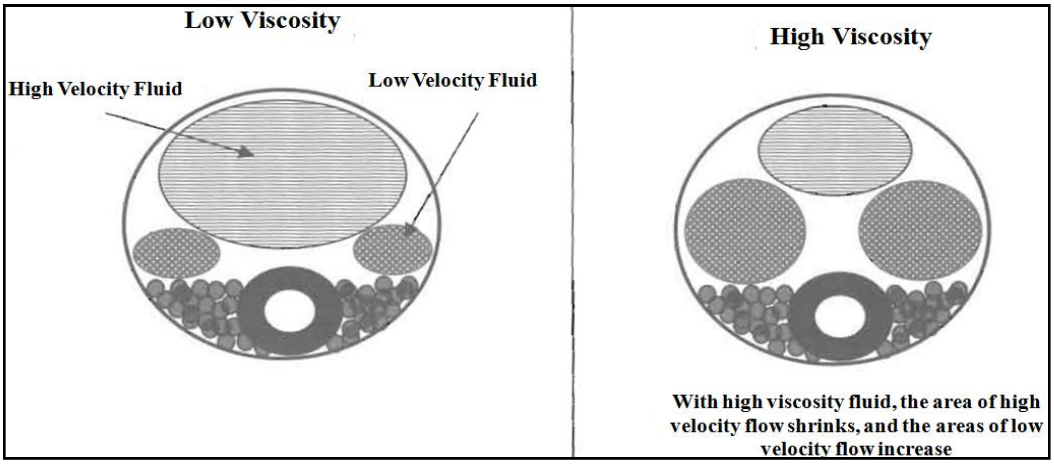

Figure 3.5: Change in Flow Area with Viscosity (Drilling Design and Implementation For Extended Reach and Complex Wells).

3.4 GUIDELINES FOR HOLE CLEANING

3.4.1 GUIDELINES FOR HOLE CLEANING WHILE DRILLING

The issues regarding good hole cleaning are quite complex and wide ranging. To achieve a good hole cleaning drilling and tripping practices are critical.

Drillpipe Rotation

Based on field experience, it is suggested that there are rotary speeds that produce step changes in hole cleaning performance on ERD wells. This has been clearly verified by cuttings return at the shakers. The following Table presents K&M recommended drillstring rpm for different hole sizes.

Table 3.1: Rotary speed rules (Drilling Design and Implementation For Extended Reach and Complex Wells)

Hole Size (in)	Desirable RPM	Minimum Effective For Hole Cleaning (rpm)
17 ½”	120 - 180	120
12 ¼”	150 -180	120
9 7/8”	120 - 150	100
8 ½”	70 - 100	60

The following factors must be taken into account when choosing the pipe rpm:

- The need for high rpm should be balanced with ECD and others effects, especially when dealing with small diameters (<8 ½”).
- Care must be exercised when rotating over 130 rpm in 17 ½” or larger hole sizes. Large annular clearance can lead to increased vibration and potential failures in the BHA and drillstring.
- If cuttings are still coming over the shakers, this means the hole is not properly cleaned.

Flow rate

Using the maximum flowrate for every section is recomended, but this is conditioned by ECD. Consideration may lead to reduction of the flow rate. Table 3.2 below presents K&M recommended minimum and maximum realistic flow rates for different hole sizes.

Table 3.2: Flow rate recommendation (Drilling Design and Implementation For Extended Reach and Complex Wells)

Hole Size (in)	Desirable Flow rate (lpm)	Minimum Workable Flow rate
17 ½”	3406 – 4542.50	3406 lpm, with ROP at 20 m/h
12 ¼”	3028.33 – 4163.95	2460.52 – 2649.79 lpm, with ROP at 10 – 15 m/h 3028 lpm, with ROP at 20 30 m/h
9 7/8”	2649.79 – 3406.87	1892.70 lpm, with ROP at 10 – 20 m/h
8 ½”	1514.16 – 2271.25	1324.89 – 1514.16 lpm, with ROP at 10 – 20 m/h

Other factors to take into account to choose the pipe rpm and for hole cleaning are:

- Off-bottom surface pressure is usually less than during on-bottom drilling, hence, higher flow rates may be used when off-bottom circulating during hole cleaning.
- The bit and BHA selection has a large effect on achievable flow rates in a pressure limited environment.
- Flow rate and rheology should be dimensioned in order to avoid washing out the wall of the hole. Many people are concerned during such procedures that turbulent flow will result in erosion of the wellbore, regardless of theoretical AV the actual velocity immediately next to the wellbore is essentially zero, due to that the fluid is viscous, and is moving slower near wellbore.

Rheology Guidelines

Viscosity should be low for pump ability. For WBM systems, maintaining a 6 rpm reading between 1 and 1.2 inches times the hole size has proven very effective in high angle applications. For OBM systems, temperature and pressure should be observed and taken into account. (Mims, Krepp, 2007)

Connection practices

The recommended baseline connection procedure is as follows:

- Drill down the stand with the current rpm and flow rate.
- Pick up off-bottom and increase flow rate and rpm to their maximum.
- Ream one stand out and back in (repeat if hole is tight).
- Determine off-bottom torque and string weight.
- Shut down the rotary.
- Reciprocate the pipe and take the Pick-up and Slack-off weights values.
- Shut down the pumps and make a connection.

The objectives of these connection practices are to:

- Move cuttings away from the BHA to ensure trouble free connection
- Condition the new section of that hole has been drilled
- Collect Torque and Drag data in a consistent manner

Hole Cleaning Pills

Proper use of mud pills improve hole cleaning in a high angle inclination well. When using a low viscosity pill, it is important to maintain the normal high flow rate and minimize non-circulate time to avoid cuttings set on the lower side of the hole. It is often necessary for lower viscosity pill to be followed by high viscosity pill in order to ensure adequate hole cleaning in the larger diameter vertical section. The specific pill volumes should be determined based on the hole size and the calculated effect on hydrostatic head. The use of low viscosity, turbulent flow pills is not recommended in a weakly consolidated formation because washout or hole collapse may occur. (Tomás, D., 2011)

3.4.2 GUIDELINES FOR CLEANUP PRIOR TRIPPING OUT OF HOLE

If the hole is cleaned adequately prior to Pull Out of Hole (POOH), this practice is imperative in order to avoid several problems such as pipe stuck. Circulation at maximum flow rate and rpm allowed while working the last stand on bottom. Circulation should not stop until the shakers clean up from cuttings even if 3-4 bottoms up have already circulated. At least two bottoms up should be required.

Depending on the drilling mode, cuttings flow over the shakers may also vary considerably with time. When the motor assembly is in the hole and periods of slide drilling have occurred, various dunes may still exist in the well, as the dunes are removed from the hole, it may give the appearance that the hole is free from cuttings. Patience is required to avoid problems such as stuck pipe.

Guidelines for standard tripping procedure

As a general rule, this procedure should be used for all trips in high angle wells.

- ❖ Clean up the hole by circulation rotating for a minimum 1.5 BU until the shakers are clean.
  - Keep rpm and flow as high as possible.
  - Rack back a stand every 30 minutes if necessary (if washout or undercutting are seen in the formation).
  - Expect at least 3-4 bottoms up to cleanup high angle 12 ¼” hole.
- ❖ When the shakers are clean, pull 3-5 stands wet to check hole condition (without rotation or circulation).
- ❖ Pump a slug and POOH on elevators.
  - Record PUW while tripping out and compare real-time to theoretical trends.
- ❖ If tight spots are encountered (20-40 lbs overpull), or drag is increased over the theoretical, always assume that the problem is cuttings.
- ❖ Run in Hole (RIH) until BHA is clear of the obstruction (3-5 stands).
- ❖ Circulate and rotate at maximum rate for 30 minutes.
  - The goal here is simply to confirm if it is a cutting dune, so as not to waste time, if otherwise.
- ❖ Pull up wet through the tight spot without rotation or circulation. If the tight spot has disappeared, then the problem could be caused by a cuttings pile which has now been moved up the hole. Go back to step one and circulate the cuttings out of the hole before repeating the tripping procedure.
  - If a tight spot remains in the same place, then another mechanical problem has occurred, such as key seating or swelling formation. In this case, reaming through the section is

required to try to eliminate the tight spot. Pull out through the tight spot again without rotation to see if everything is ok after reaming. If the obstruction has been removed, pump a slug and continue tripping out of the hole.

It is important to record, the primary rules for tripping in high angle well are:

- ✓ Always assume that any tight hole or over-pull is due to cuttings.
- ✓ Do not assume that a cased hole is a safe haven for tight hole avoidance. It is not unheard of for stuck pipe to occur inside the casing, either just inside the shoe or many thousands of feet inside the casing.
- ✓ Backreaming should be used if deemed necessary when a cuttings bed cannot be circulated out. When backreaming is started, it should be done until at least 30 degrees inclination before circulate the hole clean and POOH.

3.4.3 GUIDELINES FOR BACKREAMING THROUGH A TIGHT SPOT

When a tight spot is encountered, the pipe should be run back into the hole to ensure that the BHA is far from the cuttings bed. This may require 3-5 stands to get the bottom hole. It is imperative to never start pumping or rotating while the BHA lies within or near the obstruction because BHA can be embebbed in a cuttings dune. Start rotation and then pump slowly and gradually. At this point, circulate and rotate at the maximum rates for 30 minutes. Turn the rotary and pumps off and pull out carefully.

If the tight spot has gone, then the obstruction was cutting related. The BHA should then be run back into the hole, far from the tight spot, and the hole cleaned up with high flow rate and rotary speed. If the tight spot has not disappeared from the hole, then the obstruction may be related to something other than cuttings, and normal practices may not be enough to solve the problem. At this point, careful backreaming may be required until is past the obstruction. Never forget that a potentially dangerous cuttings dune exists above the BHA.

3.4.4 GUIDELINES FOR REMEDIAL HOLE CLEANING

When practices and parameters are combined, they allow drilling for very long intervals without any remedial measures. So is better to stay on the bottom at an optimized ROP than it is to drill in short bursts and then use the remedial operations to clean the hole. In many cases remedial actions are required due to changing conditions, such as deteriorating wellbore condition, low mud properties.

Stop and circulate

Once changes in the drilling parameters and ROP controls have proven ineffective, coming off bottom and circulating should be used as the first remedial hole cleaning option. Is important take into account that achievable off bottom flow rates and pipe rpm may be higher than those used for drilling. If T&D

returns to clean hole values following these procedures, then drilling may be resumed otherwise, a wiper trip may be required. (Mims, Krepp, 2007)

Wiper trips

In this process, the bit is pulled inside the previous casing shoe and then run back to the bottom. This may be necessary to improve wellbore conditions such as irregularities. Field experiences tell us that a high angle hole section can be drilled without wiper tripping, because wiper trip should be used as standard remedial option if deemed necessary, since good practices and strategies should be used at all times. (HERIOT WATT UNIVERSITY, 2005)

Backreaming

Although backreaming may be a good practice for vertical or near vertical wells, it does not have the same effect for high angle wells in the case of tight spots or as a primary hole cleaning tool, because it is very inefficient and can also be very risky. The cuttings bed response to backreaming and pumping out can be quite detrimental as packoff, stuck pipe and irreparable wellbore damage may occur (Mims, Krepp, 2007). The following are problems associated with backreaming in high angle wells:

- Back reaming cleans the wellbore completely below the BHA, leaving a small cuttings bed that the bit and BHA can safely trip through. The drawback is that a dangerous cuttings dune that builds up above the BHA, is likely to be higher and thicker than a cuttings bed left from hole cleaning and can increase the risk of packing off and stuck pipe. If pack off does occur, an instantaneous increase on surge effect is verify.
- Backreaming can be detrimental for casing wear if high tension forces in the drillstring are observed in the build section.
- Backreaming may also have a significant impact on the fatigue life of the drilling string.
- High vibration and shocks are often seen on the MWD when backreaming.
- It is a time consuming operation.

The following are recommended procedures if backreaming is deemed necessary:

- Backreaming should always be performed at the maximum allowable flow rate and pipe rpm.
- The pulling speed for some operators is a critical parameter, it may be as slow as 10-15 min/stand in 12 ¼” hole.
- Clean the hole up prior to starting backreaming minimum 1.5 x bottoms up then until the shakers are clean. This will reduce the risk of stuck pipe and packoff.
- After finishing backreaming should clean the hole never just POOH.
- Be careful when backreaming into a casing shoe as the larger diameter rathole below shoe may be an area where cuttings might accumulate. Consider extra circulation with rotation before backreaming into shoe.

The following procedures are recommended for backreaming through tight spot:

- Is best to consider that any tight spot during trip in is a cuttings related problem. If a tight spot is encountered, the pipe should be tripped back into the hole far enough to ensure that the BHA is away from the cuttings bed (this requires at least 3-5 stands are tripped back into hole).
- Avoid start pumping or rotating while the BHA lies within or near the obstruction, this can be risky for BHA.
- If the tight spot has moved up the hole, then the obstruction is cuttings related, and the BHA should then tripped back into the hole.

Fig. 3.19 shows how a cutting dune could be built when backreaming in a high deviated well.

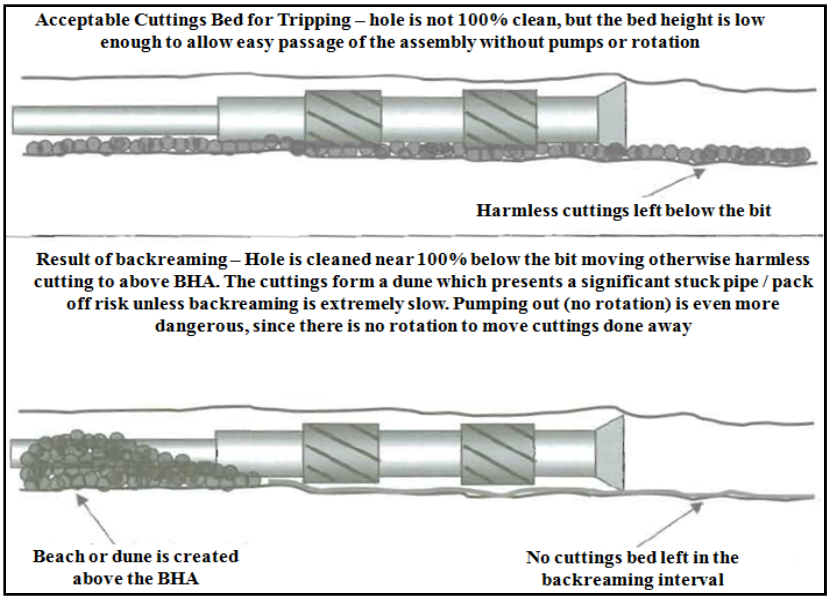

Figure 3.6: Acceptable Cutting Bed and Backreaming (Drilling Design and Implementation For Extended Reach and Complex Wells)

4. GENERAL RIG SITE PARAMETERS MONITORING

During drilling a well, too many parameters are used to monitor well stability and hole cleaning conditions. Although some drilling parameters are the least to indicate hole cleaning conditions, such as time, depth, rpm, WOB, ROP, flow rate, they provide a relative indication of changes in the system and help to understand what may happening downhole.

4.1 TORQUE & DRAG (T&D) MONITORING

Monitoring T&D has proven to be an excellent tool for monitoring hole cleaning conditions, consists in real time take torque, rotation string weight, pick-up and slack-off readings at the end of all stands drilled. This data is then plotted against predicted trends, if the results start to diverge further from the predicted trend, then a hole cleaning problem may be developing. Fig. 4.1 is an example of T&D monitoring.

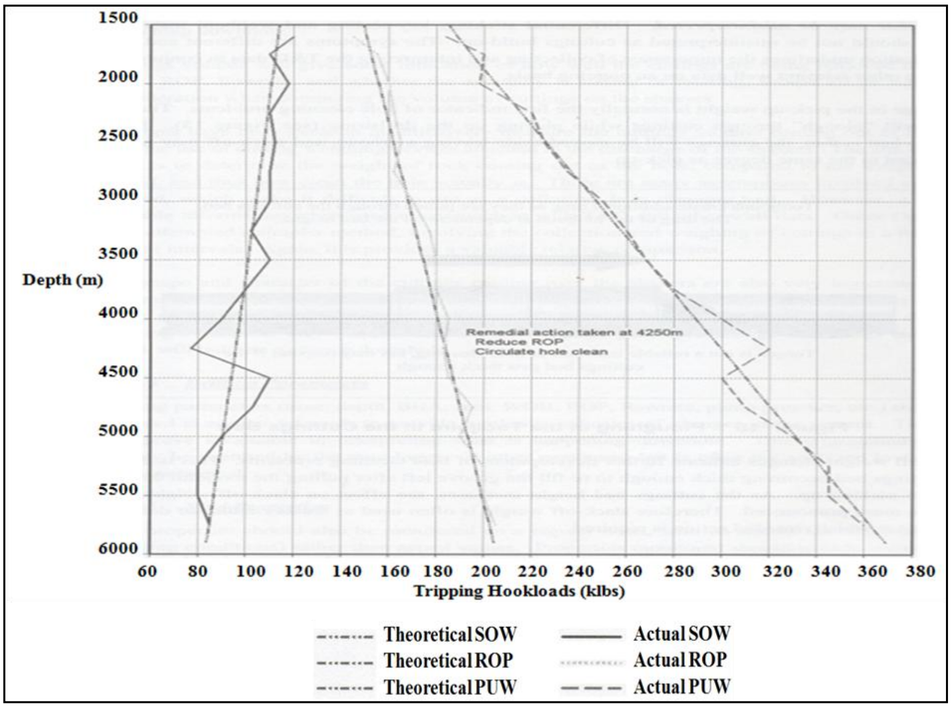

Figure 4.1: T&D Monitoring chart (Drilling Design and Implementation For Extended Reach and Complex Wells)

Drag consists of the difference between PUW and SOW that results in force acting opposite to the movement. The higher the drag the higher the force is acting opposite to the movement. This is affected by several factors such as hole cleaning, hole depth, hole inclination, dogleg severity, mud properties, hole size and drillstring components type, sizes and placement. (Mims, Krepp, 2007)

- ✓ Pick-up weight (PUW) consists of pick up drill string without rotation and takes the weight. Although the PUW is largely affected by hole inclination (when the inclination increases the contact area between BHA and borehole increases and makes the friction increase) and other factors such as hole geometry (e.g. key seats or ledges, etc), it is usually the first indicator of hole cleaning problems. During drilling, the AV on the BHA zone (with a large OD) is high, but after the BHA zone (with a smaller OD), the AV decreases and the cuttings start to fall down on the bottom side and begin to concentrate. When the BHA is picked up, the BHA drags back all the cuttings, which then results in an increas on the friction factor (FF) which leads to an increasing on drill string weight readings when is picked up. When a suddenly variation from lower friction factor to high FF is observed, we can assume hole cleaning issues, a big quantity of cuttings was not removed. Otherwise if a sudden variation from high friction factor to low FF is observed, it could be related to BHA lost, we may have lose some part of BHA, a fishing operation would be recommended. (Mims, Krepp, 2007)
- ✓ Slack-off weight (SOW) consists of weight readings when the drilling is enter in the well without rotation. When the BHA is entering in wellbore, friction opposes the downward movement which causes the weight indicator to read too low. The higer the friction the lower the SOW and the cuttings increase the friction, weight indicator will read low. More likely to be affected by FF because will slide on wiped (wiped when picked up the drillstring) area when slack off. As for PUW, the SOW is also largely affected by hole inclination and hole geometry but in opposite way. (Mims, Krepp, 2007)

Torque is a secondary hole cleaning indicator normally associated with problems such as changes to the mud system, hole geometry, etc. Although Torque is not a reliable hole cleaning conditions indicator in vertical wells, it is important when monitoring horizontal or deviated wells, and may indicate if a cuttings bed is getting high. During drilling in horizontal sections, the cuttings start to fall and accumulate. Because of the weight of the drill string, the drill string, it will be lying on the bottom before the cuttings, the cuttings will fall over and bury the drill string. These cuttings bed will add friction and weight on the drill string resulting in high torque readings when rotation starts. High torque may indicate that the cuttings bed is getting thick enough to cause serious problems. Is affected the same way as for PUW and opposite for SOW by hole inclination and hole geometry. (Mims, Krepp, 2007).

Fig. 4.2 shows how cuttings behave when a tool is plugged.

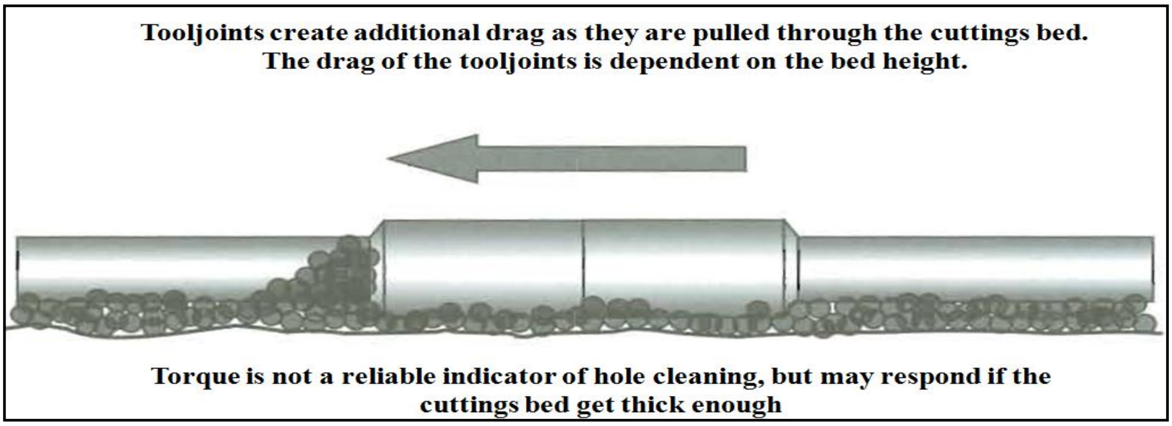

Figure 4.2: Ploughing of the Tool joint in the cutting Bed (Drilling Design and Implementation For Extended Reach and Complex Wells).

4.2 HOLE CLEANING RATE MONITORING

Cuttings returns check cuttings returns at regular intervals while drilling is a very important issue. Monitoring the volume and type of cuttings coming from downhole will help to understand how clean the hole is.

- ✓ Cuttings volume returns consist of determining the weight (or volume) of the rock coming out from downhole, compared to the expected weight being drilled. A big difference between the expected quantity and real quantity coming out from downhole indicates poor hole cleaning (expected higher than real value) or formation washout (expected lower than real value).
- ✓ Cuttings type and shape are an important evaluation because it could be used to determine how well the hole has being cleaned, if wellbore stability is affected and if the mud is doing its job. A change in the type and shape of the cuttings will indicate a change downhole. For example an unexpected dogleg leads to get out of trajectory defined and new formation started being drilled resulting in a unexpected cuttings type on shakers. (Mims, Krepp, 2007)

4.3 EQUIVALENT CIRCULATING DENSITY (ECD) MONITORING

The ECD can be defined as the additional mud weight seen by the hole, due to the circulating pressure losses of the fluid in the annulus. When the drilling fluid is circulating through the drillstring, the borehole pressure at the bottom of the annulus will be greater than the hydrostatic pressure of the mud, this extra pressure is due to the frictional pressure required to pump the fluid up the annulus. This frictional pressure must be added to hydrostatic pressure to get a true value of the pressure acting against the formation at the bottom of well. The ECD is affected directly by annular pressure loss which is affected by Flowrate, Mud Rheology, RPM, Surge & Swab pressure. (HERIOT WATT UNIVERSITY, 2005)

- Higer Flowrate contrubute to additional annular pressure loss. To control ECD, the easiest method is to reduce flow rate however, by reducing flow rate will compromise cuttings carrying capacity.

- Higher Fluid Viscosity also condrtibute to additional pressure loss by increasing the friction in wellbore. Hence reduce the viscosity of the drilling mud also will compromise cuttings carrying capacity again.

- Higher RPM in small sizes is likely to create centrifugal and shear instabilities, in that case, the vortices can be formed in the annulus causing the fluid to spiral as the fluid moves up the hole. This effect increases the distance that the fluid must travel to get the surface due to a spiralling flow path contributing to additional pressure losses. As such, hole cleaning parameter may have to be compromised together if ECD is critical. Figure 4.3 shows the effect of pipe rotation on ECD.

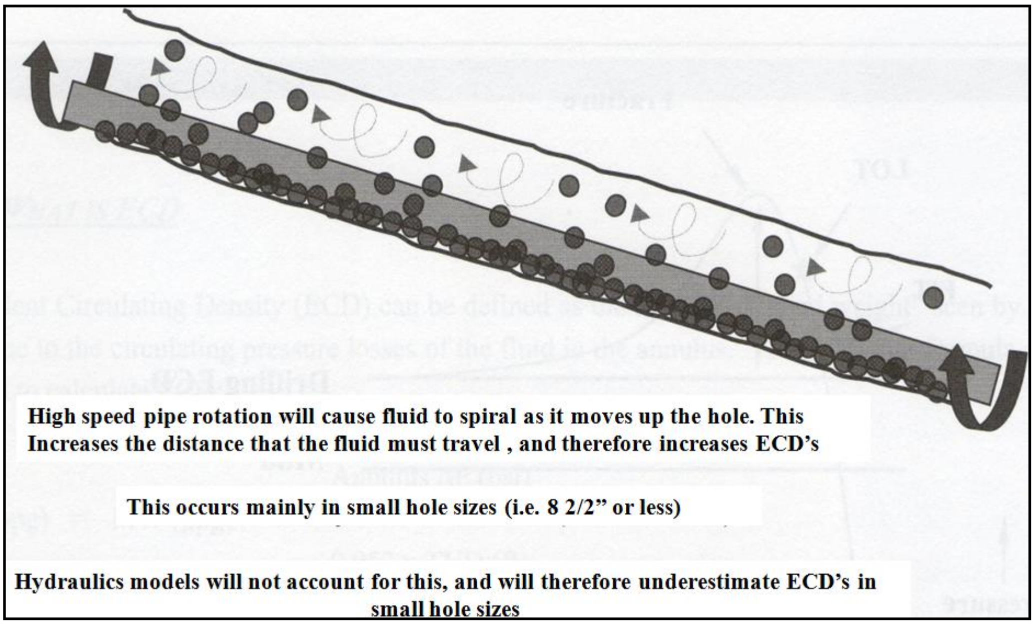

Figure 4.3: ECD Increase due to Pipe Rotation (Drilling Design and Implementation For Extended Reach and Complex Wells).

- Surge & Swab pressure are critical pressure that occur during drilling operation due to drilling movements they are hard to eliminate but can be controlled. Those pressures are not often taken into account during well design. Surge pressure is more experienced when we are tripping in hole the BHA or casings. It can cause ECD increase. Swab pressure is more experienced when we are POOH the BHA. It has the opposite effect of surge, decreases ECD.

They can also be damaging to a wellbore, as they will contribute to fatigue stress seen by the borehole wall. Swab and surge effects depend on the following factors: speed of the pipe during pulling out of hole or run in the hole, viscosity of DF and flow by area around BHA or casing.

- Cuttings concentration in the annulus will affect ECD and the concentration is a function of the slip velocity, AV of the mud which changes with flow rate, and ROP. (Mims, Krepp, 2007)

- Kick or Influx occurs when pore pressure is higher than wellbore pressure, underbalanced situation, resulting in a reduction in ECD. Less frictional pressure will be required to pump the fluid up through the annulus.

ECD [ppg] = MW [ppg] + Annulus ΔP [psi] / (0.052 TVD [ft])

ECD = Equivalent Circulate Density

MW = Mud Weight

Annulus ΔP = Annular Pressure Losses

TVD = True Vertical Depth

Equation 4.1: ECD equation (From: Drilling Design and Implementation For Extended Reach and Complex Wells)

ECD impacts

- High ECD increases the risk of lost circulation, while running or circulating long casing string.
- Wellbore instability can be caused by the constant flexing and relaxing of the wellbore when pumps are turned on and off. Effectively, the wellbore will fail through fatigue.

An indirect effect will be impact on hole cleaning if losses are encountered due to the ECD, in effort to reduce losses, flow rates will be reduced, allows build up the cuttings in hole, resulting in a poor hole cleaning. (Mims, Krepp, 2007)

5. ENVIORONMENT ISSUES DURING DRILLING OPERATIONS

5.1 ENVIRONMENT PROBLEMS

Drilling and seismic operations represent a huge source of noise underwater. As we know, sound through water carries four times faster than through air. Thus, noise could disturb the natural habitants by interfering their eco-communication, which might lead to migration of these habitants to others areas.

During drilling operations cuttings come from wellbore with Non Aquose Base Mud (NABM) which represents a big problem if it is dropped directly onto the sea bed. These cuttings are common in oil and could provide significant hydrocarbons and chemical quantities discharged into the sea, which would destroy indigenous fauna. These cuttings must be separated from oil before dropped in order to avoid several environment accidents.

The cuttings discharged into the sea drop on the sea bed and accumulate at different levels. This accumulation depends on local environment conditions such as flows, heaves, etc. But after discharges, the NABM concentration in sediments is high and benthic community may be affected. The impacts of NABM on the water column is considered low, because they set fast on sea bed, therefore for benthic organism the initial environment impact is physic burial. Due to NABM biodegradation risk such as chemistry toxicity, decreased oxygen. (BANCO MUNDIAL, AFNOR, 2007).

5.2 MITIGATION MEASURES

- ✓ Use water base mud as much as possible during drilling.
- ✓ When NABM is used, ensure that lower toxicity.
- ✓ Check if an oil static pellicle forms during discharges.
- ✓ Fit rigs with equipment that separates the oil from the cuttings at a rate of at least 95% (through centrifuge).
- ✓ It is important to anticipate th that cuttings be treated on shore if the desired performance cannot be achieved off shore.
- ✓ Cuttings treatments performance monitoring.

5.3 WASTE MANAGEMENT

The principles of waste management include the incorporation of a hierarchy of practices into development waste management plans. All waste management effort relate to prevention of pollution. If elimination of a waste is not possible, then minimizing the amount of waste generated should be investigated.

The first step in managing drillings wastes is to separates the solid cuttings from the drilling fluid. Once solid and liquid fluid wastes have been separated, many technologies and practices may be used to manage the wastes. These management technologies and practices can be grouped into three main categories: waste minimization, recycle/reuse and disposal (Owens *et al*, 1993).

- **Waste minimization**
  - Use drilling practices that minimize the generation of drilling wastes:
    - Perform directional drilling
    - Drill smaller diameter holes
    - Use drilling techniques that use less drilling fluid
  - Use muds and additives with lower environment impacts
    - Synthetic-based muds
    - New drilling fluid systems
    - Alternate weighting agents
- **Recycle/Reuse**
  - Beneficial reuse of drilling wastes
    - Recycling of mud
    - Road spreading
    - Reuse of cuttings for construction purposes
    - Restoration of wetland using cuttings
    - Use of oily cuttings as fuel
- **Disposal**
  - Onsite burial
  - Land application
    - Land farming
    - Land spreading
  - Bioremediation
    - Composting
    - Bioreactors
    - Vermiculture

- ✓ Discharge to ocean
- ✓ Offsite disposal to commercial facilities
- ✓ Slurry injection
- ✓ Thermal treatments
  - Incineration
  - Thermal desorption

6. CASE STUDY – WELL NAME: "MUCUA 10 (M-10)"

Note: Due to TOTAL E&P Angolan issues of confidentiality, the well name was changed the data provided and lithology could not be described in details.

6.1 OBJECTIVE

Application of hole cleaning monitoring fundamentals in the "M-10" well, section 9 1/2" (80-90 degrees) starting from 3041m to 3716m Measure Depth (MD) and from 2278m to 2294m True Vertical Depth (TVD) drilled by TOTAL E&P Angola.

6.2 GEOGRAPHICAL AND GEOLOGICAL GENERAL DATA

The "M-10" is situated in the "Mucua Field" area, which is situated in the eastern part of Block 17, about 150 km off the coast of Angola. It is an ultra deep water field. Fig. 6.1 shows the geographical location of "Mucua" field.

Figure 6.1: Block 17 Location. (http://www.wtgnews.com/2009/09/angolas-oil-assets-prove-their-worth . 11/2012).

The Block 17 is located at the SouthWestern edge of the huge Lower Congo Basin, mainly of Tertiary Period. The structural evolution is attributed to a westward regional thin-skinned extension that has been affecting the Upper Cretaceous to current sedimentary cover since the Albian.

The Aptian "Loeme" salt layer corresponds to the basal detachment level which permitted the westward gravity gliding of the sedimentary cover above a pre-Aptian passive deposits.

Fig. 6.2 shows the tectonic evolution from east to west of the Block 17. It has passive margin divided into four main tectonic domains with contrasted deformation styles: (1) stable, (2) proximal extensional (3) transitional and (4) compression.

The Middle Miocene – Upper Miocene (M-UM) area is located in the proximal-extensional domain marked by numerous listric and normal faults separating some tectonic rafts of Cretaceous, Eocene and Oligocene series separated by huge compensation graben (as the NW-SE oriented Oligocene E Graben) which are unfilled by Miocene to actual series.

During the Pliocene Period, the area was characterized by a significant increase in tectonic sliding activity that created a typical turtleback anticline westward and a thick Plio-Pleistocene depot-centre above the M-UM area and eastward (graben)

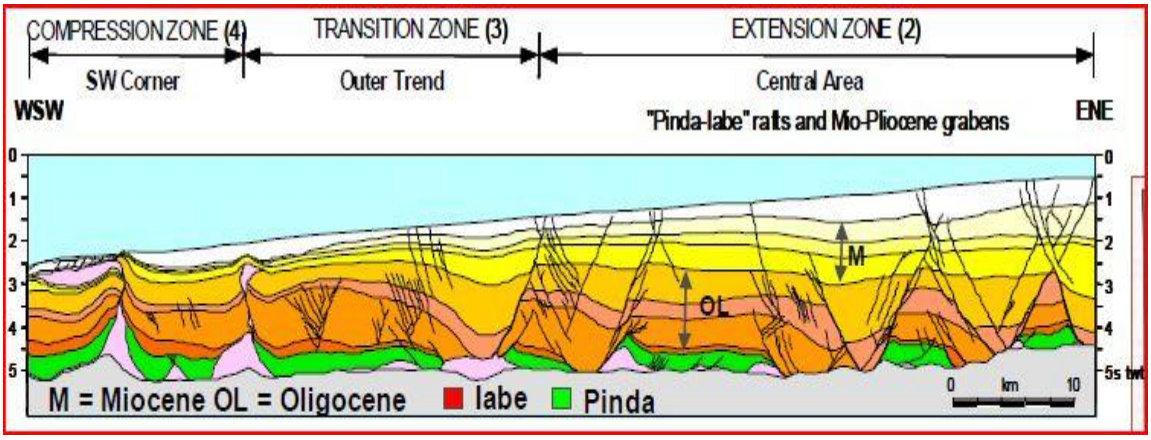

Figure 6.2: Location of Mucua field (Source: TEPA).

According to the combination of numerous faults and sand levels overall, the sedimentary series (Lower Miocene, Middle Miocene, Upper Miocene) M and UM present the same source rocks, pathway and timing migration.

According to a technical report of TEPA, the Middle Miocene interval is constituted of channel-levee turbidity complexes and initial lobe deposits. Lower Miocene interval is constituted by sand lobes and slightly erosive sandy channels, which are more or less canalized by graben axis. As we can see in Fig. 6.3 the lithology of the Block 17. is composed predominantly of sand, shale, laminations of sand-shale and turbidity's sequences from the Oligocene series.

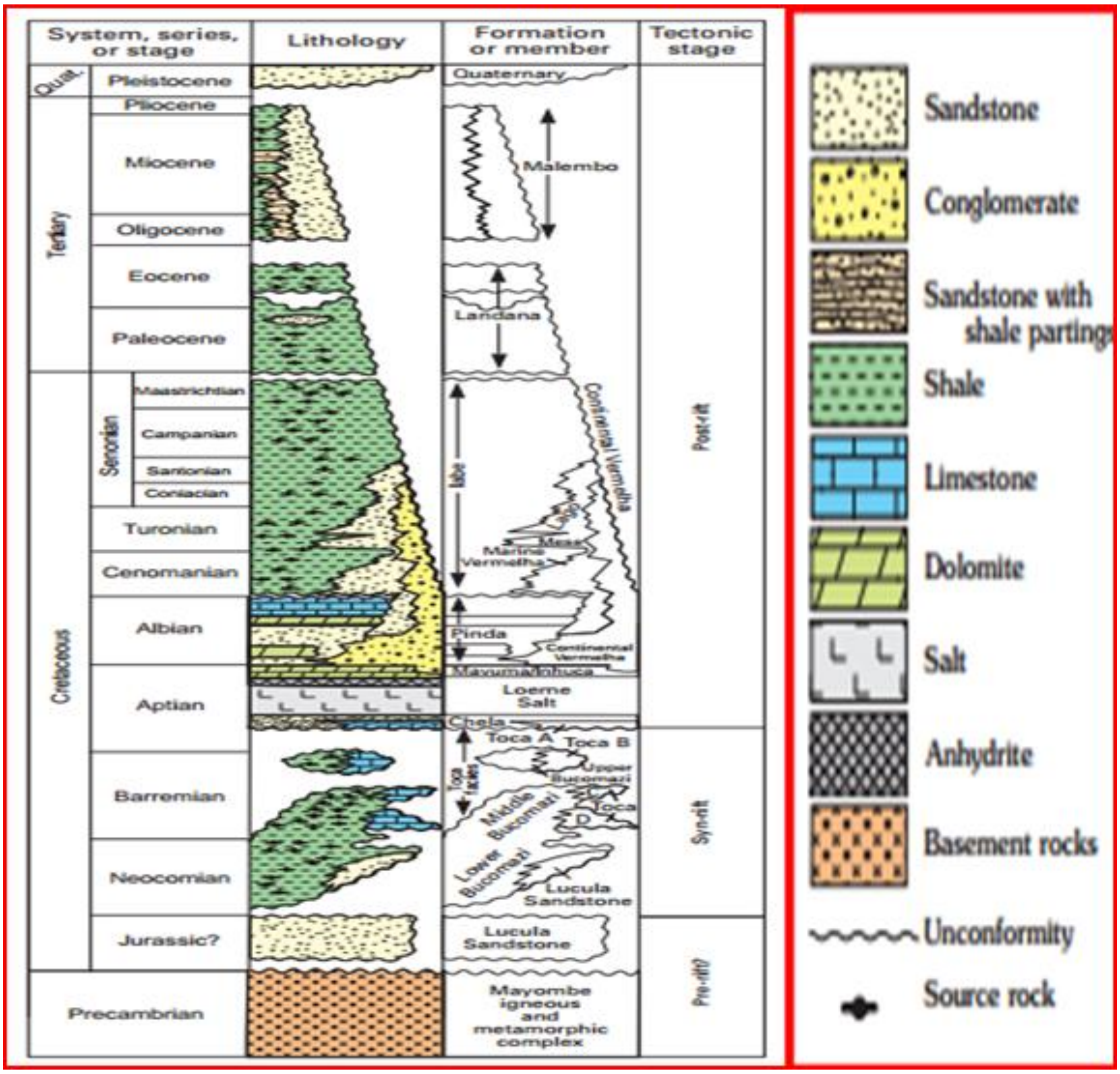

Figure 6.3: Lithostratigraphic column of the Lower Congo Basin (source: Brownfield and Charpentier, 2006).

6.3 WELL PLAN AND WELL ARCHITECTURE

According to well depth and DF weight (which depends on the formation pore pressure and fracture pressure), the architecture used for this well based on 3 cased sections (usually called as light architecture), the last section (9,5 inch) being a open hole. Fig. 6.4 shows the type of well architecture type which corresponds to light architecture.

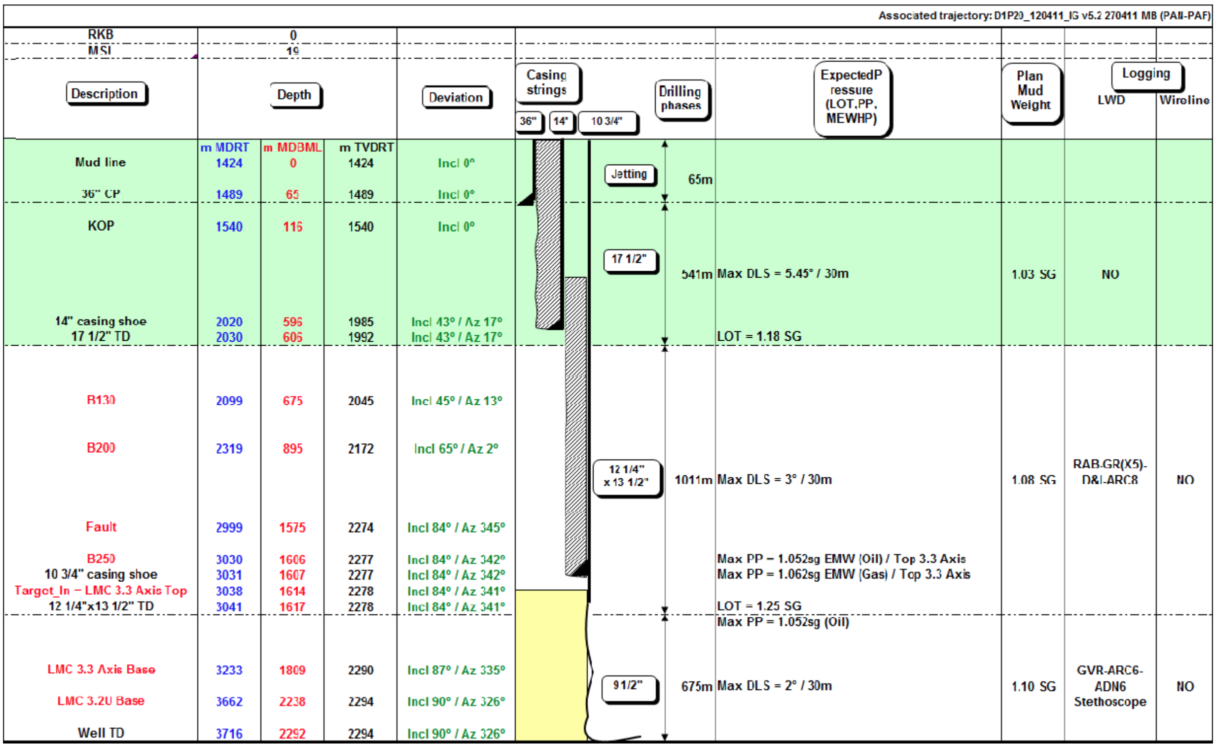

Figure 6.4: Light Architecture.

6.4 THE SPECIFIC CASE FOR 9 ½" SECTION

6.4.1 DRILLING PROCEDURES

- ✓ Drill the 9 1/2" section hole to Total Depth (TD) @ 3716m, Inclination 90degrees and Azimuth 326 degrees with typical drilling parameters as follows:
  - ▪ Flow rate: 2100 l/min is required to achieve a good hole cleaning (particularly in horizontal section), if there are no losses / directional control issues. In sandy reservoirs, decrease flow rate to 1800 l/min, even to 1600 l/min in case of a trajectory control issue (BHA dropping tendency). Keep booster pump on to improve cuttings lifting inside the drilling marine riser.

- Surface Rotation: 100-120 RPM, adjusted according to stick and slip measurement. Don't exceed 120RPM as it creates fatigue in the drill string and can lead to failure.
- WOB: 1-5 tons.
- If any problems requiring circulating (e.g. TDS failure) occur, do not circulate too long in front of sands to avoid washing the formation.

✓ Perform final wiper trip

- Circulate for 15 minutes to clean around BHA.
- Pump and circulate out tandem pills.
- RIH back straight to bottom (without rotation / circulation and controlled speed to avoid surge pressure effect).
- Take FPWD points in the reservoir while running in hole.
- At TD, tandem pills can be pumped if necessary. Circulate minimum 3 bottom up, checking for gas
- With minimum flow rate used while drilling sands and 60 RPM.

✓ Spot 1.12 sg sieved mud (325 mesh) in the open hole up to 100m inside 10in casing with drilling BHA.

✓ Pump out to 10in Casing shoe with sieved mud. Use a low flow rate (300-500 l/min). Do no rotate to avoid shale destabilization (mud cake cannot be rebuilt with sieved mud).

✓ Backream inside casing up to 30° inclination with reservoir mud at drilling flow rate and 60 RPM.

✓ Pump and circulate out tandem pill.

✓ POOH and L/D 9 1/2” BHA.

6.4.2 HOLE CLEANING WHILE DRILLING AT SECTION TD

✓ Double backream each stand (60 RPM max and drilling flow rate) while monitoring the inclination carefully.

✓ Pump tandem pills when needed: 3m3 premix (0.93sg) + 6m3 Hi-Vis pill (1.50sg).

✓ Breaking circulation: When circulation is stopped, gels develop quickly in the mud. If pumps are restarted without precautions, a surge effect is likely to occur. To minimize ECD, pipe should be rotated first at 5-10-15- 20 RPM before starting the pumps,

- Pick up the pipe slowly (this helps to minimize surge) and start the pump at low flow rate.
- Increase flow rate step by step to reach the drilling flow rate in 5 minutes.

✓ Fault crossing: ECD, mud parameters and hole cleaning must be looked at carefully before crossing faults. Drilling may be stopped before reaching the fault, in order to circulate and eventually to perform a short trip.

✓ In case of hole instability, assess mud weight strategy with town.

- ✓ It is imperative to conduct the hole clean at the end of the drilling phase, so wiper trips (if they are deemed necessary) are not skipped.

6.4.3 HOLE CLEANING PERFORMANCE MONITORING

Main indicators to be monitored during drilling

- ✓ Measurement of PUW, SOW and FRT in every stand.
- ✓ ECD at bit: this information, provided by the Pressure While Drilling tool (PWD) is useful, because it is directly linked to wellbore stability.
- ✓ Surface pressure. Monitoring stand pipe pressure.
- ✓ Cuttings: every 1 hour, report quantity, to be checked by mud loggers. (General Drilling and Completion Program).

To have a good and clear picture of what is really happening downhole, multiple friction factor lines are necessary. *T&D Modeling Software* provides theoretically calculated T&D trends, which will be plotted and compared to the real-time measurements. It will use the measured hookloads to perform a back-calculation of friction factors along the wellbore.

Pick Up Weight (PUW) Monitoring

In Fig. 6.5 we can observe a notable and suddenly diverging trend from low FF to high FF (from 3080m to 3164m MD). As mentioned before, when this happens, assume that a build up of cuttings is occurring when pick up the BHA. The cuttings are not being removed properly resulting in a big cuttings concentration downhole, which gives additional weight in drill string when is picked up. From 3179m to 3654m MD the trend is quit constant increasing as expected and, no diverging trend from low FF to high FF is observed. Good hole cleaning has been performed.

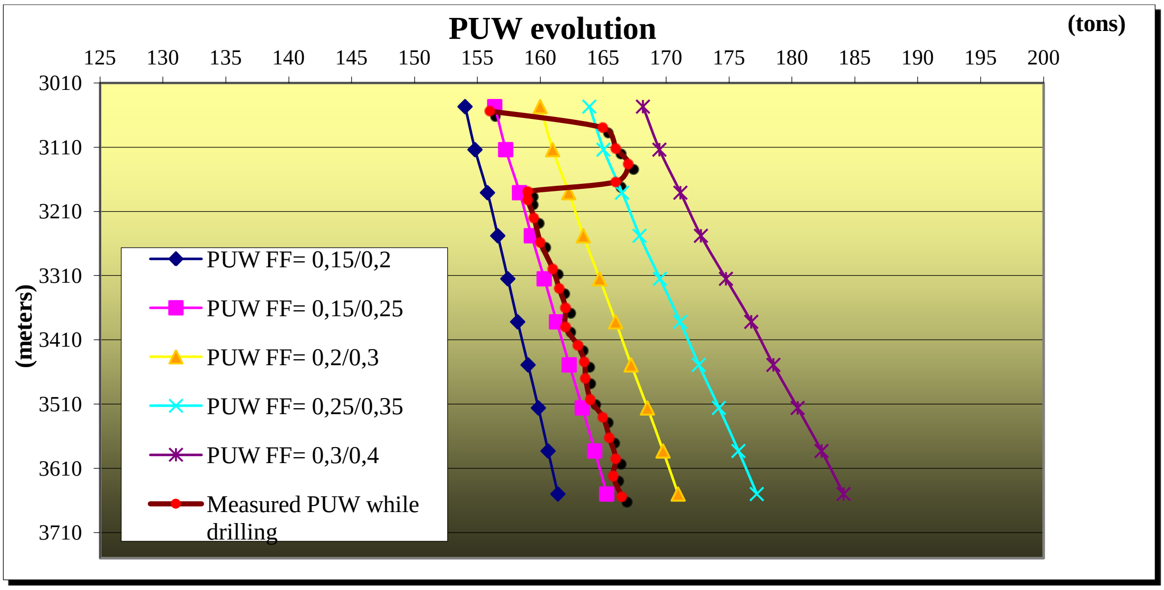

Figure 6.5: Monitoring PUW. Expected vs Actual.

Slack Off Weigh (SOW) Monitoring

Fig. 6.6 shows a pretty constant trend thatis decreasing as expected, no considerable diverging trend from high FF to low FF is observed. This means that no build up of cuttings is occurring when trip in the BHA.

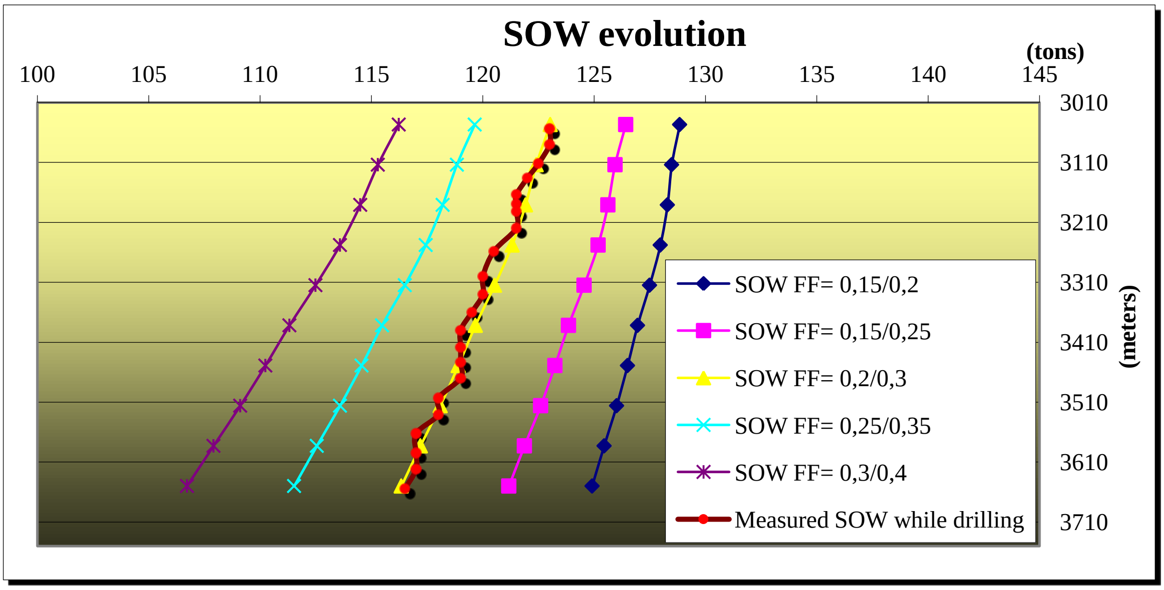

Figure 6.6: Monitoring SOW Expected vs Actual.

Free Rotate Torque Monitoring

Fig. 6.7 shows a notable and sudden variation in FF, a notable increase (from 3080m to 3164m MD). As we already know this is related to the cuttings concentration height. In this case the cuttings concentration was reaching a critical height. From 3179m to 3654m MD the trend is quite constant it is increasing as expected and no diverging trend from low FF to high FF is observed. This means the cuttings concentration was washed out.

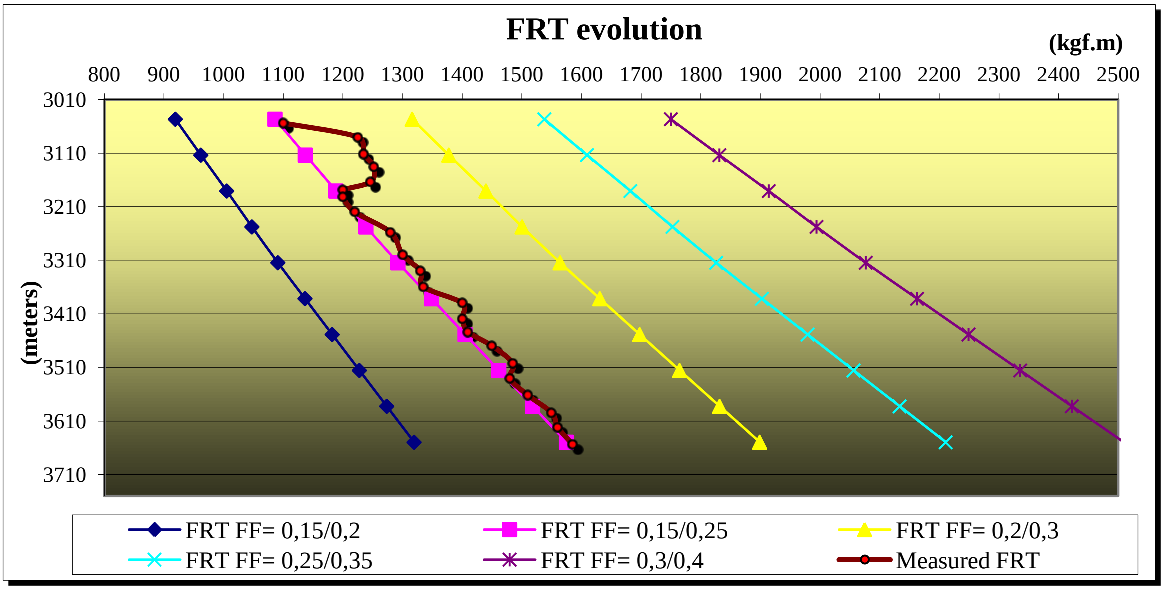

Figure 6.7: Monitoring Torque Expected vs Actual.

ECD Monitoring

In Fig. 6.8 we can observe that as the depth and RPM increase. The ECD increases (from 3179m to 3470m MD). However the level of increase is attenuated when flow rate and RPM decrease (from 3503m to 3654m MD). At high 2000 l/min and 115 rpm the level of increase is more evident and dangerous than at the lower flowrate (1600 l/min) and medium RPM (100 rpm). This happens because high flow rate will affect more annular pressure loss increases than low flow rate. In small sizes, high RPM will cause fluid to spiral as it moves up to surface, which increases the distance that fluid must travel, thus increase the ECD values, all of which could affect the well stability. The ECD should be as maximum as possible to the advise model to avoid well stability problems.

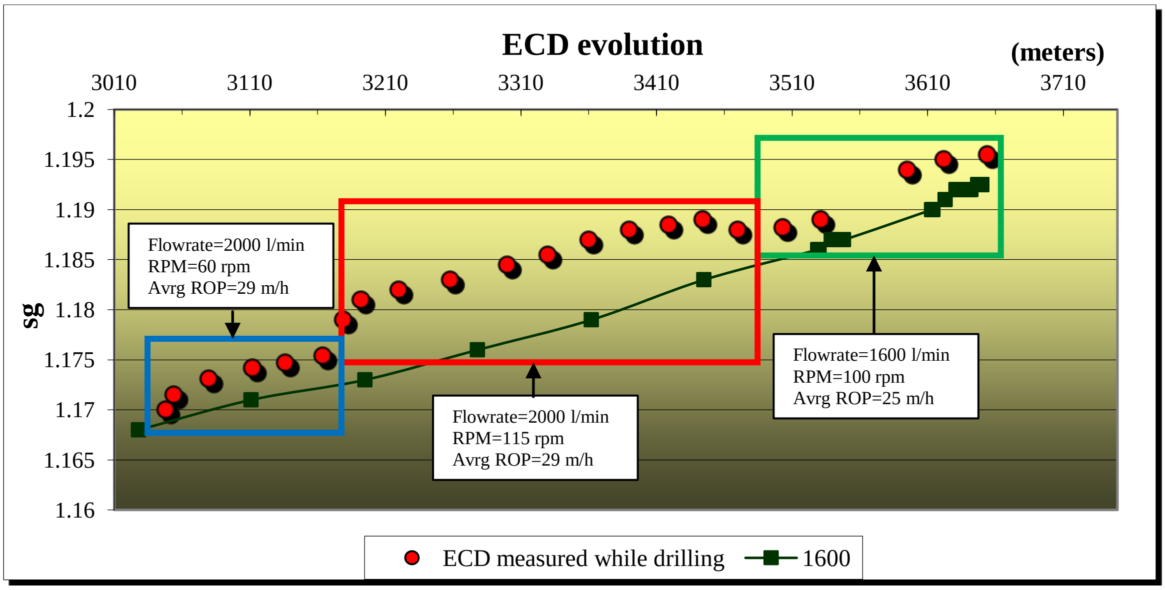

Figure 6.8: Monitoring ECD. Expected (at 1600m MDBML) vs Actual.

Hole Cleaning Performance Monitoring

Methodology

Hole cleaning performance consists of observing the quantity of the rock drilled is coming out from downhole in a period of one hour, compared to the volume being drilled expected at same time. The mud loggers have a recipient which is placed on shakers and collect the cuttings coming from downhole during one hour then is compared with the volume drilled expected. The following formulas will help to estimate the cuttings drilled expected and the residual cuttings in down hole:

$$\mathbf{Cd = SbA \times ROP}$$

Cd = Cuttings drilled (m3)

SbA = Surface bit Area (m2)

ROP = Rate of Penetration (m/h)

Equation 6.1: Extimated cuttings drilled per hour.

$$\mathbf{RC = Cd - Cs}$$

RC = Residual Cuttings (m3)

Cs = Cuttings on shkers (m3)

Equation 6.2: Extimated residual cutting downhole per hour

.

Hole Cleaning Rate

Fig. 6.9 shows that when RPM increases, hole cleaning improvement increases. However, the level of improvement was different at different flow rates and RPM. Hole cleaning performance was more effective at 1600 l/min with pipe rotation at 100 rpm than at 2000 l/min and at 60 rpm. This happened because at high hole inclination the cuttings are located on the lower side of the wellbore and the higher AV is on upper side of wellbore. With rotation these cuttings will be stirred up to high AV side and will be transported fast even with a lower flow rate. Otherwise it will take more time and use a lot of drilling fluid to have a good hole cleaning rate.

Although ROP is not an effective hole clean parameter, we can observe in Fig. 6-9 that the cuttings concentration rate was either affected at different ROP's. At a higher flow rate (2000 l/min), and at 60rpm and ROP (30 m/h) we can observe a high positive slope. This happened because we were drilling faster than cuttings were being removed. At a higher flow rate (2000 l/min), at 115rpm and ROP (30 m/h) we can observe a high negative slope. This happened because hole cleaning rate was higher than cuttings produced. However, at 1600 l/min, 100 rpm and 25 m/h the slope of the cuttings concentration became quite constant. This happened when hole cleaning rate and cuttings produce rate are almost equals. Sometimes is very important to find this point of equilibrium, because in some cases is necessary change or is not allowed exceed use high flowrate or high RPM due for instance to wellbore instability (ECD issues).

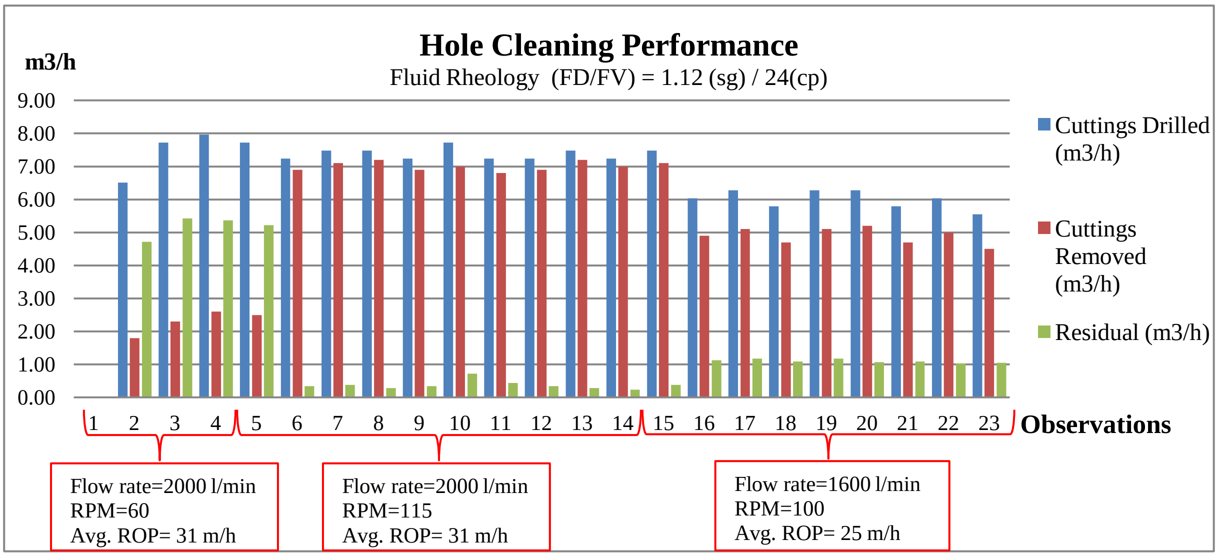

Figure 6.9: Monitoring hole cleaning performance.

However, the faster we drill the more cuttings will be produced and if the hole cleaning rate is not as fast as ROP, more cuttings will remain downhole. Table 6.1 summarizes the hole cleaning rate average results at different RPM, flowrate and ROP values:

Table 6.1: Hole Cleaning Rate Results

Conditions				Results		Ratio	Classification
Situations	Flowrate (l/min)	RPM (rpm)	Avg. ROP (m/h)	Cuttings Drilled av. (m3/h)	Hole Cleaning Rate av. (m3/h)		
1st	2000	60	29	7.4	2.31	0.31	Bad
2nd	2000	115	29	7.41	7.00	0.95	Excellent
3rd	1600	100	25	5.34	4.90	0.92	Good/Excellent

1st Condition: With these parameters at end of the well we would have removed 31% of the cuttings. According to to information given by PUW and Torque monitoring figures (Fig. 6-5 and Fig. 6-6 respectively) a stuck pipe mechanism may occur in early stage of drilling. due to porr hole cleaning rate, the cuttings were accumulating downhole and the cuttings bed was getting critical height. Preventive actions need to done. Increase RPM and manage DF rheology properties if needed.

2nd Condition: With these parameters at end of the well we would have removed 95% of the cuttings. Although these parameters give a good hole cleaning rate, fig. 6-7 shows a critical ECD increasing, which could be dangerous to wellbore stability. If ECD increases to a critical values it leads to formation fracture. Preventive action should be take, reduce RPM is needed in order to reduce ECD.

3rd Condition: With these parameters at end of the well we would have removed 92% of the cuttings. Good balance between hole cleaning performance and well stability. No risks are associated with those parameters and they give a good/excellent hole cleaning performance.

Those parameters provide good hole cleaning performance. The well was 78% free of cuttings when TD was reached. No overpull or over torques were experienced again, which means, the remains cuttings quantity were not critical allowing the BHA to be POOH without any constrain. RPM proved once again to be the most effective hole cleaning parameter at high hole inclination.

7. FINAL REMARKS

This work was intended to provide a better understanding of hole cleaning issues and how we can manage them. Removal of cuttings from the wellbore is an essential part of the drilling operation. Understanding hole cleaning is the key to avoid stuck pipe related NPT and red money.

Flow rate itself could be enough to clean a hole, but it will take time and will need more mud, which makes the operation more expensive. Drillpipe rotation and mud rheology are effective hole cleaning parameters that help to remove the cuttings faster and more cheaply.

Hole cleaning monitoring is an important practice to use to control hole cleaning performance. The ECD, T&D are the most important parameters for monitoring during drilling wells. This data should be collected in same manner for each data point to ensure consistency and reliable output, driller sensibility must take this into account when data are being analyzed. The trend of each one of those parameters must be followed and compared to the expected trend. If any significant deviation from the expected trend is observed, it must be analysed. If a hole cleaning problem is suspected, the well must be properly cleaned until the recovery before resuming drilling.

Despite recent improvements in drillings practices and technologies, hole cleaning still a great challenge, because we not know what exactly is happening in down hole we still working in the dark.

The following are addressed recommendations for improved hole cleaning process in the future:

- ✓ Monitoring and reporting the cuttings quantity at the surface in short intervals (every 30 or 15 minutes) will provide valuable information about the clean condition of the well and the possibility of taking preventive actions earlier.
  Training is also very important. Training gives people the knowledge to recognize the signals at the surface and choose the best action to take in case of hole cleaning issues.
- ✓ Increasing the drill pipe OD helps avoid the abrupt reduction in AV when the flow gets into low OD (when lives the BHA area and start flow in drill pipes area).

Environmental issues must be taken into account when planning a well. Effective and responsible waste handling and disposal are key elements in an organisation's environmental management system.

Finally, my internship in the Total E&P Angola Company was critical to developing the dissertation. It also served as a source of knowledge and familiarity with the world of oil which have positive impact on the work I do in this profession in the future.

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Appendix I

T&D from advise (modeling)			
Bit Depth	PUW FF= 0,15/0,2	SOW FF= 0,15/0,2	FRT FF= 0,15/0,2
m	Tonf	Tonf	kgf,m
3047	154.03	128.84	919.3
3114	154.82	128.48	962.1
3181	155.81	128.29	1005.5
3248	156.63	127.97	1047.7
3315	157.43	127.49	1091.2
3382	158.21	126.95	1136.7
3449	159.04	126.5	1182.3
3516	159.86	126.01	1227.9
3583	160.63	125.45	1273.7
3650	161.41	124.91	1319.6

T&D from advise (modeling)			
Bit Depth	PUW FF= 0,15/0,25	SOW FF= 0,15/0,25	FRT FF= 0,15/0,25
m	Tonf	Tonf	kgf,m
3047	156.39	126.42	1086.4
3114	157.26	125.94	1137.2
3181	158.36	125.62	1188.6
3248	159.3	125.18	1238.8
3315	160.32	124.55	1292.5
3382	161.3	123.85	1348.7
3449	162.31	123.24	1405.1
3516	163.35	122.6	1461.6
3583	164.33	121.87	1518.3
3650	165.29	121.17	1575

T&D from advise (modeling)			
Bit Depth	PUW FF= 0,2/0,3	SOW FF= 0,2/0,3	FRT FF= 0,2/0,3
m	Tonf	Tonf	kgf,m
3047	160	123.03	1316.4
3114	160.99	122.4	1377.8
3181	162.27	121.92	1440.1
3248	163.43	121.32	1500.7
3315	164.72	120.53	1564.4
3382	166	119.67	1631
3449	167.23	118.9	1697.8
3516	168.53	118.09	1764.7
3583	169.77	117.2	1831.8
3650	170.97	116.34	1899

T&D from advise (modeling)			
Bit Depth	PUW FF= 0,25/0,35	SOW FF= 0,25/0,35	FRT FF= 0,25/0,35
m	Tonf	Tonf	kgf,m
3047	163.91	119.64	1538
3114	165.03	118.84	1609.6
3181	166.51	118.2	1682.3
3248	167.9	117.44	1752.9
3315	169.52	116.5	1826.2
3382	171.12	115.48	1902.8
3449	172.61	114.56	1979.6
3516	174.21	113.59	2056.5
3583	175.76	112.55	2133.7
3650	177.22	111.53	2210.9

T&D from advise (modeling)			
Bit Depth	PUW FF= 0,3/0,4	SOW FF= 0,3/0,4	FRT FF= 0,3/0,4
m	Tonf	Tonf	kgf,m
3047	168.17	116.23	1750.2
3114	169.48	115.29	1831.5
3181	171.15	114.5	1914.2
3248	172.78	113.59	1994.4
3315	174.77	112.49	2076.9
3382	176.78	111.32	2163
3449	178.54	110.24	2249.3
3516	180.47	109.11	2335.8
3583	182.37	107.91	2422.5
3650	184.12	106.72	2509.3

ECD from Advise modeling at 2290m	
MD	ECD
m	sg
3028	1.168
3111	1.171
3195	1.173
3278	1.176
3362	1.179
3445	1.183
3529	1.186
3530	1.186
3539	1.187
3548	1.187
3613	1.19
3614	1.19
3623	1.191
3631	1.192
3632	1.192
3637	1.192
3638	1.192
3640	1.192
3641	1.192
3642	1.192
3647	1.1925
3648	1.1925
3649	1.1925
3650	1.1925
3650	1.1925
3650	1.1925

While Drilling						
Bit Depth	Measured PUW	Measured SOW	Measured FRW	Measured FRT	Calculated drags	ECD measured
	while drilling	while drilling	while drilling	while drilling	while drilling	while drilling
m	tons	tons	tons	klbs.ft	tons	emw
3048						1.17
3054	156	123	143	1100	33	1.1715
3080	165	123	143	1225	42	1.1731
3112	166	122.5	142	1235	43.5	1.1742
3136	167	122	137	1252	45	1.1747
3164	166	121.5	139	1246	44.5	1.1754
3179	159	121.5	139	1200	37.5	1.179
3192	159	121.5	140	1200	37.5	1.181
3220	159.5	121.5	140	1220	38	1.182
3258	160	120.5	141	1280	39.5	1.183
3300	161	120	142	1300	41	1.1845
3330	161.5	120	141	1330	41.5	1.1855
3360	162	119.5	141	1335	42.5	1.187
3390	162	119	141	1400	43	1.188
3419	163	119	141	1400	44	1.1885
3444	163.5	119	141	1410	44.5	1.189
3470	163.6	119	141	1450	44.6	1.188
3503	164	118	141	1485	46	1.1882
3531	165	118	141	1480	47	1.189
3562	165.5	117	141	1510	48.5	1.895
3595	166	117	142	1550	49	1.194
3622	165.8	117	140	1560	48.8	1.195
3654	166.5	116.5	141	1585	50	1.1955

Drilling Parameters

Observation	Flow av.(*100 l/min)	RPM av. (*10 rpm)	SPP av. (*10 bar)	ROP av. (m/h)	Depth (km)	Cuttings Drilled (m3/h)	Cuttings Removed (m3/h)	Residual (m3/h)
0	0	0	13	0	3.04	0.00	0.00	0.00
1	20	6	17.8	27	3.07	6.52	1.80	4.72
2	20	6	17.6	32	3.10	7.72	2.30	5.42
3	20	6	17.7	33	3.13	7.96	2.60	5.36
4	20	6	17.5	32	3.17	7.72	2.50	5.22
5	20	11.5	17.8	30	3.20	7.24	6.90	0.34
6	20	11.5	17.7	31	3.23	7.48	7.10	0.38
7	20	11.5	17.5	31	3.26	7.48	7.20	0.28
8	20	11.5	17.6	30	3.29	7.24	6.90	0.34
9	20	11.5	17.4	32	3.32	7.72	7.00	0.72
10	20	11.5	17.4	30	3.35	7.24	6.80	0.44
11	20	11.5	17.5	30	3.38	7.24	6.90	0.34
12	20	11.5	17.5	31	3.41	7.48	7.20	0.28
13	20	11.5	17.6	30	3.44	7.24	7.00	0.24
14	20	11.5	17.4	31	3.47	7.48	7.10	0.38
15	16	10	17.4	25	3.50	6.03	4.90	1.13
16	16	10	17.6	26	3.52	6.27	5.10	1.17
17	16	10	17.5	24	3.55	5.79	4.70	1.09
18	16	10	17.5	26	3.57	6.27	5.10	1.17
19	16	10	17.5	26	3.60	6.27	5.20	1.07
20	16	10	17.6	24	3.62	5.79	4.70	1.09
21	16	10	17.6	25	3.65	6.03	5.00	1.03
22	16	10	17.4	23	3.67	5.55	4.50	1.05
Total						151.78	118.50	33.28

Schlumberger

	Desc.	Manu.	OD (in) ID (in)	Max OD (in)	Bot. (in) Top. (in)	Bot Type Top Type	Bot Gender Top Gender	FN OD (in) FN Length (m)	Length (m)	Cum. Length (m)	Cum. Weight (t)
1	9 1/2" PDC Bit	Varel	6.750 3.250	9.500	 4.500	 Regular	 Pin		0.35	0.35	0.0
2	Xceed 675 9 3/8" & 8 3/8" Stabilizers	Schlumberger	6.750 5.160	9.375	4.500 5.500	REG FH	Box Box	0.000 0.00	7.62	7.97	1.2
3	GVR-6	Schlumberger	6.750 4.880	7.500	5.500 5.500	FH FH	Pin Box	0.000 0.00	3.09	11.06	1.8
4	ARC-8	Schlumberger	6.813 2.875	7.500	5.500 5.500	FH FH	Pin Box	6.813 1.47	5.87	16.93	2.7
5	Telescope 675	Schlumberger	6.750 5.109	6.890	5.500 5.500	FH FH	Pin Box	0.000 0.00	8.39	25.32	3.7
6	StethoScope 675 w/ 9 1/4" Stabilizer	Schlumberger	6.750 2.810	9.250	5.500 5.500	FH FH	Pin Box	0.000 0.00	10.16	35.48	5.1
7	ADN-6 w/ 9 3/8" Stabilizer	Schlumberger	6.750 2.250	9.375	5.500 4.500	FH NC50 (4 1/2 IF)	Pin Box	0.000 0.00	6.44	41.92	6.0
8	6 1/2" NMDC	Schlumberger	6.500 2.875	6.500	4.500 4.500	NC50 (4 1/2 IF) NC50 (4 1/2 IF)	Pin Box	0.000 0.00	9.26	51.18	7.3
9	5" HWDP		5.000 3.000	6.500	4.500 4.500	NC50 (4 1/2 IF) [illegible]	Pin Box	0.000 0.00	9.35	60.53	[illegible]
10	Hydraulic Jar	NOV	6.500 2.750	6.500	4.500 4.500	NC50 (4 1/2 IF) NC50 (4 1/2 IF)	Pin Box	0.000 0.00	9.87	70.40	8.8
11	5" HWDP		5.000 3.000	6.500	4.500 4.500	NC50 (4 1/2 IF) NC50 (4 1/2 IF)	Pin Box	0.000 0.00	9.35	79.75	9.5
12	Crossover		6.750 2.880	6.750	4.500 5.500	NC50 (4 1/2 IF) FH	Pin Box	0.000 0.00	0.96	80.71	9.7
13	5 1/2" HWDP (2 joints)		6.750 3.250	7.000	5.500 5.500	FH FH	Pin Box	0.000 0.00	18.75	99.46	11.4
14	DICV		6.500 3.000	6.500	5.500 5.500	FH FH	Pin Box	0.000 0.00	0.64	100.10	11.4
15	5 1/2" HWDP (10 joints)		6.750 3.250	7.000	5.500 5.500	FH FH	Pin Box	0.000 0.00	93.78	193.88	19.8
16	5-1/2 " 24.70 DPS to surface		5.500 4.670	7.000	5.500 5.500	FH FH	Pin Box	0.000 0.00	0.00	193.88	19.8

BHA Comments

BHA to drill 9 1/2" reservoir section to well TD.

Total Length (m)	193.88
Total Weight in Air (t)	19.8
Total Buoyant Weight (t)	17.1
Buoyant Weight Below Jar (t)	7.0
Weight in Air Below Jar (t)	8.0

Stabilizer Summary		Sensor Summary	
Blade Length (m)	Blade Mid-Pt to Bit (m)	Type	Distance to Bit (m)
0.506	0.685	Xceed D+I	4.251
0.506	3.733	Bit Res	9.073
0.588	26.788	APWD	12.795
0.762	37.578	Resistivity	13.505
Bend Summary		GR ARC	13.555
Bend Angle (deg)	Bend to Bit (m)	D&I	20.589
0.600	0.755	FPWD	26.763
		Density	38.742
		Neutron	39.721

BHA Nozzle Summary			
Bit Nozzle		Reamer Nozzle	
Count	1/32 in	Count	1/32 in
4	20.000		
4	22.000		
		TFA (in2)	
		PD Flow Restrictor	
		(1/32 in)	0.000
		Rotor By Pass Nozzle	
TFA (in2)	2.712	(1/32 in)	

Mud Properties			
Mud Weight (g/cm3)	1.1	YP (lbf/100ft2)	
Funnel Viscosity (s)		PV (cP)	

Date	20Dec2011
Designed By	Ope Oyelami
Approved By	Thierry Sailly

9 1/2 " (241.3mm) VTD813GX

Assembly: 3827
IADC Code: M432

PRODUCT SPECIFICATIONS

Body Type:	Matrix
Profile:	Short Parabolic
Cutter Type:	Alpha
Cutter Size:	13 mm
Cutter Back Up:	Ring Studs
Total Cutter Count:	69
Face Cutter Count:	51
Cutters on Gage:	10 + 8 DI
Connection:	4 1/2 Reg
Shank Diameter:	7 1/2"
Nozzle 1 Quantity/Type:	4 / 65
Nozzle 2 Quantity/Type:	4 Ports ØMaxi 20/32"
Open Face Volume:	72.2 In3
OFV Ratio:	39.9 %
Junk Slot Area:	10.1 In²
Gage Length:	3"
Gage Type:	PDC-TSP
Trimmer Length:	0.9"
Effective Gage Length:	3.9"
Gage Pad Area:	26.8 In²
Shank Length:	6.1"
Make Up Length:	13"

RECOMMENDED OPERATING PARAMETERS

Rotary Speed:	150 to DHM
Flow rate :	500 to 900 gpm
Weight On Bit:	20 to 39 Klbs (9 to 18 t)
TFA, Max:	2.711
WOB, Max:	49 Klbs (22 t)

Engineered Cutting Structure

Bits are developed using Varel's proprietary design software called SPOT™. SPOT ensures cu structure optimization for specific applications. SPOT models complete bit behavior in difference rock types during a simulated drilling process. This tool also evaluates cutter wear as a result of friction and heat transfer. Using appropriate rock geology and mechanical properties, SPOT also performs sensitivity analysis for various drilling parameters (WOB and RPM) to evaluate their effects on ROP, cutter wear, bit vibrations and footage drilled.

High Performance Cutters

Application-specific PDC cutters incorporating advance carbide interface geometry (CIG) and material are used. Diamond Grade are Selected, analyzed and prepared to maximize abrasion resistance.

Hydraulics

Bits go through elaborate Computational Fluid Dynamics evaluation to identify and eliminate possible stagnation zones. During this process, bit and bottom hole cleaning are optimized to enhance bit performance. This sophisticated process improves cleaning efficiency, cutter cooling and ROP.

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