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# THE PERFORMANCE OF FLAT RHEOLOGY FLUID ON CONTINUOUS CIRCULATION DRILLING

Trabalho de Formatura em Engenharia de Petróleo do curso de graduação do Departamento de Engenharia de Minas e de Petróleo da Universidade de São Paulo.

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To Escola Politécnica: "Escola, escola da minha vida/ Minha paixão querida/ Poli USP meu amor."

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**Abstract**

This project evaluated the performance of flat rheology fluid on Eni continuous circulation drilling, a system in which fluid circulation is not stopped while drill pipe connections are being performed. Flat Rheology is a category of synthetic based fluid characterized by minimal variation of rheological properties on a wide range of temperature and pressure. Two formulations of oil based mud (O/W = 80:20 and 70:30) and one formulation of high performance water based mud (Ultradril) were compared to flat rheology (Rheliant), considering vertical, deviated and horizontal well profiles.

Results considering only well hydraulics, showed good performance of Rheliant: a high rheology fluid that provided lower and steadier values of equivalent circulating density (ECD) and enhanced hole cleaning performance. Tests considering continuous circulation confirmed the expectations towards the combination of both technologies. Continuous drilling avoids big variations on ECD, due to the contribution of dynamic head even during connections, combined with the effect of Rheliant, which provides a high rheology fluid with minimal effect on ECD. Hole cleaning is enhanced due to continuous flow, which diminishes solids settling tendency, and higher fluid rheology, that increases its carrying capacity. With these improvements, problems such as stuck pipe, pressure spikes and ballooning effect can be avoided.

On vertical wells, performance enhancement is not as effective as in deviated and horizontal geometries, as the use of oil and water based fluids already provide satisfactory drilling performance. On technically demanding wells such as deep waters, HPHT or narrow pressures window, the combination of continuous circulation drilling and flat rheology provided remarkable enhanced drilling performance.

**Key words**: Continuous Circulation Drilling; Flat Rheology Fluid; Equivalent Circulating Density; Hole cleaning.

**Abbreviation Summary**

| | |
|---|---|
| **API** | American Petroleum Institute |
| **BHA** | Bottom Hole Assembly |
| **BOP** | Blow Out Preventer |
| **CCS** | Continuous Circulation System |
| **DC** | Drill Colar |
| **DP** | Drill Pipe |
| **DS** | Drill string |
| **ECD** | Equivalent Circulating Density |
| **E-CD** | Eni Circulating Device |
| **HCI** | Hole Cleaning Index |
| **HPHT** | High Pressure and High Temperature |
| **HWDP** | Heavy Weight Drill Pipe |
| **ID** | Inside Diameter |
| **JIP** | Joint Industry Project |
| **LSRV** | Low Shear Rate Viscosity |
| **MD** | Measured Depth |
| **MWD** | Measure While Drilling |
| **O/W** | Oil- water ratio |
| **OBM** | Oil Based Mud |
| **OD** | Outside Diameter |
| **PDC** | Pollycristalline Diamond Compact Bit |
| **PDM** | Mud motor (Positive Displacement Motor) |
| **PV** | Plastic Viscosity |
| **ROP** | Rate of Penetration |
| **SBM** | Synthetic Based Mud |
| **SG** | Specific Gravity |
| **STAB** | Stabilizer |
| **TD** | Target Depth |
| **TFA** | Total Flow Area |
| **TJ** | Tool Joint |
| **TVD** | True Vertical Depth |
| **WBM** | Water Based Mud |
| **WOB** | Weight on Bit |
| **YP** | Yield Point |

**Summary**

APPENDIX A



APPENDIX B

## 1. Introduction

The high costs associated with oil drilling stimulate the development of new technologies targeting more efficient rig operations. This project highlights two major issues faced while drilling and follow-up technologies developed in order to overcome them.

The first one concerns the problems associated with circulation stop while making connections: gel formation; cuttings settlement; barite sag and variation of ECD (Equivalent Circulation Density), which may result in excessive rig downtime, circulation loss or blowouts. The second one concerns the susceptibility of drilling fluids rheology to temperature and pressure changes, which makes it very complicated to set a correct mud density, specially on deep wells, as rheology may vary with temperature and lithostatic gradients. Such problems resulted, respectively, in the development of the Eni Continuous Circulation System, which allows drill pipe connections to be performed without circulation stop, and Flat Rheology Fluids, which have minimal rheological variation on a wide range of pressure and temperature.

In particular, this project evaluates the combination of both technologies by analyzing flat rheology fluid (Rheliant formulation) performance on continuous circulation drilling, with aid of a drilling simulator software (Virtual Hydraulics), in attempt to present an alternative procedures which may increase drilling efficiency.

To sum up, this project is motivated by three major strands: technological innovation, drilling performance enhancement and rig safety, by introducing a pioneer evaluation of state-of-the-art technologies whose results have the prospects of mitigating many problems associated with drilling, establishing a safer working environment and providing more efficient drilling operations.

## 2. Objectives

The objectives of this project are to evaluate the performance of flat rheology drilling fluid in combination with the Eni continuous circulation drilling system, by comparison with oil based fluids and high performance water based fluid. A drilling simulator software (Virtual Hydraulics) is used and the main parameters evaluated were Equivalent Circulating Density and Hole Cleaning Index.

## 3. Bibliographic Review

### 3.1 Conventional Rotary Drilling

Nowadays, rotary drilling is the most widespread method for the drilling of oil and gas wells. Made popular in the 1930s, rotary drilling is much more efficient than its predecessor, cable tool drilling. According to Bourgoyne Jr (1986), it comprises of a hoisting system, a power system, a fluid circulating system, a well control system and well monitoring system.

An illustration of a rotary drilling rig layout can be observed on Figure 1 and Figure 2. Such figures represent an onshore facility. For offshore rigs, the surface layout is essentially the same. The main difference is that offshore, space availability is limited, so equipments must be more compact and might be stacked one the top of other. Also, the illustrations represent the system that comprises the use of a rotary table and kelly. Nowadays, such equipments are being replaced by a topdrive, which provides more efficient drilling.

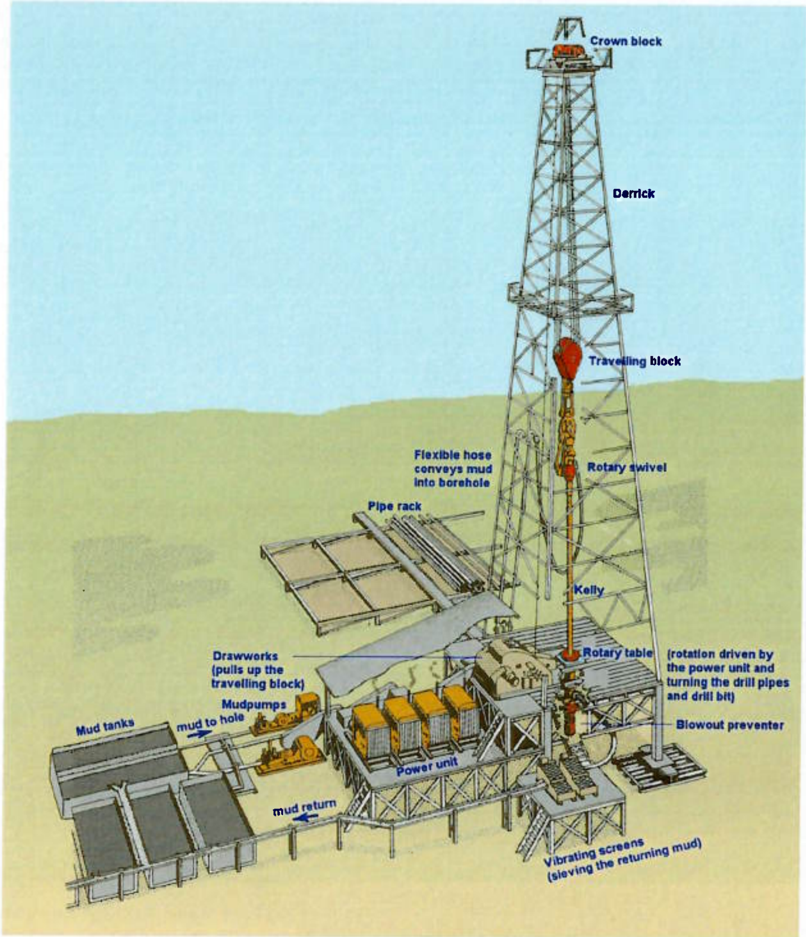


Figure 1 - Simplified diagram of the traditional type of onshore petroleum drilling equipment. (NOMENCLATURE, TEARDOWN, EXPLODED DIAGRAM WEBSITE)

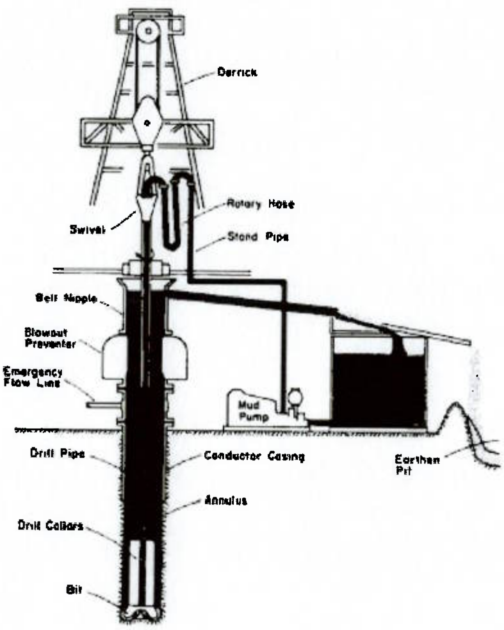


Figure 2 – The Rotary drilling Process (BOURGOYNE JR et al, 1986)

The rotary table provides rotation to the kelly, a section of pipe with square or diagonal outside cross section which is fitted at the rotary table. The kelly transmits torque to the drill string. In such configuration, only one pipe is lowered into the well at once.

The topdrive (Figure 3) is also responsible for the transmission of rotation to the drill string. It is suspended by a hook, so it is able to move upwards and downwards the derrick. Its great advantage is that it is able to work with 3 pipes at once, what accelerates drilling procedures by diminishing number of connections to be performed.

Figure 3 - Top drive (SCHLUMBERGER a)

Briefly, as illustrated on Figure 4, drilling procedures consist in lowering the drill string into the well. At the lower part of the string is set the Bottom Hole Assembly (BHA), which provides force to the bit, that drills the formation. To improve the bit's performance, a fluid is pumped into the well. The fluid goes down through the drill string and goes out by the bits nozzles, helping with lubrication and cooling of equipments. The fluid, now in the well, is circulated out, through the annular space between bare rock/ casing and drill pipes, carrying up cuttings and solids residues, and thus providing hole cleaning.

According to McCann (1982), an essential feature of the rotary drilling process is the circulating system, also known as the mud system. In order for rotary drilling to proceed, the drilled cuttings must be lifted out of the hole, therefore fluid must be pumped up through the annulus.

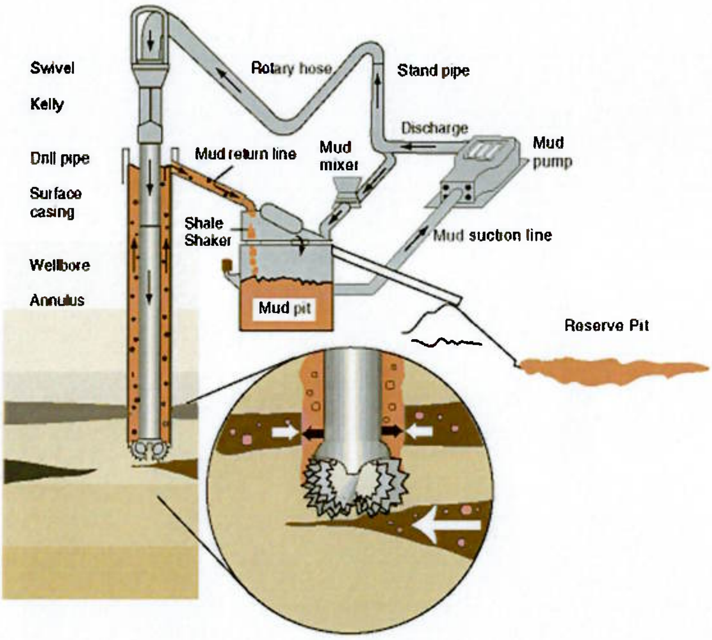


Figure 4 – Schematic illustration of drilling and mud circulating system. Mud goes into the well inside the drill pipes and is ejected by bit nozzles. It flows out of the well through annular space. On the surface mud is treated, cleaned and can be reused. (UNITED STATES DEPARTMENT OF LABOUR)

When the section of drill pipe is completely lowered into the well, another set of pipes has to be installed at the top of the previous one, before resume drilling. To perform this activity, circulation of drilling fluid has to be stopped.

Figure 5 illustrates how a connection is performed. It shows procedures using a rotary table, so only one pipe is able to be lowered at once, in opposition to 3, if a topdrive were employed instead.

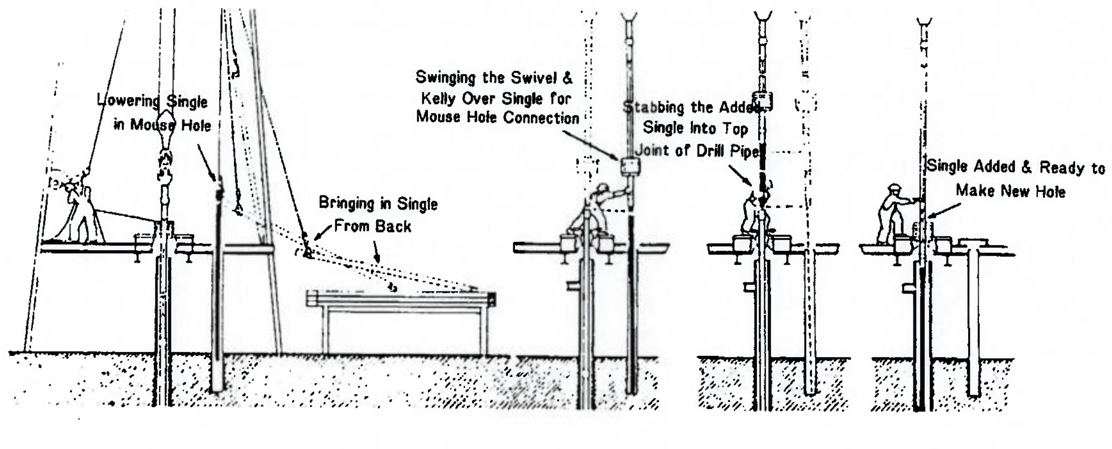


Figure 5 - Making a connection: While a section of pipe is being lowered, mud is circuiting into and out of the well. When another pipe is to be connected mud circulation is stopped. When connection is done fluid circulation is resumed. (BOURGOYNE JR et al, 1986)

### 3.1.1 Problems with Circulation Stop

Though so far necessary, circulation stop may bring various problems:

a) On static conditions, the exchange of heat between the equipments, formation and drilling fluid is hindered, causing an increase on mud temperature. Many of the fluid properties are temperature-dependent, so rheology properties such as viscosity, yield point, density, tixotropy, etc. may vary. This change in properties is usually observed in a non-homogeneous way, resulting in several layers of varying temperature and cuttings concentration. Such conditions are hard to be monitored and may jeopardize well control. This phenomenon is particularly enhanced in high temperature/ high pressure (HTHP) wells, where temperature and pressure gradients are higher.

b) When circulation is stopped, there is a pressure drop in the annular space. Thus, the equivalent circulating density (ECD) is lost. The ECD is an important well control parameter in drilling, especially in wells with a narrow operational window between the fracture and pore-pressure gradients. ECD can be written as shown on Equation 1:

$$ECD = \rho + \frac{P_{annulus}}{0{,}052 * TVD} \qquad (Eq.1)$$

While circulation is conducted, the down hole pressure in the annulus is equal to the static head of mud and cuttings plus the friction loss (dynamic head), while when the circulation is stopped, the dynamic head is zero and the down hole pressure in the annulus is only the static head of mud and cuttings. Both scenarios are illustrated on Figure 6. The stop and resume of fluid circulation causes ECD to vary and this situation may induce a kick and damage exposed formation, especially when the gap between fracture and pore pressure is narrow (if downhole annulus pressure is higher than fracture pressure, fractures may be induced on the formation. On the other hand, it is lower than the pore pressure, formation fluid will enter the well).

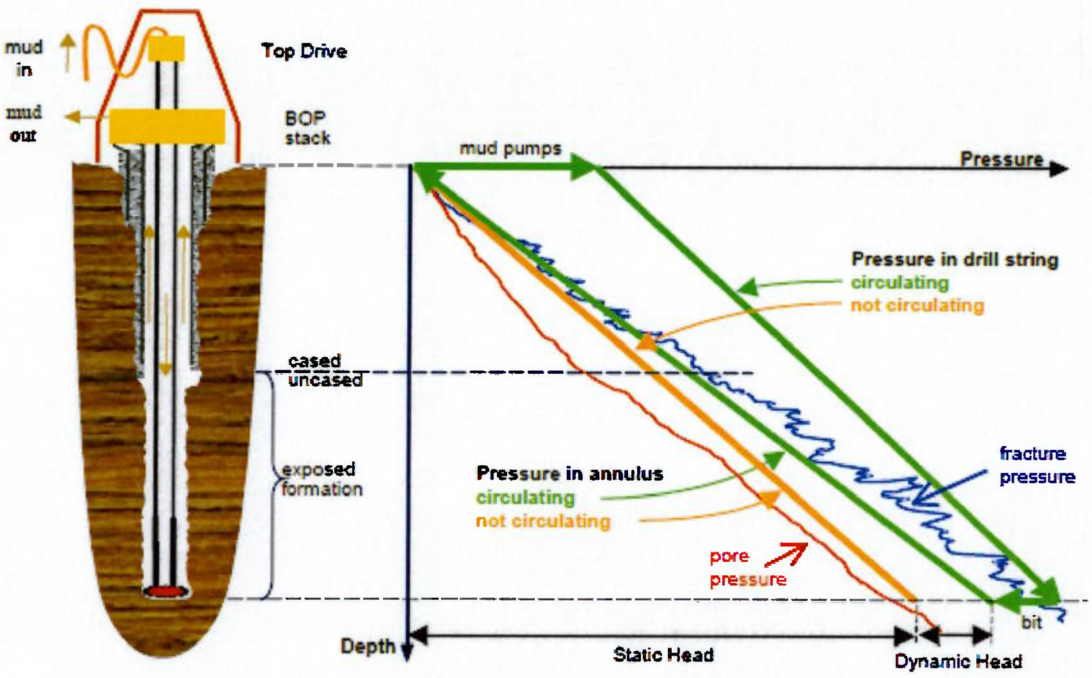


Figure 6 - Down Hole Mud Pressure Circuit. When circulationis stopped, the dynamic contribution of pressure to ECDD is zero. ECD has to be kept in between pores pressure and fracture pressure. (AYLING, JENNER, ELKINS, 2002)

c) In horizontal and high angle directional wells, cuttings are more likely to fall to the lower side of the hole. The accumulation of cuttings affects significantly hole cleaning. Also, this accumulation results in reduction of the effective hole diameter and in increase of torque/ drag and twist-off on the drill string, what may lead to tool failure.

d) In a situation which the differential pressure between the well and reservoir is high, the drill pipe and bottom hole assembly are pulled towards the wall of the hole, and the equipment bonds to the mud cake by the wall. Its removal is quite difficult, what may require several non-working hours trying to recover the tools and on some extreme cases, the well can be lost. This phenomenon, known as differential sticking, is one of the most common problems faced while drilling and is illustrated on Figure 7. Pressure variation due to circulation stop may increase the likelihood of differential sticking.

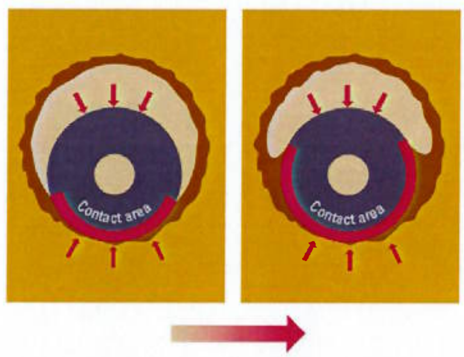


Figure 7 - Differential Sticking (SCHLUMBERGER b)

e) When circulation is stopped, the fluid tends to behave as a gel phase, keeping solids in suspension. The longer the period with no circulation, the stronger the gel is. When circulation is re-started, this gel has to be broken before reestablishing drilling conditions. This may cause wearing of tools and may result in significant non-productive time.

f) When circulation is re-started, the bit has to drill through settled cuttings before reaching the formation itself. This results in significant non-productive time.

## 3.2 An Alternative to Circulation Stop - Continuous Circulation Drilling

As previously pointed out, circulation stop may result in several problems while drilling, which significantly increase rig down-time and costs. Many efforts have been conducted aiming diminish such problems and improve drilling operations.

A successful endeavour was the development of a continuous circulating drilling system. Such project was led by a Joint Industry Project (JIP) managed by Maris International ltda. and supported by six major oil companies: Shell UK, BP, Statoil, BG, Total and Eni. (CALDERONI et al, 2006a)

The project was presented on the year 2000 and the first field trial was carried out in 2003 in Oklahoma, USA (CALDERONI et al, 2006a, 2006b). Finally, by 2005, after good performance in trial runs, the system started to be commercialized, having its debut on a rig in Italy and right after it was successfully moved to an offshore rig in Egypt (CALDERONI et al, 2006a).

"The Continuous Circulation System, by maintaining uninterrupted circulation when making or breaking drill pipe connections, eliminates pressure surges associated with stopping/ starting the pumps and a steady pressure regime and ECD can be established in the wellbore. This removes the problems associated with making connections [...], allowing the well to be controlled using the ECD rather than the specific gravity of the static mud column." (CALDERON et al, 2006a, p.2)

From the beginning, Eni recognized the benefits of the continuous circulation system and has always been an enthusiastic supporter of such technology. By the year 2006, Eni had developed its own continuous circulation system and started field trials at an extended reach well in Val D´Agri Field, in the South of Italy (CALDERONI, 2011).

### 3.2.1 The Eni Continuous Circulation System

The continuous circulation system created by Eni enables circulation not to be stopped when connections are being done or undone. It mainly works through the Eni Circulation Device (E-CD) which is composed by two parts: E-CD subs and E-CD manifold.

All the details concerning the Eni Continuous Drilling System and its equipments and operation procedures here described are according to Calderoni and Girola (2009).

The E-CD Sub (Figure 8) is a short section of pipe with a lateral inlet that is connected to the E-CD manifold by a flexible hose. The subs have the same pin/ box thread of DPs and are to be installed on the top of DPs (after every 3 DPs, if topdrive is being used) every time a connection is to be performed.

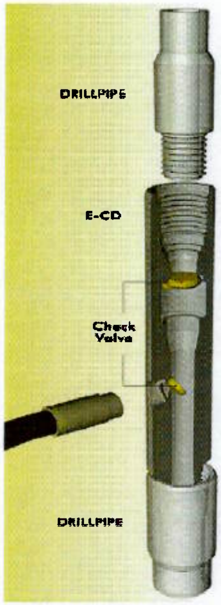


Figure 8 - E-CD Sub (CALDERONI and GIROLA, 2009)

The E-CD manifold (Figure 9) ensures the diverting of the drilling fluid from the topdrive line to the side entry of the E-CD sub. E-CD manifold is installed on the rig floor or at the ground level when the rig floor is short of room.

Figure 9 - E-CD Manifold (CALDERONI and GIROLA, 2009)

All the E-CD subs together with the E-CD manifold form the E-CD system, illustrated on Figure 10.

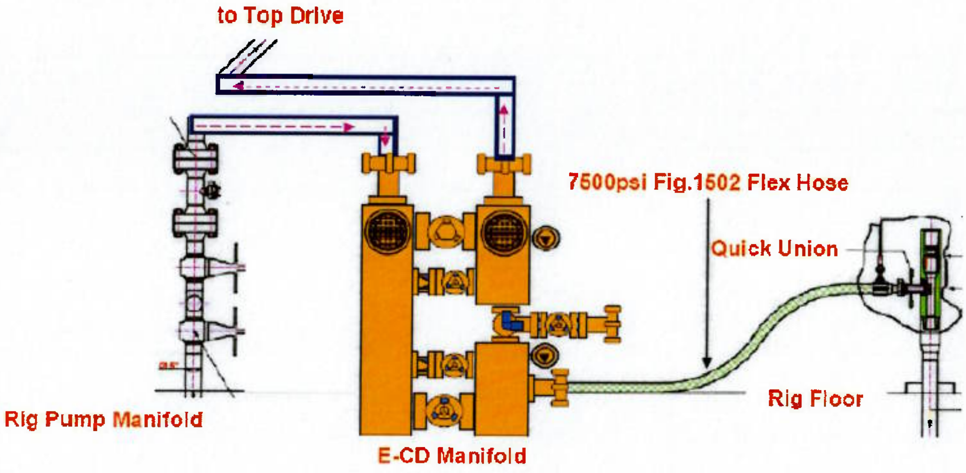


Figure 10 - E-CD System (CALDERONI and GIROLA, 2009)

Concerning rig up, the E-CD system can be installed on every existing rig, from land rigs to jack ups and floaters (semi submersible), using either conventional rotary table or topdrive system, with only minor modifications from one another The installation can be carried out during non productive time such as operations following the cementation of casing at the end of the hole section. A layout of rig with modifications for the installation of the E-CD system can be observed on Figure 11.

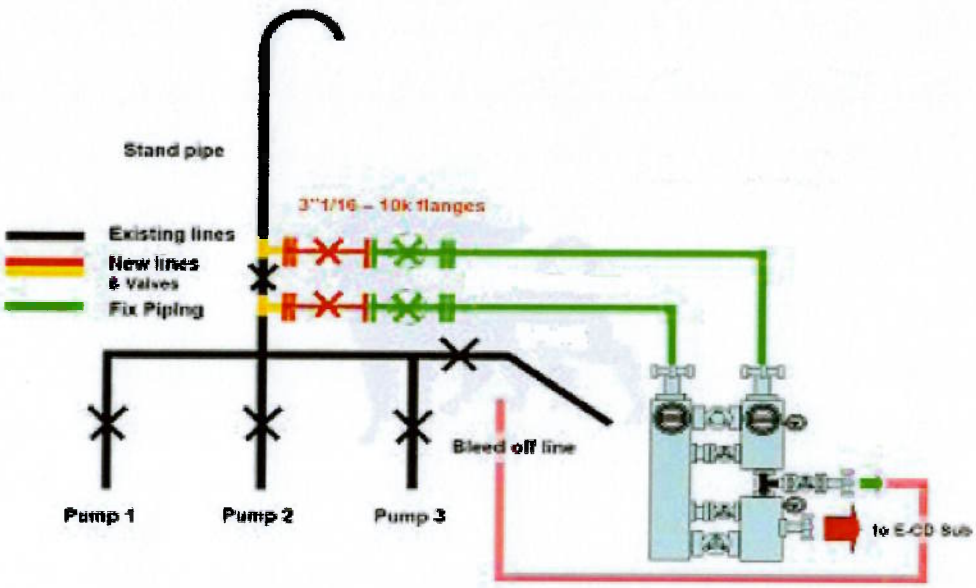


Figure 11 - Rig modifications for E-CD installation (CALDERONI and GIROLA, 2009)

When drilling operations are conducted, the valve that connects the E-CD manifold and E-CD sub is closed, so drilling fluid is pumped through the manifold and goes straight to the topdrive and from there to the drill string, as in a regular drilling operation.

When connections are to be performed, the valve between the top drive and manifold is closed, while the valve between the E-CD sub and manifold is opened. Thus, drilling fluid flow is switched to the E-CD sub, enabling the top drive to be disconnected with no need of interrupting fluid circulation, and a new set of DPs can be installed.

"To give an idea of the experiences to date, the E-CD tools independently have accumulated more than 1200 working days over 7 challenging wells, including one extended horizontal at 5650m, two HPHT, and one complicated deep sidetrack. Mud weight has ranged from 1,06 to 2,23 SG (8,80 to 18,6 ppg), with flow rates up to 950 gpm and pressures of 5000 psi. More than 3000 DP connections have been made with a current reliability of 97 to 100%, depending on the severity of the environment – HPHT, flow rate, drilling fluid conditions, pressure, etc." (CALDERONI et al, 2009, p.3)

**3.2.1.1 Benefits of the Continuous Circulation System**

The Continuous Circulation System has proven to be an effective technology to be employed on drilling, providing significant benefits.

With continuous flow, the settlement of cuttings and solids is avoided, and mud stagnation is prevented, providing improved hole cleaning and preventing stuck pipe during connections. In static conditions, the fluid tends to be at a gel phase. The longer is the circulation stop period, the stronger this gel is, making it very hard to reestablish drilling conditions. Continuous drilling eliminates this static condition (no gel formation), permitting a drilling job at faster rate and lower costs.

Besides that, the E-CD allows drilling in a steady state regime. In such conditions, mud properties tend to remain constant, allowing an improved control of ECD. Negative and positive pressure surges when stopping and starting circulation are eliminated. A good control of ECD provides safer drilling conditions, ensuring mud density to be always kept in between pore pressure and fracture pressure gradients, avoiding fluid losses and kicks. This benefit is particularly important on wells where this interval between gradients is narrow, and even minor variations may place ECD out of such expected interval.

The phenomenon known as Ballooning Effect is also reduced when Continuous Circulation System is used. This phenomenon is defined as a variation in volume of returned mud, giving either a too low or a too high volume. When pumps are turned off, a mud back flow is observed. These situations may be misinterpreted and potential kicks might not be recognized. Thus, reduction of the ballooning effect provides a better well control, and more safety on rig floor.

According to Calderoni (2011), such benefits provided by the continuous circulation drilling can be divided in three major categories:

a) **Quality:** improved hole cleaning, fewer stuck pipe incidents; prevention of ballooning effect
b) **Well control/ safety** : reduced kick likelihood
c) **Enabling technology**: drilling through difficult formations; narrow pore/ fracture pressure gradients window; prevention of overheating downhole tools; increased lifetime of downhole instruments; maximized potential for HPHT drilling

According to Francis (2010), the constantly rising demand for oil stimulates the development of high efficiency - low cost technologies (Figure 12). As observed with the continuous circulation drilling technology, the result is the enablement of a higher recovery rate at lower costs.

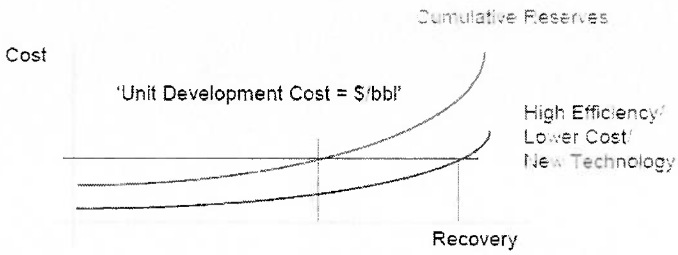


Figure 12 - Reduce cost of existing operations through automation efficiencies to access currently 'unaffordable reserves' (FRANCIS, 2010)

The use of the continuous circulation system enabled the exploration of areas previously economical and/ or technologically unfeasible. Pointed out by Jenner (2005), potential wells to be successfully explored with continuous drilling are extended reach and horizontal wells, near underbalanced or underbalanced wells, deep water wells, narrow pressure window wells and pressure sensitive wells.

a) **Extended reach and horizontal wells:** these wells particularly benefit from the fact that nonstop circulation avoids cuttings from settling on the low side of the hole, preventing building up and stuck pipe situations. Also, a clear annulus provides less torque on drill string, enabling a better directional control of the drill string.

b) **Underbalanced drilling**: When drilling underbalanced, bleeding down and re-pressuring the drill string when performing a connection (with circulation stop) is a procedure that takes a long time until desired conditions are achieved. Also, damaging the reservoir when circulation is re-established is likely to occur. Thus, continuous circulation provides less rig downtime and prevents well damage.

c) **Deep water wells**: Continuous circulation improves the ability of drilling unstable formation, as the occurrence of hole-collapse and stuck-pipe situations can be reduced.

d) **Narrow Pore-Pressure/Pressure-gradient wells:** The use of Continuous Circulation enables the control of ECD by adjusting circulation rate and drilling fluid density. Without such system, each time pumps are restarted, high bottom-hole pressure spikes are imposed, what may lead to dangerous situations such as lost circulation or ballooning effect.

e) **Pressure sensitive wells**: Drilling with Continuous Circulation eliminates start/stop pressure surges, reducing wellbore stress and maintaining formation stability. Without the system, formation is liable to relax or squeeze into the wellbore, what may lead to stuck pipe or hole loss. This is particularly important in pressure sensitive formations, such as shale and salts.

## 3.3 Drilling fluids

Drilling fluids is a key chapter on a drilling programme. While drilling, a fluid is circulated through the string and ejected into the well by the bit nozzles. Once in the well, the fluid moves upwards inside the annular space between the drill string and casing/ bare hole carrying solids and residues from the drilling activities.

### 3.3.1 Types of Drilling Fluids

Drilling fluids are usually composed of two phases: fluid phase and solid phase. The fluid phase can be oil, water or gas and many chemicals may be dissolved into this phase to provide a desired characteristic to the mud. The solid phase consists in various nature and size particles, maintained in suspension in the fluid, also with the aim of reaching a particular desired property.

Drilling fluids can be classified according to the type of base fluid used as continuous phase. There are four main categories: water based (WBM), oil based (OBM), gas based and synthetic based (SBM) fluids.

Water based fluids are formulated with fresh water, sea water, brines at different concentrations or saturated solutions. Though environmental friendly, of easier disposal and cheaper, WBM is known to be highly reactive with the formation, easily contaminated and harder to manage well control.

Oil based fluids are formulated with water-free oils (such as diesel or mineral oil). When the mud contains emulsified water or brine it is known as an inverted emulsion system, while a water/brine system in which oil is emulsified is known as direct emulsion system. According to Galate and Mitchell (1984), the benefits of oil based mud are thermal stability in deep and high temperature wells, increased lubricity in offshore wells and hole stability in thick, water sensitivity shales. Some drawbacks are however, high toxicity, difficult disposal and higher incidence of lost-circulation. Nevertheless, oil-based systems are widely used in view of its outperformance over water based muds on drilling jobs, specially on more challenging wells.

Gas based fluids are formulated with gas as continuous phase, usually air, nitrogen or carbon dioxide, with the addition of water. The concentration of water determines the classification of the gas based mud. When water is present in low concentrations, the system is known as mist, while when present in higher concentrations the system is classified as foam.

Finally, synthetic based muds (SBM) are non-aqueous inverted emulsions in which the external phase is a synthetic oil, usually with much lower toxicity than the natural ones. SBMs have been gaining large market share, as they may combine good drilling performance, reduced environmental impact on disposal and introduction of new desired features. Especially on technological demanding wells, such as deepwater, SBM is preferred, due to its better performance in achieving high penetration rates and maintaining wellbore stability. Nevertheless, SBM properties are highly influenced by temperature and pressure, so the appropriate mud system must be carefully chosen.

### 3.3.2 Role of drilling fluids

The role of drilling fluids is wide and fundamental to the success of drilling activities. Some of its main functions are listed below:

**a) Pressure control**: Facing formation pressure is known to be one of most important functions of drilling fluids. Well control while drilling is achieved by means of mud density, which is designed to be within fracture and pore pressure gradients.

The pore pressure is defined as the pressure held by fluids in a reservoir. If the mud weight exerts a pressure lower than pore pressure, reservoir fluid will flow into the well, and if not controlled may result in severe consequences, as hole instability and blowouts. On the other hand, the formation is characterized by a fracture pressure. If mud weight exerts pressure bigger than the fracture pressure, the formation is likely to fracture hydraulically. Figure 13 illustrates the window of pressure allowed to the drilling fluid.

It is important also to point out that the bigger the weight of the mud, the lower are the penetration rates achieved, resulting in longer drilling procedures. Thus, mud weight is a parameter that must be carefully evaluated to best fit drilling requirements and formation conditions.

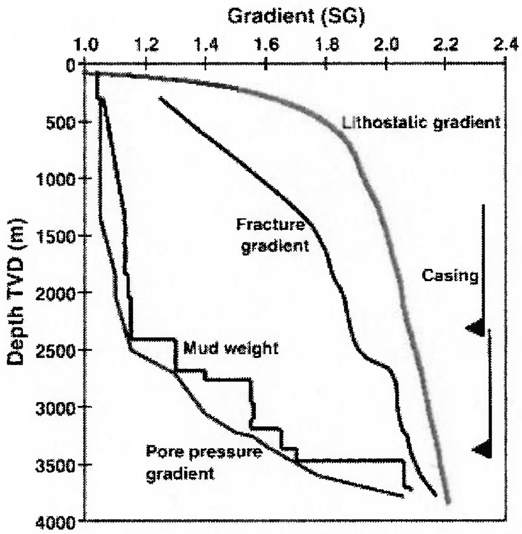


Figure 13 - Pore pressure gradient, fracture gradient, lithostatic gradient with depth (ZHANG, 2011)

**b) Hole Cleaning and Solids Suspension**: When formation is drilled, a big quantity of cuttings and residues is produced, all of which must be removed from the well to allow better performance of the bit and allow hole cleaning. Thus, drilling fluid has to be able to carry these sediments when circulated out of the well.

Not only that, when circulation is stopped, (during tripping procedures or when connections or disconnections are being performed) the fluid is expected to have enough gel strength so that when in such static conditions it has a gel behavior, being able to make sediments remain in suspension in the fluid, preventing them from settling on the bottom of the well.

Viscosity is known to be an important parameter concerning solids suspension. Solids settlement is very fast in low viscosity fluids, while carrying capacity increases in high viscosity fluids.

**c) Cooling and Lubrication:** The rotation of the drill string and friction of the bit with the rock formation generates a big amount of heat. The fluid has to be able to absorb this heat, cooling down the equipments in order to avoid tool failure.

Also, the additives on the fluid have a lubricant action, lowering the friction coefficient between the drill string and bit with the drilled formation.

**d) Stabilization of Borehole Walls**: When drilling, the fluid suffers a partial loss of water to the permeable formation. The solids tend to stick to the borehole walls and is known as mud cake or filter cake.

The mud cake is important as it protects the rock formation from further liquid filtration and provides wall stabilization, avoiding problems such as hole caving and sloughing.

It is important to point out that the mud cake has to be as thin as possible, impermeable, elastic and has to be able to regenerate quickly, in order to avoid increase of friction, pipe sticking and circulation losses.

**e) Corrosion Control**: Drilling equipment works under harsh conditions. Corrosion is one of the main causes of tool failure and should be controlled. Oxygen, carbon dioxide and hydrogen sulphide are the main corrosive fluids.

The pH of the mud and corrosion control agents added to the drilling fluid are expected to provide corrosion control.

### 3.3.3 Flat Rheology Technology

Rheological properties of a fluid are usually temperature dependant: on lower depths, temperatures are likely to be lower, what causes increase of viscosity. On the other hand, as drilling deeper, temperature increases significantly, resulting in lower fluid viscosities. This problem is particularly enhanced on off-shore and ultra deep wells, where a wide range of temperature conditions are faced. Such variations may cause difficulty in setting correct ECD, as in the first condition (shallow depths), offset negative ECD effects are faced, while on the second condition (higher depths) excessive ECD and gel strength are faced.

High rheology fluids provide a good hole cleaning and barite suspension, but the resulting ECD is high, and may lead to formation fracture. On the other hand, low rheology fluids provide a low ECD, which can be more effective for drilling procedures( as long as it is still bigger than pore pressure gradient), but with the consequence of enhanced barite sag and poor hole cleaning.

The big challenge is finding a balance in rheology conditions. To overcome such challenges, a new category of fluid has been developed, providing almost constant rheological properties at a wide range of temperature and pressure, consequently allowing a more effective drilling, with good hole cleaning and barite suspension at low ECD. This new technology is known as flat Rheology. Figure 14 illustrates the difficulties in balancing fluid properties and how flat rheology fluids can be an alternative to overcome such problems.

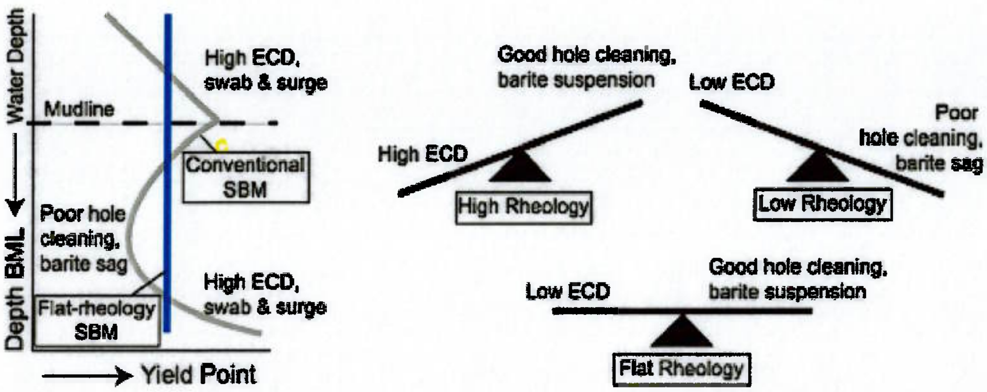


Figure 14 - Comparison between conventional and flat rheology drilling fluid (VAN OORT, LEE, FRIEDHEIM, 2004)

The key properties that determine the flatness of a fluid are the Yield Point, 6 and 3 rpm readings and 10 minute gel strength measured on VG meter. On a flat rheology fluid, such properties suffer minimal variation at a wide range of temperature and pressure (40-300° F and 14-17,500 psi, respectively). It is important to highlight that Plastic Viscosity does not remain constant with temperature change, but this does not influence ECD nor hole cleaning.

As illustrated on Figure 15, general tests comparing conventional synthetic mud fluid with flat rheology fluid confirm temperature independent rheology. On conventional fluid, the increase of temperature results in decrease of Yield Point (YP), 6rpm reading (6rpm), 10 minute gel reading (10' gel), while on flat rheology fluid, such parameters remain almost constant despite temperature increase.

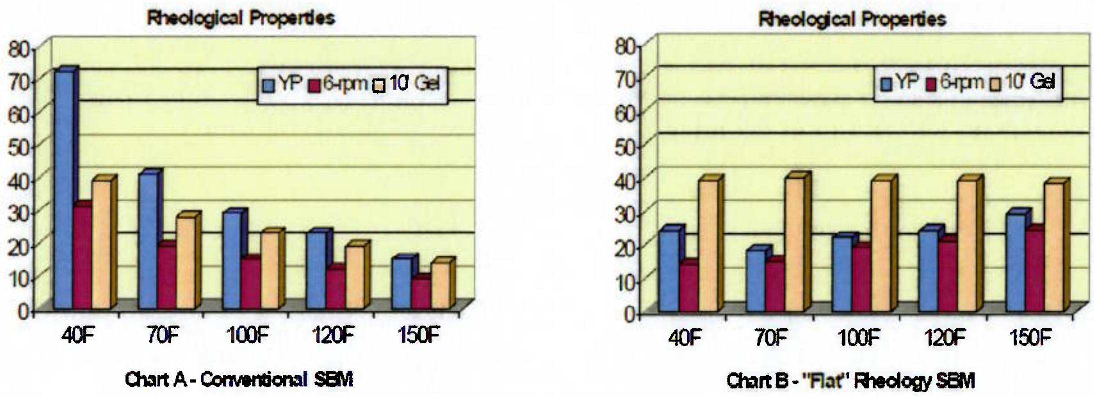


Figure 15 – Profile of Yield Point, 10 minute gel strenght and 6-rpm reading of a 13,8lb/Gal conventional SBM (chart A) and new "Flat" Rheology SBM (chart B) in the temperature range between 40°F and 150°F. (LEE et al, 2012)

Such flat rheology characteristics provide a more constant ECD, diminishing barite sag and improving hole cleaning. Besides that, due to its low clay content, gel strength is kept at low levels, even on static conditions, virtually eliminating pressure spikes when circulation is reestablished (Figure 16 and Figure 17). Such characteristic enables a more efficient and secure drilling.

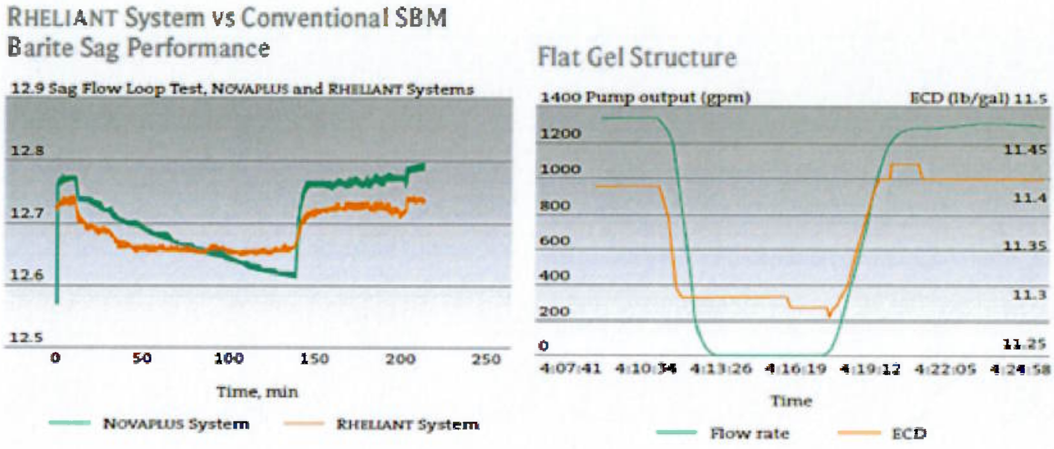


Figure 16 - Rheliant Fluid Behaviour – reduction of barite sag and small variation of ECD on circulation stop (M-I SWACO, 2003)

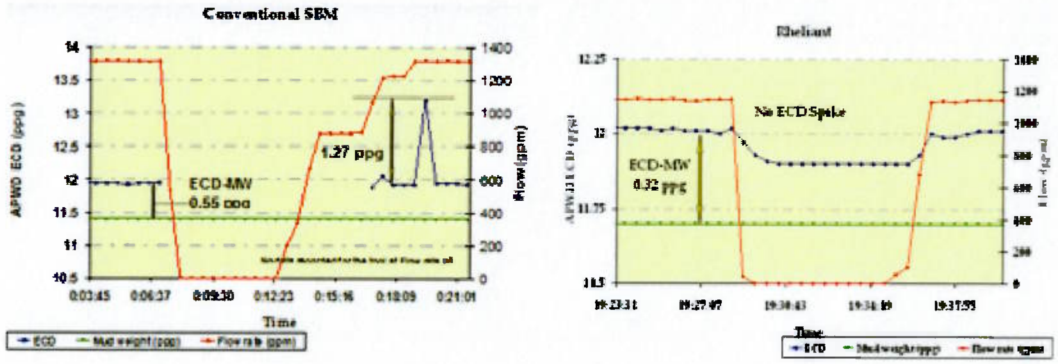


Figure 17 – Comparison between conventional and Rheliant fluid pressure spikes (M-I SWACO)

The overall result is a fluid with a higher viscosity than regular muds, what aides with hole cleaning and barite suspension, but does not affect ECD.

“The unique flat rheological profile of the new SBM is generated from the interaction of the rheology modifier and reactive solids such as organophilic clays. Although the exact mechanism involved is not known, it is believed the flattening effect is derived from the change of the molecular size and shape of the rheology modifier with temperature” (LEE et al, 2004, p. 3).

According to Young et al, (2012), Flat Rheology technology was introduced by the year 2002. This type of fluids have been used in the Gulf of Mexico since 2004 (SCHLEMMER and SHELDON, 2010; and VAN OORT, LEE, FRIEDHEIM, 2004). And in 2007 it was successfully introduced in deepwater fields offshore Malaysia (VAN OORT, LEE, FRIEDHEIM, 2004). Lee et al (2012) shows good performance of such fluid in extended reach wells.

# 4. Materials and Methods

In order to evaluate flat rheology performance, it was compared to other fluids formulation: two oil based fluids (O/W = 80:20 and O/W = 70/30) and one high performance water based fluid formulation.

## 4.1 Laboratory tests

Laboratory tests for mud properties characterization were carried out on M-I SWACO Headquarters in Ravenna, Italy. Tests were conducted according to API standards and the detailed procedures are described on Appendix A.

Two formulations of oil based and water based mud were tested. A list of formulations and codes used to refer to them on this project is provided on **Erro! A origem da referência não foi encontrada.**.

Table 1 - List of fluids tested and their respective code

| Code | Base | O/W | Additives |
|---|---|---|---|
| OIL80 | **Oil** | **80:20** | **-** |
| OIL80HRP | **Oil** | **80:20** | **HRP** |
| OIL70 | **Oil** | **70:30** | **-** |
| OIL70HRP | **Oil** | **70:30** | **HRP** |
| Ultradril | **Water** | **-** | **-** |
| Rheliant | **Synthetic** | **-** | **-** |

HRP is a gellant agent. It is used to provide better suspension to the fluid. It results in increased yield point with minimal change on plastic viscosity (PV). On site, fluid is sheared when flowed through the bit, what provides increased Yield Point (YP). Though not as effective, HRP was here added to simulate this effect. It avoids the use of high amounts organophilic clay, what could lead to undesired high viscosity.

### 4.1.1 Oil based mud

Oil based mud was mixed according to specific gravity, oil/water ratio and amount of additives. Specific gravity was set at 1,3 and two formulations of oil/water ratio were mixed: O/W = 80:20 (OIL80) and O/W = 70:30 (OIL70). Details of the formulations are described on Table 2, also with overall formulation of the fluid.

Table 2 - Detailed Oil Based fluid formulation

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## Oil based mud formulations

| | | SG | OIL80 | OIL70 | |
|---|---|---|---|---|---|
| OIL RATIO | | | 80 | 70 | % |
| BASE COMPOSITION | Oil | 0,79 | 653 | 575 | $l/m^3$ |
| | Water | | 151 | 228 | $l/m^3$ |
| ADDITIVES | $CaCl_2$ | | 53 | 80 | $Kg/m^3$ |
| | Lime | 2,4 | 20 | 20 | $Kg/m^3$ |
| | VG69 | 1,6 | 18 | 18 | $Kg/m^3$ |
| | Ecotrol RD | 1,03 | 10 | 10 | $Kg/m^3$ |
| | Novatec P | 0,95 | 20 | 20 | $l/m^3$ |
| | Novatec S | 0,92 | 15 | 15 | $l/m^3$ |
| | Barite | 4,2 | 514 | 471 | $Kg/m^3$ |
| $CaCl_2$ | % P | | 20 | 20 | % |
| | Purity | | 77 | 77 | % |
| | Activity | | 0,84 | 0,84 | - |
| | SG | | 1,19 | 1,19 | - |
| OVERALL | final SG | | 1,3 | 1,3 | - |
| | SG without barite | | 0,9 | 0,93 | - |
| OVERAL MUD CHARACTERISTICS (% volume) | Oil | | 65,3 | 57,5 | % |
| | Water | | 16,3 | 24,7 | % |
| | Solids High gravity | | 12,2 | 11,2 | % |
| | Solids Low gravity | | 2 | 2 | % |
| | Salts | | 0,9 | 1,3 | % |
| | Other | | 3,3 | 3,3 | % |
| OVERAL MUD CHARACTERISTICS (% mass) | Oil | | 39,7 | 35 | % |
| | Water | | 12,6 | 19 | % |
| | Solids High gravity | | 39,5 | 36,2 | % |
| | Solids Low gravity | | 2,9 | 2,9 | % |
| | Salts | | 3,1 | 4,7 | % |
| | Other | | 2,2 | 2,2 | % |

The role of each one of the additives used on the oil based muds are described below:

**$CACL_2$** is used in most oil based mud systems to reduce the activity ($A_W$) of the mud for shale inhibition. High purity (95-98%) granular or powdered calcium chloride is preferred to tech grade (77 – 80% purity) or flaked products.

**LIME ($CaOH_2$)** is used in all oil based mud systems for alkalinity control to increase the $P_{OM}$[1] maintaining some excess lime. In conventional systems, it is used in higher concentrations as a source of calcium for forming soaps with the primary emulsifiers.

**VG69** is a viscosifier and gelling agent. It is used to provide increased viscosity and gel strength to the fluid. Good agitation and shear is necessary to develop the desired viscosity on the mud.

**ECOTROL RD** provides superior high shear stability without polymer degradation and maintains suspending capability

**NOVATEC P** is used as primary emulsifier providing good emulsion stability and as secondary agent, provides good wetting of solids. Besides, it contributes with HPHT filtration control, temperature stability and has high contamination tolerance.

**NOVATEC S** is used as primary wetting agent and as secondary emulsifier. It improves oil-wetting and reduces water wetting, improves thermal and emulsion stability and prevents water in the filtrate.

**BARITE** is use, as a weighting agent to provide increased density to the fluid.

### 4.1.2 High Performance Water-Based Mud

The water based fluid chosen to this project is a high performance fluid commercially know as Ultradril. Such fluid system attempts to enhance WBM benefits and diminish its side effects, resulting in a drilling performance near to Synthetic and Oil based- muds.

Main features of Ultradril are inhibition of highly reactive shales, low dilution, low toxicity, environmental compliance, encapsulation of cuttings with a thin layer of polymer promoting reduction on shale dispersion, better hole cleaning, increase on rate of penetration and wellbore stabilization.

Ultradril fluid was mixed on the lab with specific gravity set on 1,3. Its formulation is detailed on Table 3.

Table 3 - Deatailed Ultradril formulation

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**Ultradril Formulation**

| | | SG | Ultradil | |
|---|---|---|---|---|
| ADDITIVES | Duovis | 1,5 | 3 | Kg/m³ |
| | Ultrahib | 0,99 | 22 | Kg/m³ |
| | Resinex II | 1,35 | 16 | Kg/m³ |
| | Pac ULV | 0,7 | 9 | Kg/m³ |
| | Barite | 4,2 | 480 | Kg/m³ |
| | Lube 167 | 0,98 | 23 | Kg/m³ |

[11] $P_{OM}$: The alkalinity of an oil mud is determined by breaking the emulsion and titrating the mixture rapidly to the first color change. The number of milliliters of 0,1 N sulphuric acid solution used in the titration per milliliter of mud is reported as the alkalinity of the mud or $P_{OM}$.

Additives used on the formulation of Ultradril are described below:

**DUOVIS** is a high molecular weight xanthan gum biopolymer used to provide higher viscosity and enhanced solids suspension, resulting in a fluid that is highly shear-thinning and tixotropic.

**ULTRAHIB** is a polyamine shale inhibitor. It avoids clay hydration by intercalating and reducing the space between clay platelets, so that water molecules do not penetrate, preventing clay swelling.

**RESINEX II** is a lignite resin that helps stabilizing fluid under high bottom hole conditions, controlling HPHT filtration rates. It helps with shale stability and hole whashout, with minimal influence on rheological parameters.

**PAC ULV** is a polyonic cellulose polymer. It helps diminishing fluid loss by the formation of a tough and thin filter cake, minimizing differential sticking occurrences.

**BARITE** is used as a weighting agent to provide increased density to the fluid.

**LUBE 167** is a water-dispersible lubricant used to reduce the friction coefficient on the drill string, what enables lower torque and drag on wellbore. It has minimal influence on rheological parameters.

## 4.2 Synthetic based fluid – Flat Rheology System

### 4.2.1 The Rheliant fluid

In regard of flat rheology fluid, the Rheliant formulation was chosen to be tested on this project.

Its formulation is quite specific and it is not being used in Europe at the moment, therefore, its data (rheoloy behavior, composition etc) was acquired from M-I SWACO database instead of performing laboratory tests.

### 4.2.2 The Rheliant fluid composition

The Rheliant fluid characteristics are achieved by addition of redesigned viscosifiers, rheology modifiers, emulsifiers and minimal addition of organophilic clays. Emulsifiers minimize the impact of drill solids on rheological properties, rheology modifiers provide lower viscosity at lower temperatures and viscosifiers provide enhancement in overall viscosity and suspension capacity. A brief comparison of composition of conventional mud and flat rheology mud is found at Table 4.

Table 4 - A comparison of the key components of conventional SBM and flat rheology SBM used for deepwater drilling (VAN OORT, E.; LEE, J.; FRIEDHEIM, B)

| | CONVENTIONAL SBM | FLAT RHEOLOGY SMB |
|---|---|---|
| Organophilic Clay | Organophilic bentonite, typically 4-6 ppb | Similar but ~50% lower concentration, typically 1-3 ppb |
| Emulsifier | Blend of surfactants | Modified to improve performance |
| Wetting agent | Surfactant | Different chemistry with no adverse solids interactions |
| Fluid loss control | Polymer | Polymer |
| Rheology modifier | Fatty acid based | Fatty acid based |
| Viscosifier | Polyamide | Polyamide |

The Rheliant fluid used on this project presented 1,26 specific gravity. It's formulation is detailed on Table 5.

Table 5 - Rheliant Fluid Formulation

MI SWACO
A Schlumberger Company

RHELIANT FORMULATION

| | | SG | | |
|---|---|---|---|---|
| ADDITIVES | Suremul | 0,9 | 20 | Kg/m$^3$1 |
| | Surewet | 0,89 | 6 | Kg/m$^3$ |
| | Rheflat | 0,9 | 4 | Kg/m$^3$ |
| | Rethik | 1 | 2 | Kg/m$^3$ |
| | VG Plus | 1,57 | 6 | Kg/m$^3$ |
| | VG supreme | 1,7 | 2,5 | Kg/m$^3$ |
| | Rhebuild | 0,95 | as needed | Kg/m$^3$ |
| | Reduce | 0,85 | as needed | Kg/m$^3$ |

The key chemicals used in Rheliant fluid are Suremul, Surewet, Rheflat, Rethik and Reduce.

**Suremul**: is used as a primary emulsifier, providing emulsion stabilization. Secondarly, it helps with filtration control, enhances oil wetting, minimizes dispersion tendency of reactive clay solids, improves thermal stability and contamination resistance.

**Surewet**: is used as a primary wetting agent, and when used in combination with Suremul, acts as a secondary emulsifier. It provides preferential oil wetting of barite and other solids preventing water wetting, improving thermal and rheological stability, improving filtration control and improving resistance to contamination.

**Rheflat**: is the key component to enhance flat rheology, providing almost constant rheology with minimal viscosity increase, even when under low temperatures. ECD control in such conditions is significantly enhanced and a shear-thinning rheological profile is observed, improving the rate of penetration.

**Rethik**: is a viscosifier that acts providing increased yield point and gel strength to enhance hole cleaning and solid suspension

**VG-Plus:** is an organohilic clay (more specifically, an amine-treated bentonite) used as a viscosifier, improving suspension capacity and hole cleaning. It also improves filter cake quality for reduced fluid loss.

**VG-Supreme:** is an organophilic clay with low shear rate viscosity and suspension properties. It enhances hole cleaning and prevents barite sagging. It also stands out for its rapid yielding capacity.

**Rhebuild**: is a viscosifier used to provide the fluid with temporary suspension of solids, used during transportation of the fluid to rig location. It helps preventing excessive addition of organophilic clays on initial formulation, what could mislead to undesired high viscosity fluid. Once circulated into the well, the viscosity effect is dissipated when under temperatures above 38°C.

**Rheduce**: is a dispersant used as thinner and contidionner. It acts through reduction of viscosity and gel strength due to macromolecules that disperse solids in the system without the need of dilution or change water ratio.

## 4.3 Virtual Hydraulics Software

Fluid performance on drilling was evaluated through computational simulations on Virtual Hydraulics Software. Such software, developed by M-I SWACO, permits efficient planning for effective ECD management and hydraulics optimization as well as realistic hydraulics assessments and projections based on real conditions and field measurements (M-I SWACO, 2006).

### 4.3.1 Parameters

Each fluid formulation was tested under the same simulation parameters for three different well profiles (vertical, deviated and horizontal wells).

#### 4.3.1.1 Well Geometry

From well head down to 2500 meters drilled a 9 5/8 inches casing was used, followed by a 500 meters open hole section, completing 3000 meters drilled (MD). Specifications on each section can be found on Table 6.

Table 6 – Detailed Well Geometry

| Type | Start [m] | End [m] | OD [in] | ID [in] | Weight [Kg/m] | Grade |
|---|---|---|---|---|---|---|
| Casing | 0 | 2500 | 9,625 | 8,681 | 69,9 | L-80 |
| Open Hole | 2500 | 3000 | - | 8,5 | - | - |

From top to bottom, the drill string comprises of 2683,5 meters of drill pipes (DP) – drill pipe joint length was 10 meters - followed by 150 meters of heavy weight drill pipes (HWDP) and 150 meters of drill collars (DC). Followed by 3 meters of stabilizer equipment (stab), 5 meters of "Measure While Drilling" tools (MWD), 5 meters of mud motor tools (PDM), another 3 meters of stabilizers and finally 0,5 meter of 8 ½ inches PDC bit. Weight on bit (WOB) was $80.10^3$ Newtons. A frontal view of well can be observed on Figure 18 and further details on the drill string (DS) are described on Table 7 and Table 8.

Table 7 - Drill String Specifications

| Section | Lenght [m] | Hole ID [m] | Pipe OD [in] | Pipe ID [in] | TJ OD [in] | TJ lenght [in] | TJ ID [in] | Description |
|---|---|---|---|---|---|---|---|---|
| 1 | 2500 | 8,681 | 3,5 | 2,992 | 4,75 | 16 | 2,125 | DP/ Casing |
| 2 | 183,5 | 8,5 | 3,5 | 2,992 | 4,75 | 16 | 2,125 | DP/ Open Hole |
| 3 | 150 | 8,5 | 6,625 | 4,5 | 8,5 | 19,7 | 4,25 | HWDP/ Open Hole |
| 4 | 150 | 8,5 | 7 | 2,813 | 0 | 0 | 0 | DC/ Open Hole |
| 5 | 3 | 8,5 | 7,75 | 3 | 0 | 0 | 0 | Stab/ Open Hole |
| 6 | 5 | 8,5 | 7 | 3 | 0 | 0 | 0 | MWD/ Open Hole |
| 7 | 5 | 8,5 | 7 | 3 | 0 | 0 | 0 | PDM/ Open Hole |
| 8 | 3 | 8,5 | 7,75 | 3 | 0 | 0 | 0 | Stab/ Open Hole |
| 9 | 0,5 | 8,5 | 8,5 | 0 | 0 | 0 | 0 | PDC/ Open Hole |

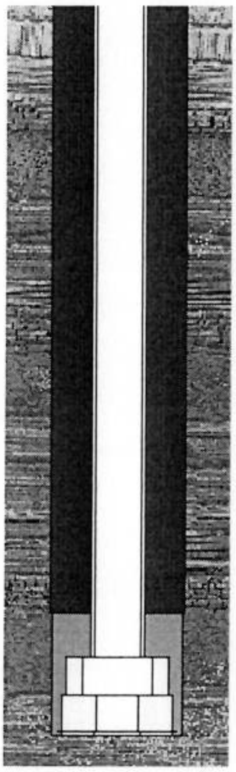


Figure 18- Frontal View of Drill String

Table 8 - Details on Drill String

| | |
|---|---|
| Annular volume | 89.602 $m^3$ |
| DS volume | 14.386 $m^3$ |
| Total Volume | 103.988 $m^3$ |

#### 4.3.1.2 Bit Nozzles

The evaluation was carried out considering utilization of a standard 8 ½ inches Mi616 PDC bit (Figure 19). Specific information concerning such bit is according to SMITH. Relevant specifications are shown on Table 9.

Table 9 - Bit specifications

| | |
|---|---|
| Number of nozzles | 6 |
| Nozzle size (1/32 in) | 6 x 16 |
| Calculated TFA ($in^2$) | 1,178 |
| Cutter size (in) | 0,625 |

Figure 19 - Standard 8 1/2 bit (SMITH)

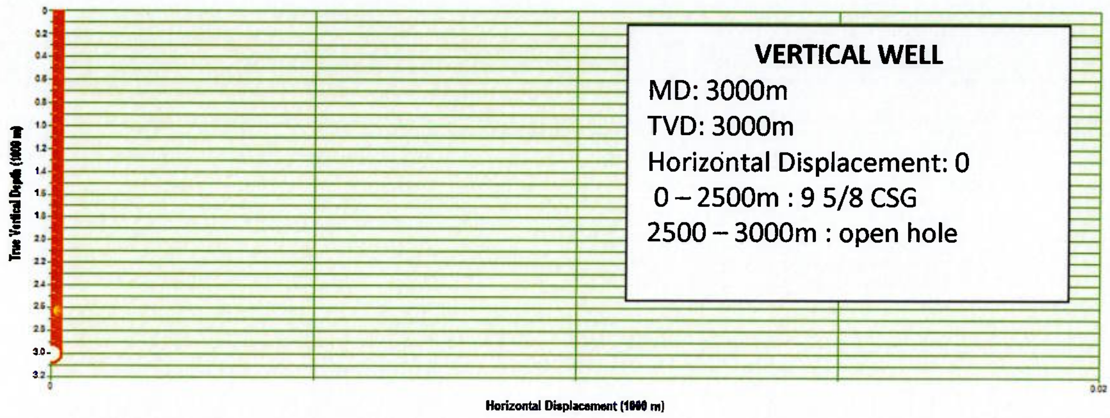
#### 4.3.1.3 Flow rate

Flow rate was set at 2500 l/min, using two pumps with an efficiency of 90%, liner diameter of 6 inches and stroke length of 10 inches.

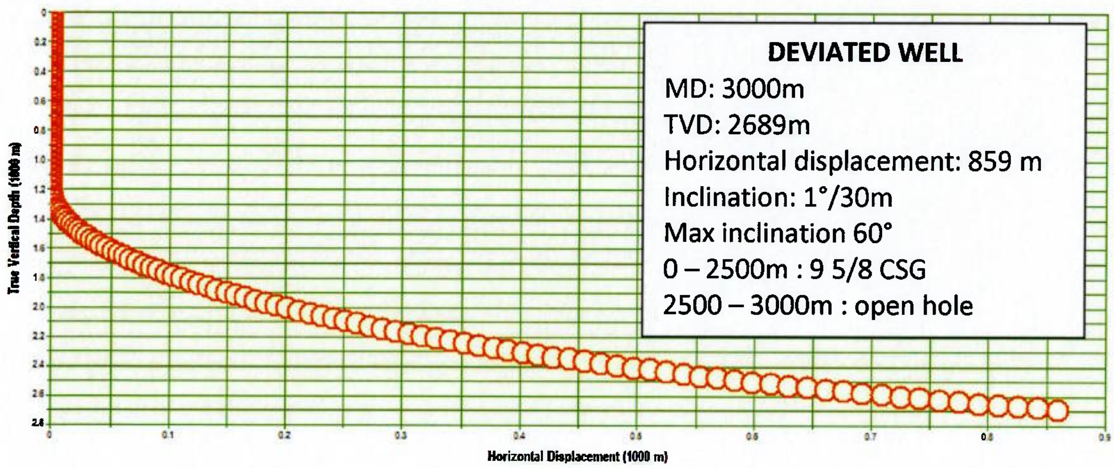
#### 4.3.1.4 Directional Profile

Three general well geometric profiles were considered in this study: vertical well, deviated well and horizontal well. Each profile details can be observed on Figure 20.

A) Vertical Well




B) Deviated Well




C) Horizontal Well

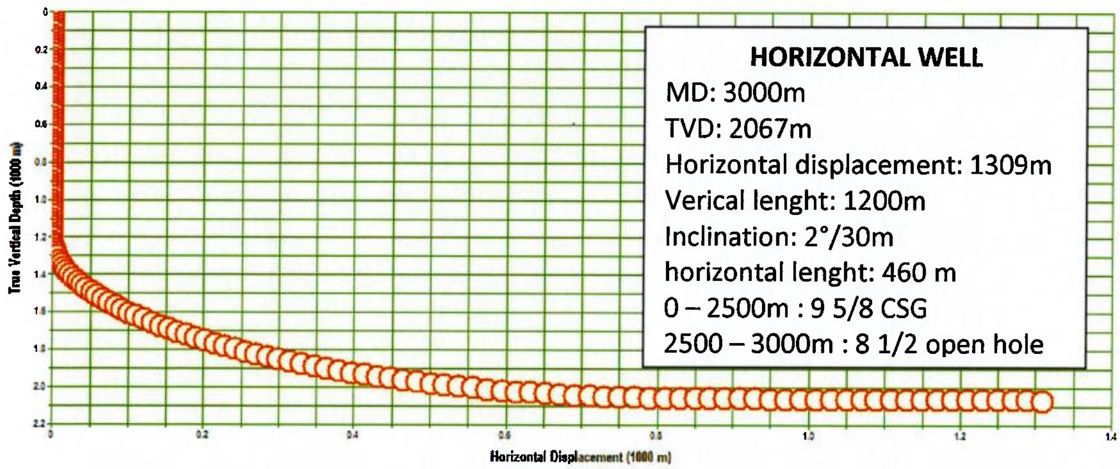



Figure 20 - Ilustration of well profile geometry. a) Vertical well; b) deviated well; c) horizonrtal well

#### 4.3.1.5 Temperature

Suction temperature at mud pit was considered 35°C and ambient temperature 25°C. Formation temperature was estimated according to SCHULBERGER c, considering an average geothermic gradient of 25°C/Km. Figure 21 ilustrates circulating temperature profiles.

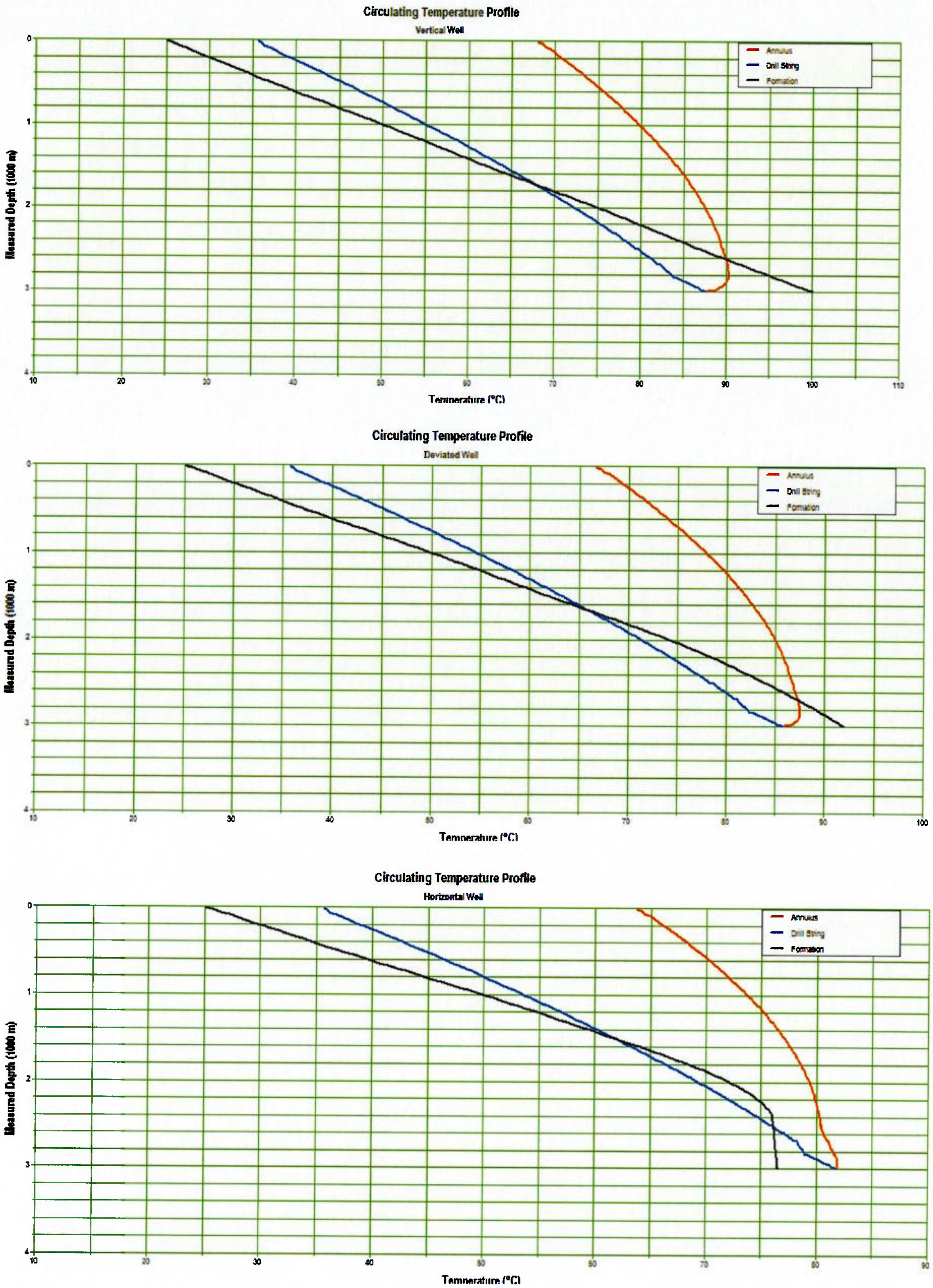



Figure 21 - Circulation Temperature on annulus (red), drill string (blue), formation (black) on three well profiles

#### 4.3.1.6 Other parameters

For hole cleaning purpose, cuttings were considered as medium size, presenting a specific gravity of 2,6 and shale composition.

The operating parameters were set as 10 m/hr rotating rate of penetration (ROP). Sliding Rate of Penetration was considered zero. Bit rotary was considered 300 rpm.

## 5. Data from laboratory test

Below are detailed the results obtained on laboratory tests: Table 10 shows details of the rheological characterization of both oil based and water based formulation. Table 11 shows rheological characterization of Rheliant fluid (acquired from MI SWACO database).

Table 10 - Rheology of oil and water based fluids obtained on lab test results

MI SWACO
A Schlumberger Company

## Rheology – OBM and WBM

| | | | OIL 80 | | | OIL 80 HRP | | | OIL 70 | | | OIL 70 HRP | | | ULTRADRIL | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MUD BALANCE | Mud Weight | lb/Gal | 10,8485 | | | | | | 10,76505 | | | | | | 10,76505 | | |
| | Specific Gravity | - | 1,3 | | | | | | 1,29 | | | | | | 1,31 | | |
| FANN VG METER | TEMPERATURE | °F | 75 | 120 | 150 | 75 | 120 | 150 | 75 | 120 | 150 | 75 | 120 | 150 | 75 | 120 | 150 |
| | R600 | ϴ600 | 37 | 29 | 26 | 57 | 37 | 31 | 47 | 35 | 29 | 80 | 60 | 56 | 47 | 35 | 29 |
| | R300 | ϴ300 | 20 | 15 | 14 | 34 | 23 | 19 | 25 | 20 | 18 | 50 | 38 | 34 | 25 | 20 | 18 |
| | R200 | ϴ200 | 14 | 10 | 9 | 21 | 16 | 13 | 18 | 13 | 12 | 38 | 27 | 25 | 18 | 13 | 12 |
| | R100 | ϴ100 | 9 | 6 | 5 | 17 | 10 | 8 | 10 | 7 | 6 | 25 | 18 | 16 | 10 | 7 | 6 |
| | R6 | R6 | 3 | 1 | 1 | 8 | 3 | 3 | 3 | 2 | 1 | 10 | 7 | 6 | 3 | 2 | 1 |
| | R3 | R3 | 2 | 0,5 | 0,5 | 7 | 3 | 2 | 2 | 1 | 0,5 | 9 | 6 | 5 | 2 | 1 | 0,5 |
| | 10sec gel | | 4 | 2 | 2 | 11 | 6 | 5 | 4 | 2 | 2 | 13 | 7 | 6 | 4 | 2 | 2 |
| | 10min gel | | 5 | 3 | 3 | 18 | 7 | 6 | 5 | 3 | 3 | 17 | 9 | 8 | 5 | 3 | 3 |
| | Ap. Viscosity | cP | 18,5 | 14,5 | 13 | 28,5 | 18,5 | 15,5 | 23,5 | 17,5 | 14,5 | 40 | 30 | 28 | 23,5 | 17,5 | 14,5 |
| | Plastic Viscosity | cP | 17 | 14 | 12 | 23 | 14 | 12 | 22 | 15 | 11 | 30 | 22 | 22 | 22 | 15 | 11 |
| | Yield Point | lb/100ft² | 3 | 1 | 2 | 11 | 9 | 7 | 3 | 5 | 7 | 20 | 16 | 12 | 3 | 5 | 7 |

Table 11 - Rheological Characterization of Rheliant (MI SWACO database)

MI SWACO
A Schlumberger Company

| | | | Rheology – SBM | | | | |
|---|---|---|---|---|---|---|---|
| | | | RHELIANT | | | | |
| MUD BALANCE | Mud Weight | lb/Gal | 10,5147 | | | | |
| | Specific Gravity | | 1,26 | | | | |
| FANN VG METER | Temperature | °F | 35 | 40 | 80 | 120 | 150 |
| | Temperature | °C | 2 | 4 | 27 | 49 | 70 |
| | R600 | Θ600 | 165 | 154 | 93 | 65 | 53 |
| | R300 | Θ300 | 96 | 89 | 57 | 44 | 40 |
| | R200 | Θ200 | 69 | 65 | 44 | 35 | 34 |
| | R100 | Θ100 | 41 | 39 | 30 | 26 | 26 |
| | R6 | R6 | 11 | 1 | 12 | 13 | 12 |
| | R3 | R3 | 9 | 10 | 11 | 12 | 12 |
| | 10sec gel | | 11 | 12 | 14 | 14 | 13 |
| | 10min gel | | 20 | 21 | 23 | 20 | 15 |
| | Apparent Viscosity | cP | 82,5 | 77 | 46,5 | 32,5 | 26,5 |
| | Plastic Viscosity | cP | 69 | 65 | 36 | 21 | 13 |
| | Yield Point | lb/100ft$^2$ | 27 | 24 | 21 | 23 | 27 |

# 6. Results and Data Interpretation

## 6.1 Preliminary Results on Regular Drilling – Comparing Fluids Performance

In order to compare the fluids and have a preliminary idea of their performance, an evaluation considering only well hydraulics was conducted, without the introduction of the Continuous Circulation Drilling System. The fluids were compared by means of rheology, equivalent circulating density (ECD) and hole cleaning performance.

Figure 22 illustrates rheological behavior (plastic viscosity and yield point) of the tested fluids at different temperatures. Due to its higher water content, OIL70 showed bigger values of plastic viscosity and yield point than OIL80. It is important to point out that these values are lower than the actual values of rheology obtained on rig site, due to the fact that on laboratory it was not possible to simulate the shear effect provided by the bit, which increases yield point. The addition of HRP was intended to simulate this effect of shear, increasing yield point with little influence on viscosity, but yet, it is not as effective as the action of the bit itself, so YP values here presented are actually lower than those expected on rigsite. Water based fluid (Ultradril) intermediate values of plastic viscosity and high yield point. As expected, Rheliant fluid presented high values for plastic viscosity and yield point had minimal variation of YP with temperature increase, due to flat rheology technology.

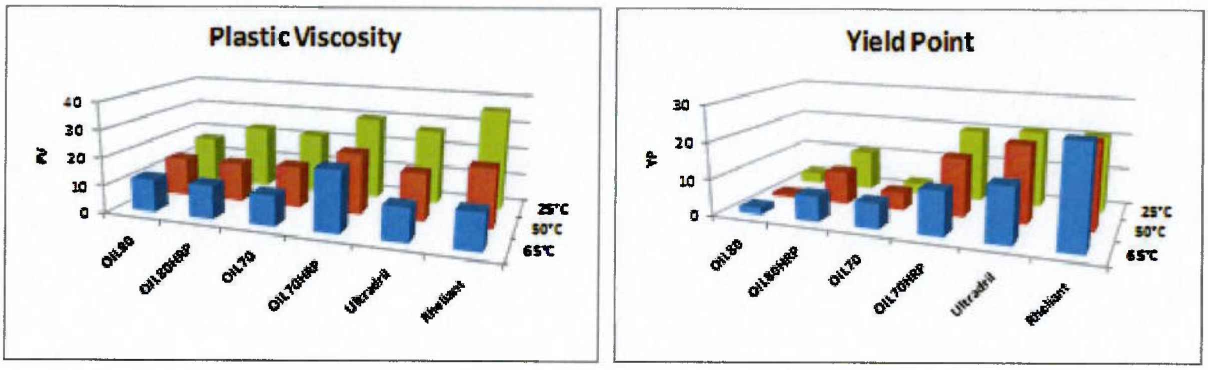



Figure 22 - Rheological behavior (Plastic Viscosity and Yield Point) of fluids on different temperatures

Concerning Equivalent Circulating Density, Virtual Hydraulics calculates this parameter by a complex mathematical algorithm based on Modified Power Law[2], a model used to describe rheology of fluids. Therefore, rheological behavior is intrinsically connected to ECD.

A graph illustrating ECD variation against depth can be observed on Figure 24. However, these results cannot be directly compared. The Equivalent Circulating Density is composed of two terms, the static head (hydraulic head) and the dynamic head (friction pressure), and can be written as illustrated on Equation 2:

$$ECD = \rho + \frac{P_{annulus}}{0{,}052 * TVD} \qquad (Eq.2)$$

[2] A brief description of Modified Power Law model is found at Apendix B

Where:

$\rho$ = mud weight (ppg)

$P_{annulus}$ = pressure drop on annulus (psi)

TVD = true vertical depth (ft)

Since the specific gravity of Rheliant fluid is 1,26 and other fluids 1,3, the static contribution on ECD for each fluid will be different. The comparison has, thus, to be done considering only the dynamic contribution, which is given by Equation 3.

$$Dynamic\ Contribution = \frac{P_{annulus}}{0{,}052 * TVD} = ECD - \rho \qquad (Eq. 3)$$

The variation of dynamic contribution on ECD versus depth is illustrated on Figure 25.

This dynamic contribution is highly influenced by rheological behavior of the fluid, so Rheliant is expected to present much higher values than other fluids. This figure indicates that Rheliant Dynamic contribution in ECD is indeed bigger than other fluids, however not as big as expected due to the effect of its higher rheology.

On vertical well, this effect is not very distinctive, but on deviated and horizontal wells it can be observed that the values of dynamic contribution for Rheliant and other fluids are very close. It should also be pointed out that some values of ECD for Rheliant are actually smaller than those for OIL80 and OIL70HRP fluids, despite the higher rheology of the first fluid.

These results may seem contradictory at first analysis but in fact, they illustrate the effect of the Flat Rheology properties: a fluid with higher rheology that provides minimal effect on ECD.

It is important to point out that on vertical well, the curve that illustrates ECD for Reliant is distant from the curves of ECD for other fluids, while on deviated and horizontal wells, Rheliant`s curves are much closer to the other fluids, indicating that the impact of use of flat rheology is much bigger on challenging wells, while on conventional wells, the know-how on oil and water based fluids are able to provide satisfactory drilling performance results.

Another interesting approach for well hydraulics evaluation, is the variation of ECD. For well control reasons, it is desired that ECD is kept as stable as possible, especially when drilling a formation with narrow window of pore and fracture pressures. The variation of ECD was evaluated by means of the standard deviation of this parameter while drilling for each fluid. The standard deviation gives an idea of how much variation ECD is subject to in each condition.

Figure 23 indicates that oil based muds tend to have bigger variations of ECD, while the Rheliant fluid has a smaller standard deviation, meaning that it succeeds in keeping ECD steadier. Such behavior is a result of its flat rheology properties, which provide the fluid with lower variation of rheology, compared to standard drilling fluids, even on a wide window of temperature and pressure. Ultradrill presented values of standard deviation just slightly bigger than those of Rheliant fluid. This happens because water base fluids have less influence of temperature and pressure on rheology than oil based fluids

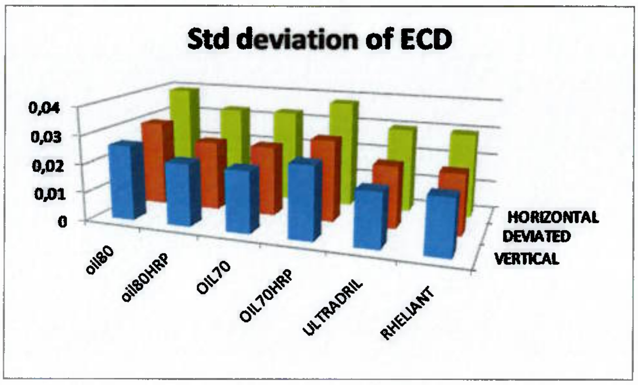



Figure 23 – Comparison of standard deviation of ECD for each fluid on the well profiles tested. The standard deviation gives an idea of how steady the ECD is kept along the well

Hole cleaning is also a good indicative of fluid performance on drilling. Virtual Hydraulics calculates this parameter by a complex mathematical model considering fluid and formation properties, rate of penetration and flow rate. The output given by the program is the Hole Cleaning Index (HCI). The lower the HCI, the better is the cleaning performance. These results are illustrated on Figure 26.

The vertical well does not provide good comparable data, as no harsh conditions are faced and hole cleaning tends to be reasonably good for all the fluids, depending mainly on flow rate.

However, differences are clearly identified on directional and horizontal parts of the wells, as illustrated on Figure 26. At these sections, a big increase in HCI is observed. Debris tend to settle at the bottom of pipe and solids transportation is hindered.

Rheology plays an important role on the hole cleaning performance. Viscosity and Yield Point are important parameters that influence the carrying capacity of solids. Therefore, Oil based muds with lower rheology, present lower cleaning performance, followed by Ultradril and Rheliant.

Besides Rheology, the fluid mud weight is also a key parameter for hole cleaning, as it helps buoy cuttings and slow down settling rates. It is important to point out that despite its lower mud weight (1,26, compared with 1,3 of the other fluids) the Rheliant fluid still manages to provide better hole cleaning.

Rate of Penetration is a key parameter for hole cleaning: the faster the formation is drilled, the more cuttings are produced, the harder it is to suspend them and flow them out of the well. The Cuttings Concentration is a useful parameter to indicate cuttings transportation and consequently, hole cleaning. It can be described by equation 3:

$$C_{conc} = \frac{1{,}667 * ROP * D_b^2}{(D_h^2 - D_{p)}^2 * (V_{annu} - V_{slip})} \qquad (Eq.3)$$

Where:

ROP = Rate of Penetration (ft/hr)

$D_b$= Bit diameter (in)

$D_h$= Hole diameter (in)

$D_p$= Pipe OD (in)

$V_{annu}$ = Annular velocity (ft/min)

$V_{slip}$ = Slip Velocity (ft/min)

Figure 27 shows represents a comparison of hole cleaning performance for different fluids at a rate of penetration of 10m/h.. Rheliant fluid was also tested under ROP of 15m/h. Once again, on vertical well, no distinctive results are observed, as the well cleaning is relatively satisfactory for all the fluids, depending more on flow rate,

On the other hand, on deviated and vertical well it is observed that at the same flow rate and rate of penetration, Rheliant fluid provides better hole cleaning.

Not only that, it can also be observed that for determined flow rates, Rheliant is able to perform at higher rate of penetration, and still provides better hole cleaning results. Besides the hole cleaning benefits, increase in ROP is highly desired as it means less time to reach the target depth (TD).

Considering the parameters evaluated: rheology, ECD and hole cleaning, flat rheology fluid presented a great performance while drilling, showing benefits over the oil based and high performance water based fluids tested. In terms of Equivalent Density, Rheliant is able to yield lower ECDs, with increased rheology, what contributes to enhanced hole cleaning. Due to its flat rheology properties, it is able to keep rheology almost constant in a wide range of pressure and temperature, what provides steadier ECD along the well, avoiding pressure spikes, which could cause damage on the well and hinder well control.

In face of all these indicators, it is expected that the combination of both technologies, Flat Rheology and Continuous Circulation Drilling System, will provide enhanced drilling performance.

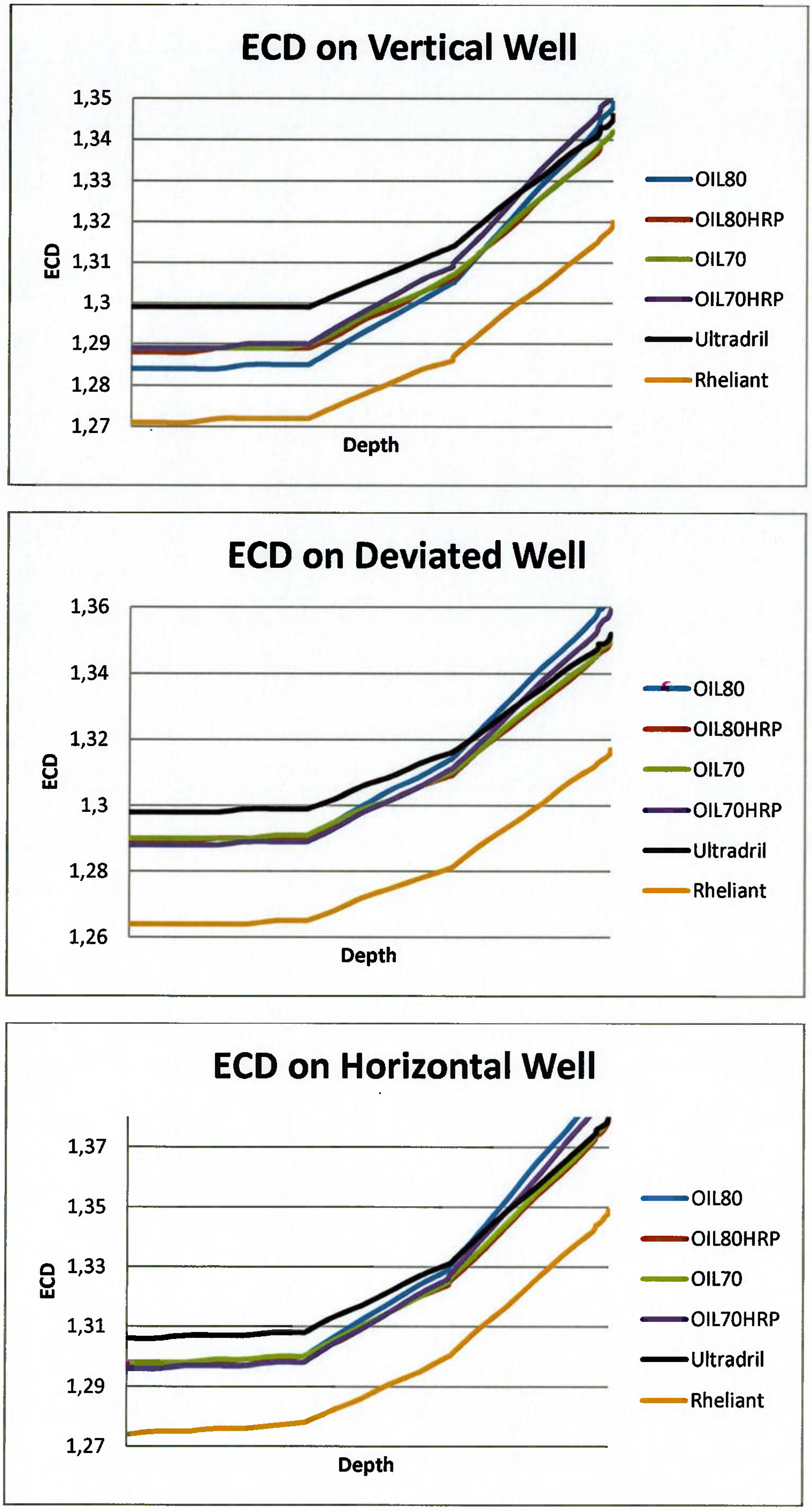



Figure 24 - Behavior of ECD along depth for the three well profiles tested

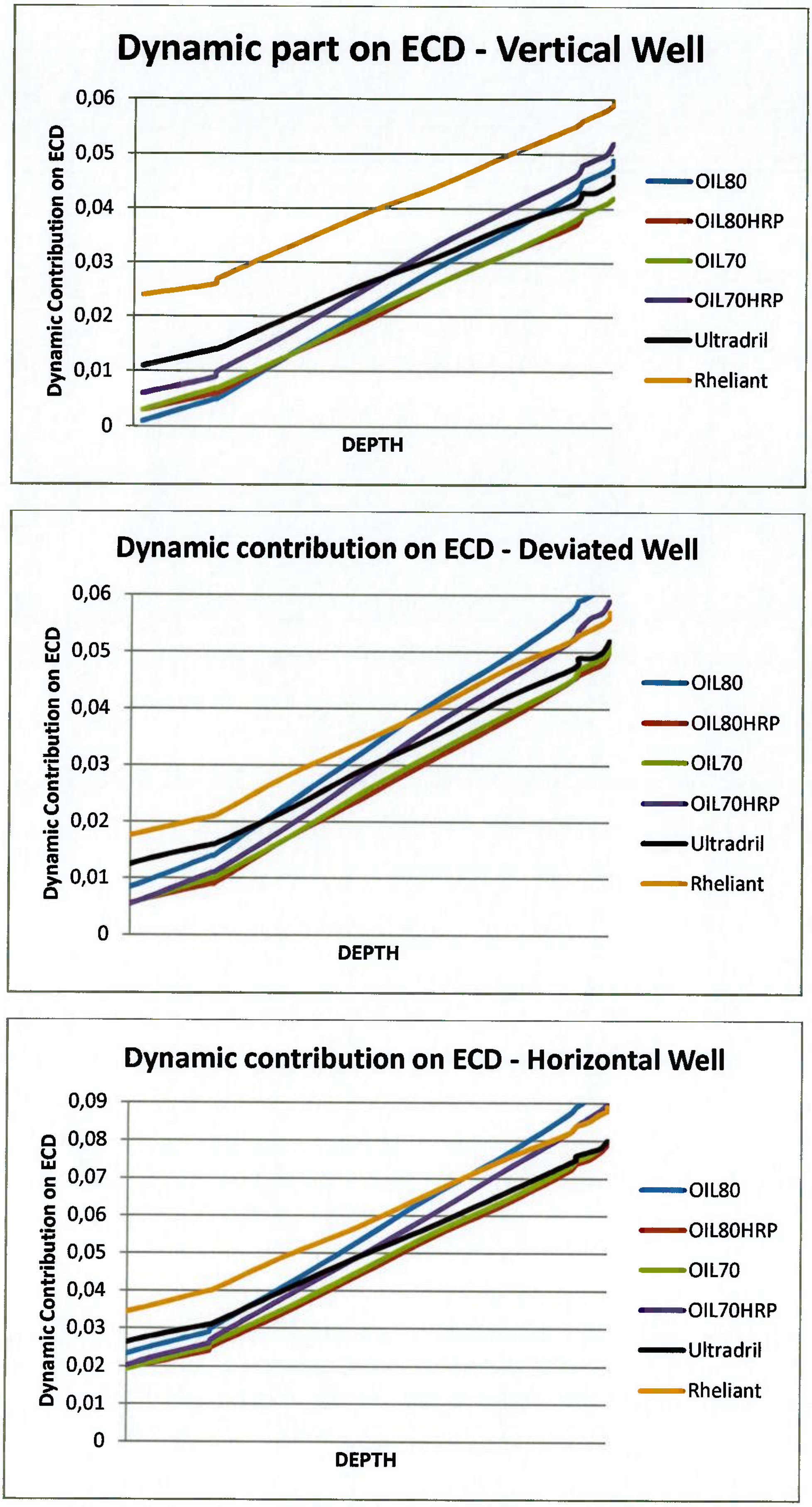



Figure 25 - Dynamic contribution of ECD for all three well profiles tested

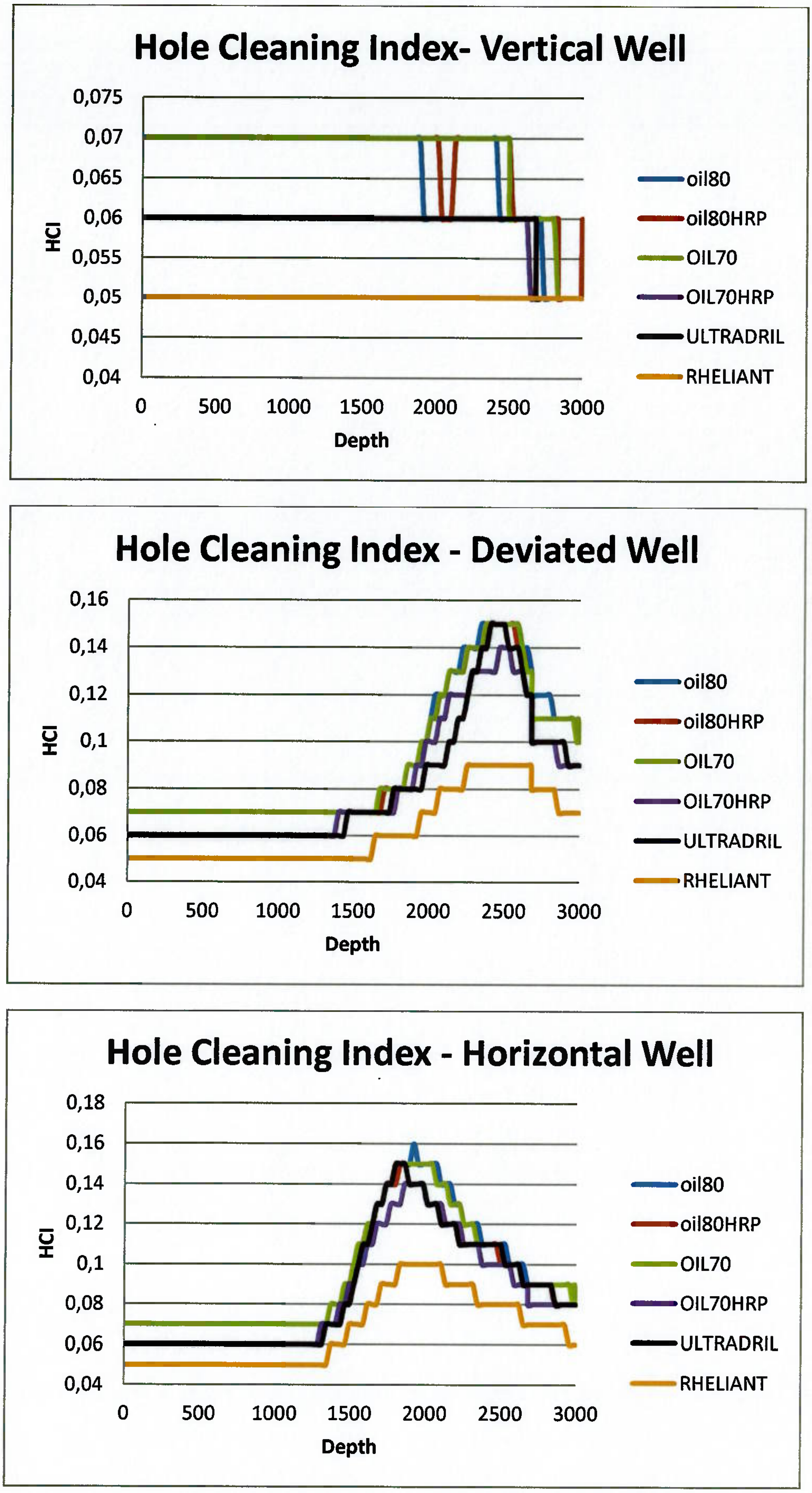
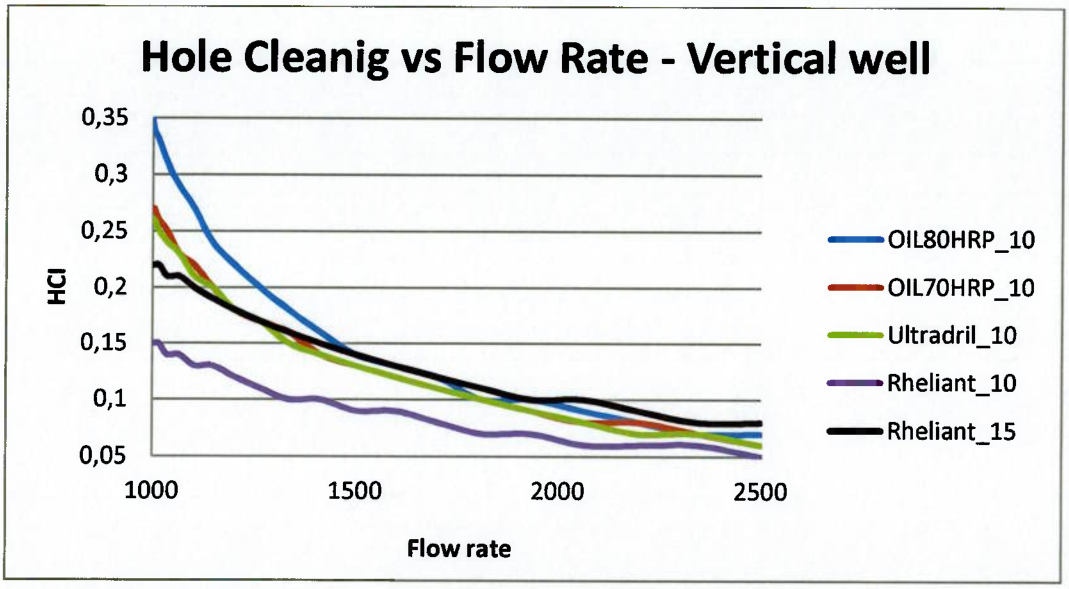
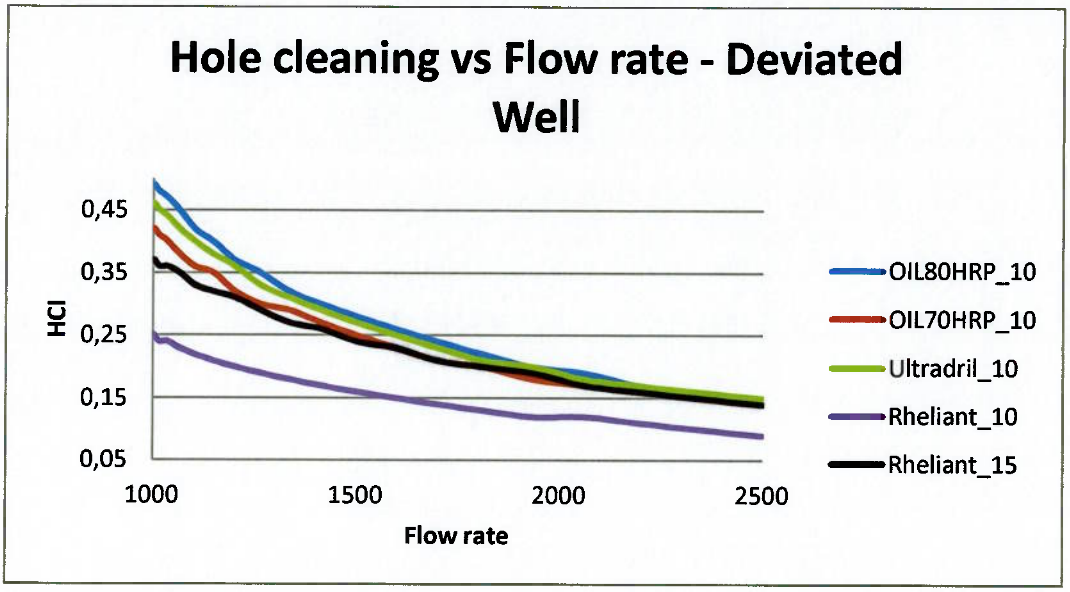



Figure 26 – Hole cleaning performance along depth on different well profiles



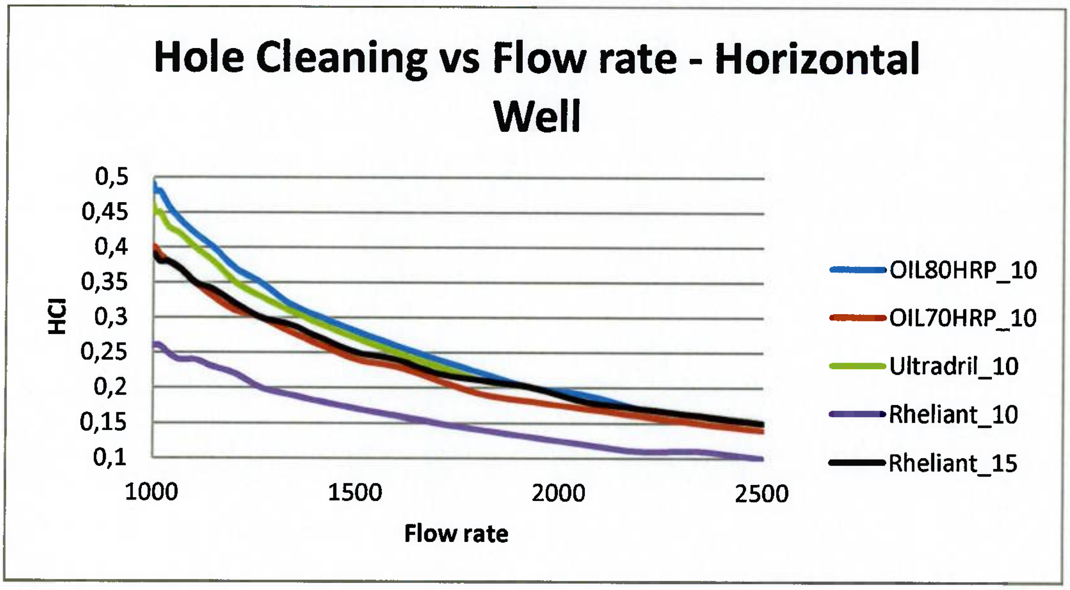




Figure 27 – Hole Cleaning Performance vs Flow rate at different rates of penetration for different well profiles

## 6.2 The Use of Flat Rheology with Eni Continuous Circulation Drilling

The performance of Flat Rheology fluid in combination with Eni Continuous Circulation Drilling was performed by ECD and hole cleaning analysis.

As in the previous section, ECD was compared, by means of Dynamic Contribution (to total ECD) since mud weight is not the same for all fluids. Figure 30 represents the variation of Dynamic Contribution while connections are being done. The first spike represents a connection performed with circulation stop, while the second spike represents a connection performed with continuous circulation.

Rheliant fluid provides lower Dynamic Contribution, despite its higher rheology. It can also be observed that on horizontal well, where drilling conditions are more severe, oil based fluids and water based fluid provide a considerably bigger dynamic contribution than on vertical and deviated wells, while, Rheliant fluid provides nearly the same Dynamic Contribution on the three profiles tested.

The most remarkable aspect of this figure, though, is the effect provided by the use of continuous circulation. As illustrated on Figure 30, the first spike (regular drilling) is much bigger than the second one (continuous circulation). ECD is composed by a hydraulic head part and a dynamic head part. When circulation is stopped, the dynamic part is zero, so a big reduction on ECD is observed. In contrast, on continuous drilling, dynamic part is always present, indicating that continuous drilling enables connections to be performed with reduced variation on ECD, contributing to well control and also enabling jobs on wells with narrow window between pore pressure and fracture pressure.

Figure 31 represents hole cleaning performance during connections. As previously done for ECD analysis, the first spike represents connection with circulation stop while the second spike represents connection without circulation stop.

It clearly shows the effectiveness of continuous drilling in terms of hole cleaning during connections. When circulation is stopped debris are likely to settle at the bottom of the well, increasing significantly the hole cleaning index, what is represented by a big spike on the graphic. In contrast, when connections are performed without circulation stop, solids are always being flown out of the well, resulting in better HCI.

The profile of a well has deep influence on its hole cleaning efficiency. As illustrated on Figure 28 vertical and near vertical wells are very easy to clean, as no cutting beds are formed. In contrast directional wells, cleaning difficulty is greatly increased. The sections with inclination angle varying from 30° to 60° are particularly difficult to clean, since cuttings beds can slide or slump opposite the direction of the flow, problem enhanced by particles settling. Sliding tendencies start dissipating at angles bigger than 60°, as observed on Figure 28, due to decrease in gravitational force vector

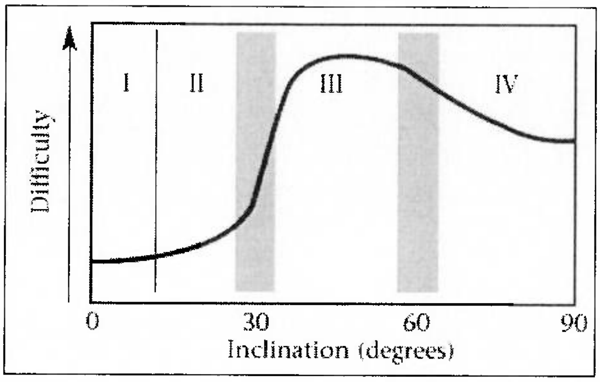



Figure 28 - Indication of difficulty on hole cleaning according to well inclination (M-I SWACO. 1998)

It is interesting to observe the effect of hole cleaning while using continuous drilling on the three well profiles considered. Although circulation is kept constant, rotation of the drill string is stopped in both situations when connections are being performed. On the vertical well, the effect of no drill pipes rotation is very small, and hole cleaning during connections is nearly as good as it was during drilling. HCI is kept nearly constant (no HCI spike is observed).

On the other hand, the effect of stop on drill pipes rotation is evident on deviated and horizontal wells, where solids tend to settle at the bottom of the pipe and without pipe rotation, they tend to accumulate (Figure 29), impairing hole cleaning performance.

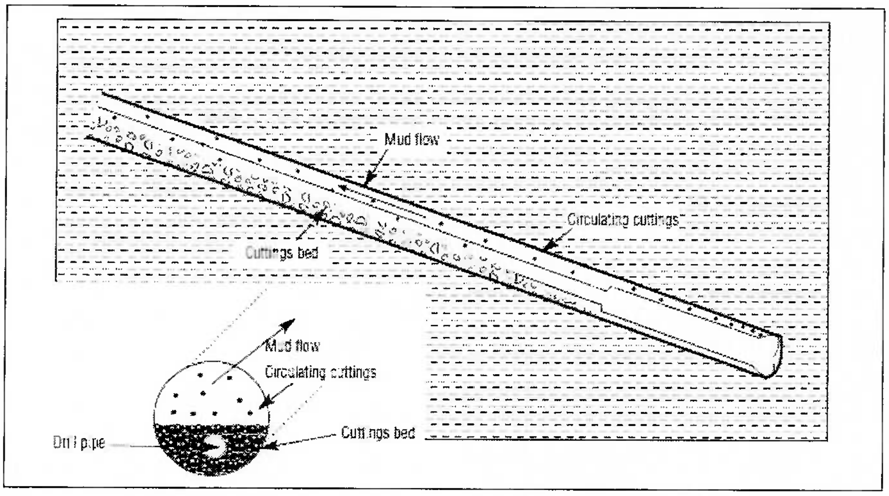



Figure 29 – Illustration of settling and accumulation of debris on deviated and horizontal sections (M-I SWACO. 1998)

The presented results highlight the effectiveness of combining the use of flat rheology and continuous drilling, specially on deviated and vertical wells, where harsh conditions are faced and a more rigid well control and improved hole cleaning conditions are required.

A final analysis compared Hole Cleaning performance of the fluids while using continuous circulation while performing connections. They are illustrated on Figure 32. It can be observed that drilling at a rate of penetration of 10m/h, Rheliant fluid had a significantly better performance than other fluids.

Not only that, it also outperforms other fluids at ROP=12m/h. At a higher drilling rate, the fluid still managed to provide a better well cleaning.

As pointed out before, the effect of hole cleaning on deviated and horizontal well is much higher than on vertical well.

Figure 33 gives a good visualization of the effect provided by the continuous circulation, flat rheology fluid and the combination of both technologies. It compares the hole cleaning performance during connection of different situations. Details of these situations can be found on Table 12.

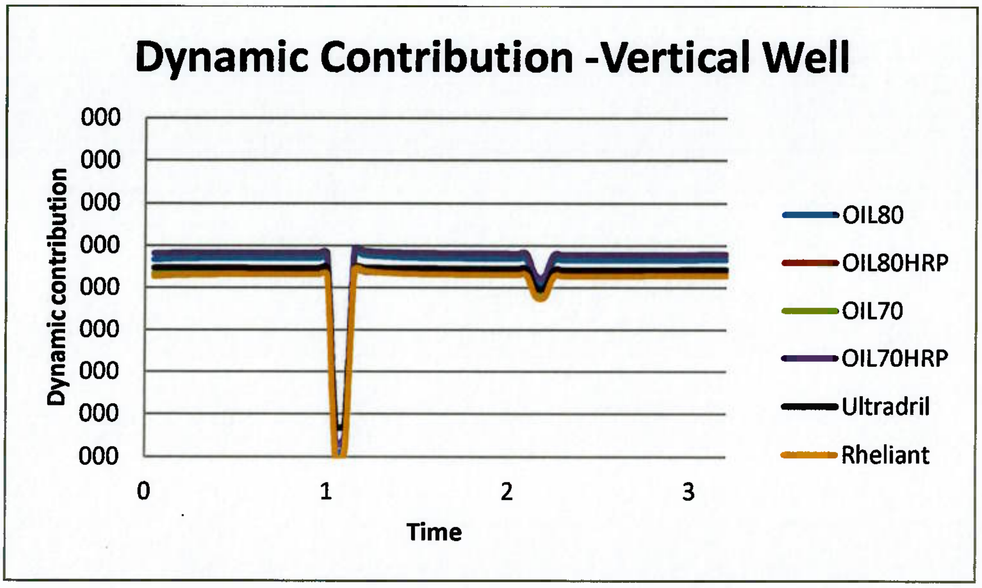
Table 12 - Details of situations tested in order to compare Rheliant fluid and continuous circulation drilling performance on Hole Cleaning at different rates of penetration (ROP)

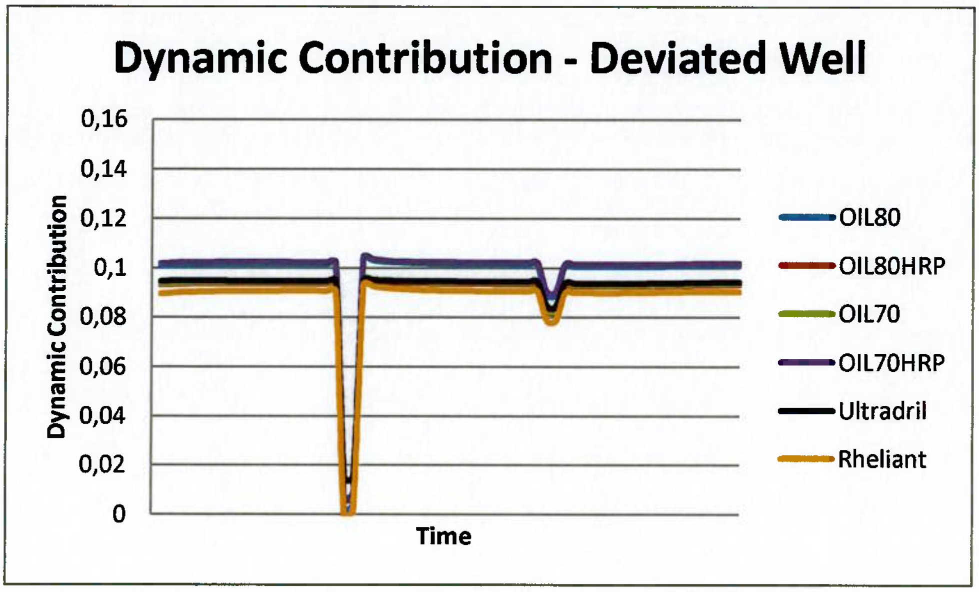
| | FLUID | DRILLING | ROP |
|---|---|---|---|
| 1 | OIL80HRP | Regular | 10 |
| 2 | OIL80HRP | Continuous | 10 |
| 3 | Rheliant | Continuous | 10 |
| 4 | Rheliant | Continuous | 12 |
| 5 | Rheliant | Continuous | 15 |

On Figure 33, Situations 1 and 2 indicate, under the same rate of penetration, and using a conventional oil based fluid, the effect of continuous circulation over regular drilling. Due to no interruption of mud flow, solids are not likely to settle at the bottom of the well, so continuous circulation drilling provides enhanced hole cleaning.

Situations 2 and 3 indicate, under the same rate of penetration and using continuous circulation drilling the effect of Rheliant. Due to its flat rheology technology, hole cleaning is significantly improved when compared to conventional oil based mud.

Situations 4 and 5 show Rheliant fluid performance under higher rates of penetration. An overview of the whole graphic (Figure 33) indicates that the combination of flat rheology and continuous circulation allows drilling at a higher rate of penetration with similar or improved hole cleaning performance.



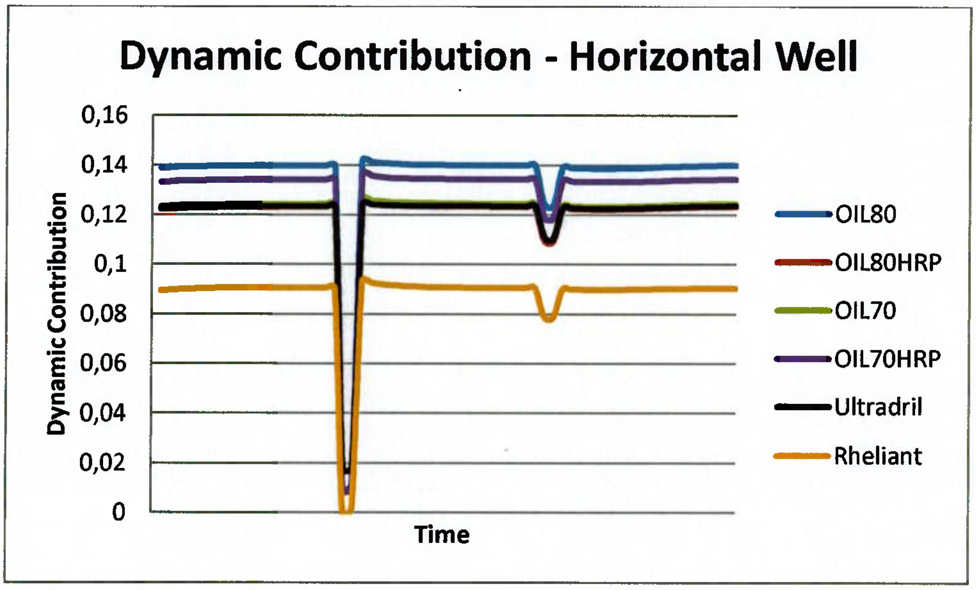




Figure 30 - Dynamic contribution on ECD during connections for all three well profiles

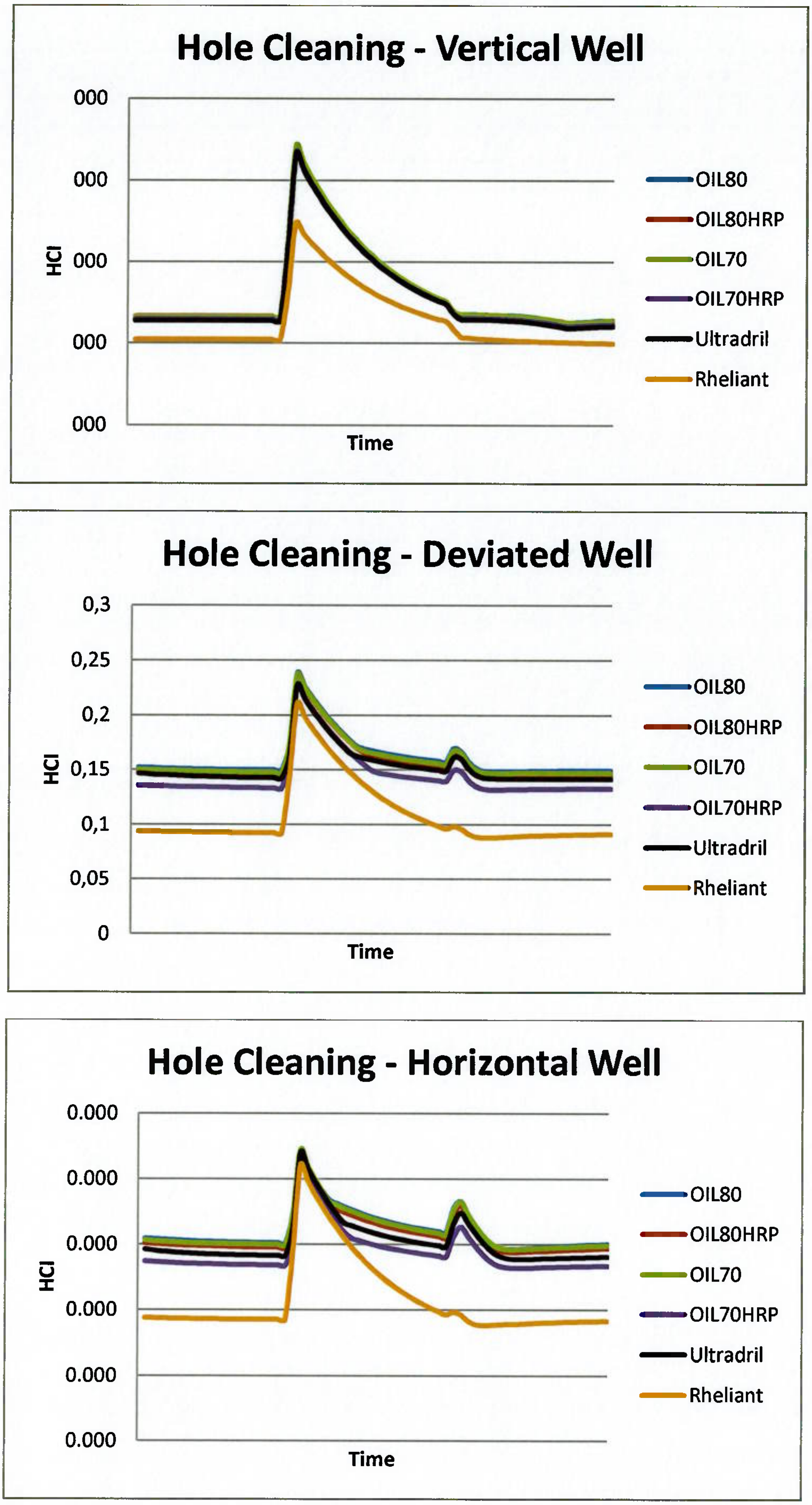



Figure 31 - Hole cleaning during conections for all three well profiles

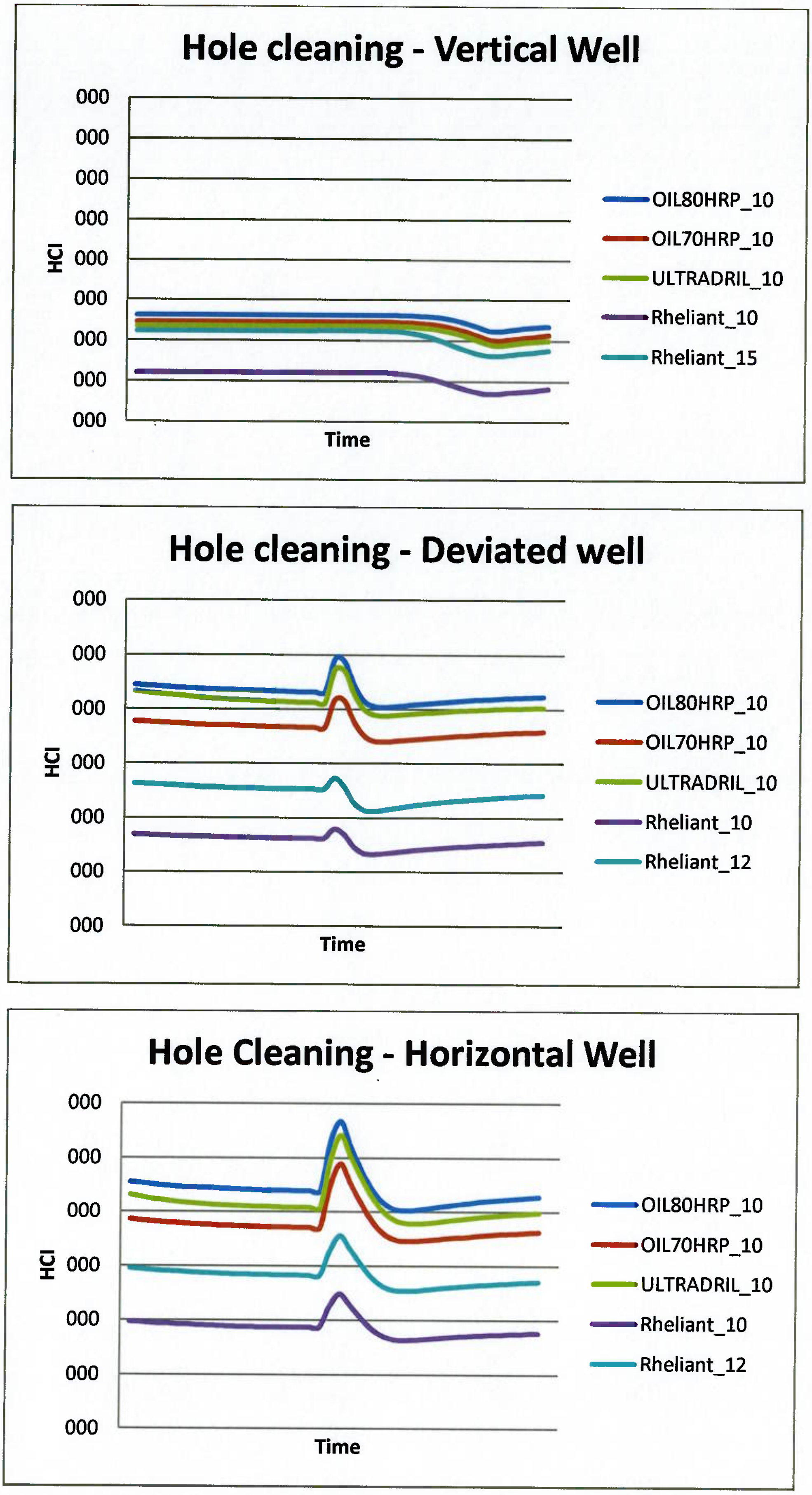



Figure 32 - Hole cleaning at different ROP (using continuous circulation)

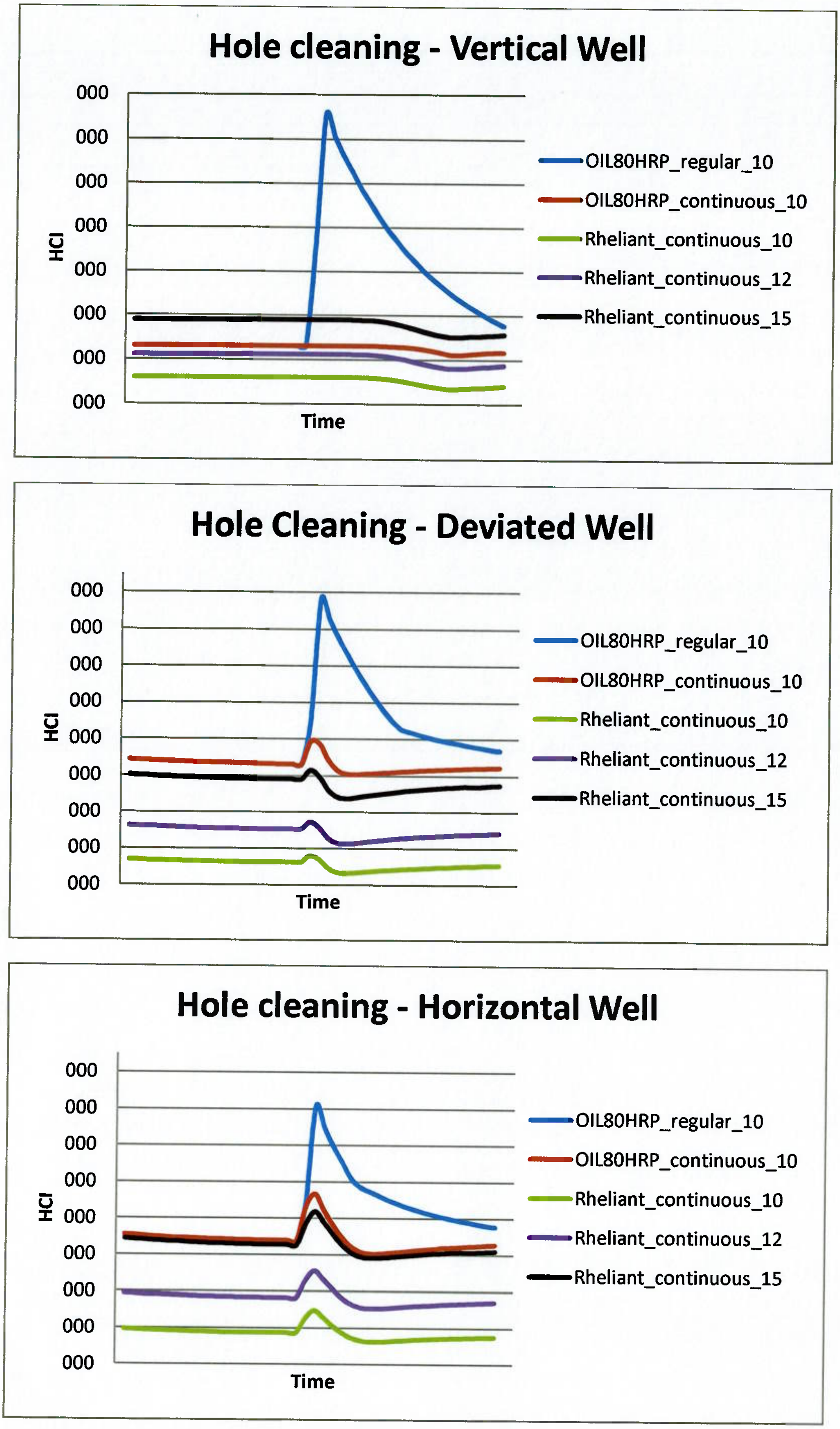



Figure 33 - Comparison of hole cleaning performance during connection

## 7. Considerations on fluid selection

As shown above, the use of flat rheology fluid combined with continuous circulation provided a good improve in drilling parameters: a better hole cleaning was observed with a steadier equivalent circulation density.

However, many parameters must also be taken into consideration when a fluid system is chosen. Environmental requirements, well depth, formation composition, location of the well, well geometry, range of formation pressure and financial issues cannot be taken for granted.

Water based mud is preferentially used on not challenging wells: shallow depths, wide range between pore pressure and fracture pressure, when no major complications are expected. In this conditions, water based fluid is enough to handle well control and provide good drilling performance. Besides, costs are much lower, since fluid base is water. Also, WBM are more environmental compliant. This is an important benefit, as environmental laws are becoming more and more restrictive, and treatment and disposal of water based fluid are less costly and much easier.

The major drawbacks of water base fluids are its likelihood to be contaminated and its reactiveness with formation. Any substance present in the well may contaminate water base mud, causing problems with the balance of additives of the fluid. When water based is used, fluid must be monitored constantly, in order to maintain a proper balance between additives required, ensuring its good performance.

Also, formation is more likely to react with water based fluids, particularly when shales and clays are present, jeopardizing well stability and well cleaning. Shales are prone to swell, causing stuck pipe and washout problems. Such problems can be greatly minimized by the use of high performance water based fluids, which provide an inhibition approach, avoiding both reaction with clays and dispersion of particles. In this situation, water based mud is able to perform nearly as a oil based mud, as it can be observed on Figure 26 presented on preliminary discussion of results.

Water based fluids are hence usually advised for drilling on shallow depths, where no harsh situations are to be faced.

In opposition, oil based fluids are less likely to suffer contamination and are not reactive with shales and clays, a providing better hole stability. Lower O/W ratios provide higher rheology, what improves hole cleaning, but increases ECD, so these parameters have to be carefully balanced so that fracture pressure is not exceeded. The biggest problem of oil based fluids is due to environmental issues. This type of fluid cannot be easily treated and disposed. Oil based fluids are widely used on both off-shore and land rigs, providing satisfactory results.

The harsher the environments drilled, the better performance is expected from the fluid system. Synthetic fluids are designed according to the difficulties and needs faced during operations. The flat rheology system was designed taking into consideration both the need of little ECD variation during drilling and the need of controlling rheology at different temperatures.

This project tried to show that the combination of flat rheology with continuous drilling is an effective alternative to improve drilling. As presented on the previous sections, the use of these technologies provided lower ECDs and better hole cleaning performance.

However, drilling fluid selection must take in consideration many parameters. As shown, when no harsh situations are faced, the vertical well, for example, the impact of the use of such technologies is very little compared to the investments required. Under these conditions, the drilling know-how accumulate is wide and performance of oil based and water based fluids are satisfactory enough.

New types of wells are now the biggest challenges: ultra deep-waters, complex well geometry (deviated and vertical wells), narrow window between pore pressure and fracture pressure. In these cases, traditional fluids do not have a satisfactory performance, and on such cases the use of flat rheology combined with continuous drilling figures as a powerful tool to overcome such challenges faced.

## 8. Conclusions

Flat rheology fluid presented outstanding results when used with Eni Continuous Circulation Drilling. The combination of technologies enhanced their benefits, providing a better hole cleaning and lower and steadier equivalent circulation density, what results in better well control and allows drilling on more challenging conditions.

ECD is benefited from both the continuous circulation (that allows little variation of this parameter during connections) and from flat rheology properties (that provide a fluid with high rheology properties, that vary very little in a wide range of pressure and temperature, providing minimal variation on ECD).

Hole cleaning was significantly improved due to higher rheology, that provide better carrying capacity of solids, combined with the benefits of continuous circulation, that prevents solids from settling on the bottom of the well.

A final analysis showed that due to its improved drilling parameters, the combination of continuous drilling with continuous circulation enables drilling to be conducted at a higher Rate of Penetration and providing better hole cleaning, when compared with other fluids,

The combination of these technologies is effective, and it has been shown that the improvements provided are much more significant on wells that exhibit a level of challenge. Drilling companies have a good know-how on drilling many lighter conditions such as land rigs and low depths wells, so the results provided by traditional fluid system are satisfactory enough. However, the big challenge now lies on overcoming challenges such as deep water, HTHP wells, narrow pressure window wells, extended reach wells and on those cases, the use of flat rheology on Eni continuous drilling presented remarkable performance, providing better well control and improved hole cleaning.

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# APPENDIX A

## 1. Characterization of the drilling fluid

It is of fundamental importance to monitor drilling fluids physical and chemical properties, as they are bounded to the fluid performance while drilling. The main physical properties of interest are density, viscosity, yield point and gel strength. The main equipments and experimental procedures used to perform tests are described below. They are all according to API standards.

### 1.1 Density and Specific Gravity

The density of a fluid is an important parameter, as it is one of main ways of well control. Density is defined as unit of mass divided by unit of unit of volume and is measured by means of weight and volume. The weight of mud can be expressed as hydrostatic pressure gradient in psi/1000ft of vertical depth, as density in lb/gal or lb/ft³ or as specific gravity (SG) - Equation 1:

$$SG = \frac{lb/gal}{8{,}345} = \frac{lb/ft^3}{62{,}3} = \frac{g}{cm^3} \qquad (Eq.1)$$

The equipment used to determine density and specific gravity is a mud balance (Figure 34). It consists on a graduated arm on a base. On one side of the arm there is a cup of known volume and on the other a counterweight, that can slide through the arm when weighting the mud. A mud sample has to be placed on the cup, making sure it is completely filled. The counter- weight has to be slide over the arm until equilibrium is reached. A "level bubble" placed on the arm helps indicating the correct measurement reading.

It is important to highlight that density might suffer small variations with temperature, so fluid temperature should be monitored for more accurate results.

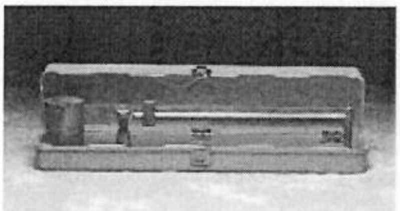

Figure 34 - Mud Balance (MI SWACO, 1998)

Occasionally, air bubbles may be trapped within the fluid placed in the balance's cup, what may lead to misreading of results. So, a variation of the mud balance enables the use of a device to pump the extra air out of the cup, and perform a more accurate reading.

### 1.2 Marsh funnel and vg meter

Both the Marsh Funnel and the VG meter are equipments used to evaluate Rheological parameters of fluids. The later provides more precise and quantitative results, while the first only provides an idea of the fluid rheology, with qualitative and comparative results.

The Marsh funnel is a simple equipment that comprises of a copper funnel with standard measures (as shown in Figure 35) – and a receiving cup with a level indication of 1-qt ( ~ 946 ml).

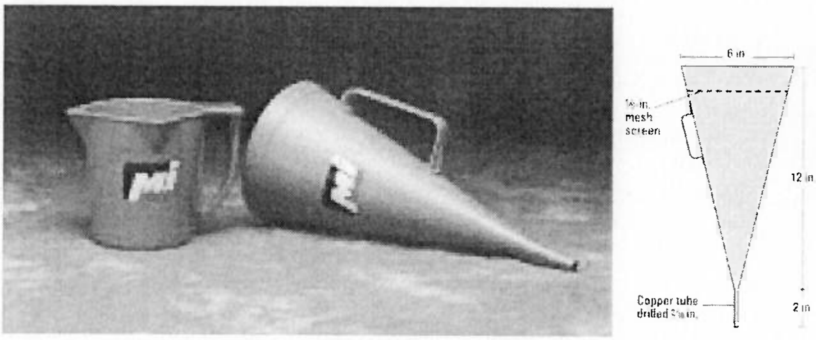


Figure 35 - Marsh Funnel (MI SWACO, 1998 / SCHLUMBERGER )

The test consists in covering the lower orifice of the funnel with a finger and pouring fresh fluid with the equipment in the upright position until it reaches the 1500ml mark. The amount of time required by the fluid to flow from the funnel orifice to fill the sampling cup is to be measured. The test provides an idea of the rheology of the fluid, specially when comparing different samples, but it does not provides actual values of plastic viscosity nor yield point. For this project rheology was only evaluated with results from the VG meter.

It is important to highlight that rheological parameters are temperature dependant, so that is a parameter that has to be cautiously monitored in order to avoid systematic errors.

On the other hand, the VG meter is an electric powered rotational viscometer (Figure 36). It´s operation consists in two concentric cylinders, and the fluid to be tested in their annular space. The outer cylinder is driven at constant rotation, producing a torque on the inner cylinder. A torsion spring restrains the movement of the bob, enabling a dial to register its displacement. The equipments constants are calibrated in such a way that plastic viscosity and yield point can be calculated by the readings when the cylinders velocity is at 600 and 300 RPM.

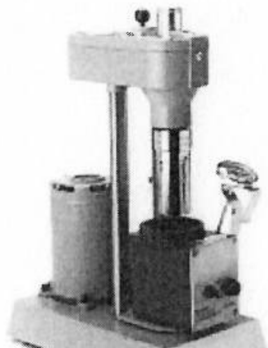

Figure 36 - Viscometer (MI SWACO, 1998)

The effective viscosity may be referred as apparent viscosity and is defined as the mud viscometer reading at 300 rpm ($\Theta_{300}$) or one half of the reading at 600 rpm ($\Theta_{600}$).. Figure 37 illustrates how rheological properties are calculated.

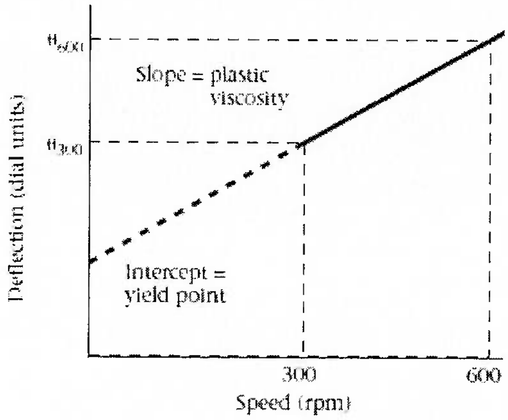


Figure 37 - Typical flow curve of a drilling mud (MI SWACO)

The Plastic Viscosity is defined as the part of the resistance to flow caused by mechanical friction and can be describe by equation 2:

$$PV = \Theta_{600} - \Theta_{300} \;\; [cP] \qquad (Eq. 2)$$

The main aspects that may affect the fluid's plastic viscosity are: solids concentration, size and shape; presence of long chain polymers; oil to water ratio and type of emulsifier added.

The Yield point is a measurement of attractiveness or electro-chemical interactions in the fluid. These forces are due to negative and positive charges located near the particle surface. It can be described by equation 3:

$$YP = 2\Theta_{300} - \Theta_{600} = \Theta_{300} - \mathrm{PV} \;\; [\mathrm{lb/100ft^2}] \qquad (\mathrm{Eq.}\, 3)$$

The main aspects that influence the Yield Point of a fluid are: surface properties of solids; volume and concentration of the solids; concentration and types of ions present on fluid phase.

To perform the rheology tests, a recipient has to be filled with mud sample and the bob is placed inside this recipient. The equipment has to be turned on and readings are to be made at 600rpm, 300rpm, 200rpm, 100rpm, 6rpm and 3rpm.

The gel strength represents the ability of a fluid to form a gel structure while static and become fluid again when shear is applied. Gel strength readings are made with a VG meter at 10-sec and 10-min intervals and in critical situations at 30-min intervals.

The main parameters that may influence the gel strength are amount and type of solids in suspension; time; temperature and chemical treatment (additives).

To acquire gel strength values, the equipment is put at 600rpm until its reading is stable. Equipment has to be turned off. After 10 seconds the equipment is turned on again and the maximum reading has to be registered as 10 second gel strength. For the 10 minute gel strength, procedures are the same, but the interval in which the equipment is off is 10 minutes.

For this project, the tests were conducted at 75°F (ambient temperature), 120°F and 150°F (the last two, being conduct with a recipient provide with heating system and a thermometer).

## 2. Bibliography

M-I SWACO. M-I Drilling Fluids Engineering Manual.Version 2.0 – 4/01 , 1998

SCHLUMBERGER, Schlumberger Oilfield Glossary. Available on http://www.glossary.oilfield.slb.com/Display.cfm?Term=Marsh%20funnel. Access on 1 April 2012

# APPENDIX B

## 1. Modified Power Law

A rheological model describes the relationship between shear stress and shear rate. The most common models used are Newtonian model , Bingham Plastic model, Power Law Model and Modified Power Law. This project used the later.

API standards uses the Power Law model as the standard one to description of rheological behavior of a fluid. However, it does not describe fully the behavior of drilling fluids, as it does not have a yield stress (stress required to initiate movement) and it underestimates low shear rate viscosity (LSRV), as illustrated on Figure 38.

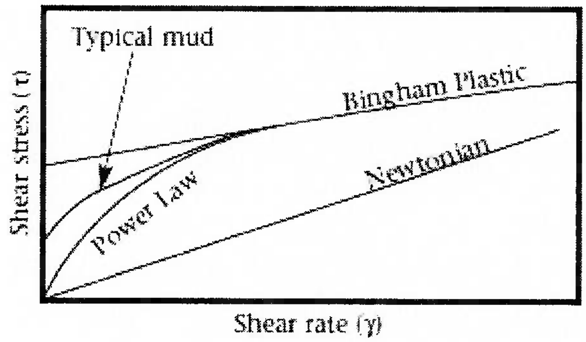


Figure 38 – Power Law Model cmparison (M-I SWACO, 1998)

Modified Power Law or Herschel-Bulkley model is an approach that accounts the yield stress in rheological behavior, and thus is able to provide a more approximate description of drilling fluids rheology. It envolves a complex mathematical model described below on Equation 1 and Equation 2:

$$\tau = \tau_0 + K\gamma^n \quad (Eq. 1)$$

Where:

$\tau$ = Shear stress

$\tau_0$ = Yield stress

K = Consistency Index

$\gamma$ = Shear rate

n = Power Law index

$$n = \frac{\log(\frac{\Theta_2 - \Theta_0}{\Theta_1 - \Theta_0})}{\log(\frac{\omega_2}{\omega_1})} \quad (Eq. 2)$$

Where:

n = Power Law index or exponent

K = Power Law consistency index or fluid index (dyne $sec^{-n}/cm^2$)

$\Theta_1$ = Mud viscometer reading at lower shear rate

$\Theta_2$ = Mud viscometer reading at higher shear rate

$\Theta_1$= Zero gel or 3rpm reading

$\omega_1$ = Mud viscometer (rpm) at lower shear rate

$\omega_2$ = Mud viscometer (rpm) at higher shear rate

Figure 39 and Figure 40 illustrates a comparison of behavior of Modified Power Law Mode

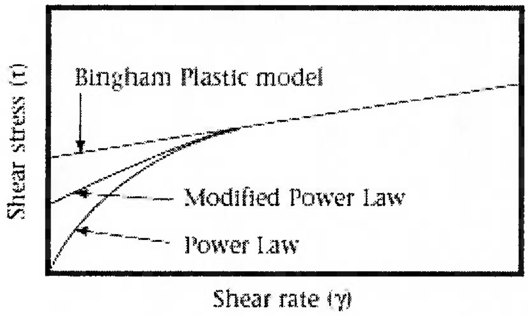


Figure 39 - Rheological Model Comaprison (MI SWACO, 1998)

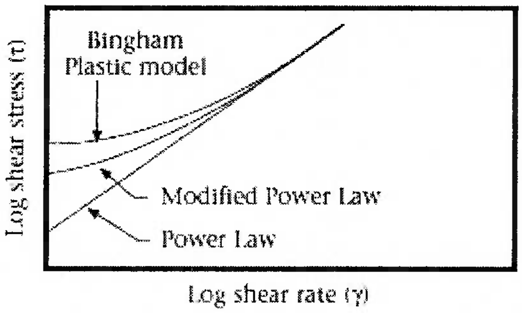


Figure 40 - Log plot rheological model comparison (MI SWACO. 1998)

## 2. Bibliography

M-I SWACO. M-I Drilling Fluids Engineering Manual.Version 2.0 – 4/01 , 1998