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Drilling Geological Hazards: Wellbore Stability, Total or Partial Loss of Drilling Fluids, Abnormal Pressures

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Εικόνα Εξωφύλλου:……………………………………

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Chapter 1: Introduction

Drilling operations for the exploration and production of hydrocarbons become more difficult and demanding as time passes. The increasing demand in energy resources that the whole world has, makes the exploitation of deeper resources and the research for new ones even more essential. The role of petroleum geologists and engineers is very significant for the achievement of this goal. Moreover, the constant demand for more environmental restrictions affects the drilling costs and therefore requires the development of environmentally friendly exploitation methods, which will also be affordable for the drilling operators. The purpose of this thesis is to highlight the importance of the drilling process and specifically the importance of the drilling mud in a drilling operation as well as the description and analysis of significant drilling problems that make operation more difficult and therefore they need to be well examined and solved.

What makes drilling such an important process when it comes to exploration and production of hydrocarbons, is that drilling is the only process that can identify precisely the existence of hydrocarbon reserves as well as their quantity. In general, when organizing a drilling program there are four basic domains in which geologists and engineers should focus on to succeed. These are the casing and perforation program, the drilling bit program, the drilling cost and the drilling fluid program. In this thesis, they will be presented some of the characteristics and challenges of the drilling fluid program.

This program determines the type of drilling fluid that best fits in a particular region, the mechanisms and equipment necessary for operation, and of course the detection of problems related to drilling fluids and their probable solutions. Drilling fluid or else drilling mud is essential for the drilling part as it can help in the avoidance of a lot of problems and without it the drilling costs would be non-affordable for the companies. The types, functions and characteristics of drilling fluids are also important for the selection of the appropriate, depending on the circumstances (geological formations, geographic position, tectonic conditions), mud.

The equipment needed in order not only to insert the mud into a well but also to clean it or create it is also described in this thesis and is an important task of the drilling program. The mud used in almost every operation circulates into the well and in this way, we can easily gain information about the conditions existing in the subsurface. Simultaneously, this mud circulation allows the drilling operators to clean the mud and then reintroduce the mud into the well, saving money which otherwise they would need to create the mud from the beginning.

However, drilling fluids are related to some drilling problems, as they interact with the drilled formations' fluids. The interaction depending on the formations drilled and the type and characteristics of the drilling mud can be hazardous or non-problematic, leading to a successful drilling program. These problems are very common, and a lot of research has been made to overcome them. Some of the most significant drilling problems connected to the drilling mud are; loss of circulation, shale instability and abnormal formation pressures.

These are the most frequent problems existing in almost every drilling operation in a smaller or greater extent, depending on the prediction and detection efficiency of the operators. However, as every problem, they can be overcome when the proper to every occasion solution is applied.

Chapter 2: Drilling Fluids

2.1. **Introduction**

Performing a successful and cost-effective oil well drilling can be a challenging and often difficult situation. A lot of factors need to be controlled and the role of geologists and engineers is significant to determine the as more appropriate as possible drilling program. The least cost-effected but simultaneously most important feature of a drilling program is the drilling fluid. The choice of the most suitable for each drilling case fluid is decisive for the better and on the budget development of a well. Thus, the decision of the composition and properties that the drilling fluids should have is a very important process that needs to be made based on numerous factors such as cost, environmental impact and technical performance [2].

The significance that these fluids have in an oil well is connected to the different functions that they perform during the exploration and production of hydrocarbons. In this chapter are presented all these features, highlighting the importance of drilling fluids in the oil industry.

2.2. **Composition of drilling fluids**

To drill the geological formations for oil or natural gas production it is essential to use the drilling mud. The liquid or continuous phase of this mud discriminates against the different drilling fluids. There are four basic categories of drilling fluids used in contemporary drilling companies: **water-based fluids (WBF)**, **oil-based fluids (OBF)**, **synthetic-based fluids (SBF)** and **pneumatic-drilling fluids (PDF)**. Each one has specific use as well as the advantages and disadvantages presented in the following table (Table 1).

<u>WATER-BASED FLUIDS</u>

They constitute 80% of drilling fluids used in oil wells[1]. Water-based muds contain freshwater or saltwater as the continuous phase and particles of minerals such as clays (mostly bentonite) or heavy minerals (mostly barite) suspended in it. The use of freshwater or seawater depends on the formations drilled or the condition of the hole. For example, to drill salt formations or to prevent shale instability, the best choice is the saltwater based fluid. It is less expensive than the other types of fluids but is less efficient in drilling shales due to the reaction of clays to water.

[1]Spears & Associates, 2004

OIL-BASED FLUIDS

In the 1960s oil-based muds were developed to deal with the shale instability created by the water-based muds. In these fluids, oil is the continuous phase in which particles of minerals such as clays are suspended, like the first category. This type of mud is environmentally unfriendly and needs to be cleaned before its or cuttings' deposition in shores, increasing the cost for offshores companies.

SYNTHETIC-BASED FLUIDS

These fluids were developed in the 1980s to provide a solution to the environmental impact of oil-based muds. Their components are either synthetic hydrocarbons or esters. They are more effective in offshore drilling and although they are more expensive, they have some important advantages: best for the environment fluid base, higher penetration rates and less mud-related nonproductive time [2], which makes them suitable for deep-water wells.

PNEUMATIC-DRILLING FLUIDS

This type of fluids has this particularity: Compressed air or gas id used to export the cuttings from a well using specific equipment. These fluids have some important advantages such as a high penetration rate in hard rocks, almost none damage to the formations and prevention of loss circulation [2].

[2]www.petrowiki.spe.org

	WBF	OBF	SBF	PDF
ADVANTAGES	· Cheap Fluid	· Shale inhibition	· Reduced environmental impact	· High penetration rate in hard rocks
	· Reduced environmental impact		· Suitable for offshore drilling	· None damage to formations
	· Most common			· Reduced environmental impact
DISADVANTAGES	· Shale instability	· Environmental impact	· Expensive	· Specific equipment
		· Expensive		
		· Reduced offshore use		

Table 1: Advantages and disadvantages of the different drilling fluids.

2.3. **Functions of the drilling fluids**

The importance of the drilling mud is reflected by the functions that it achieves, which facilitate the drilling process and can make it successful. No matter what type of drilling fluids are used in a well, they all have similar results regarding the functions that they accomplish. Some of these functions are presented and analyzed below.

1) Removal of cuttings

This is the most important function of the drilling mud. During the drilling process, the drilling bit crushes the rocks and leaves in the drilled surface some remnants of the rock, the cuttings. These remnants need to be removed to let the bit continue its crushing. The mud helps the system, transferring these cuttings to the surface, where they are being separated and examined. How does the mud exactly help this process? By transmitting the needed hydraulic energy from the surface to the rock surface[3]and by the appearance of bentonite. Bentonite has lower specific gravity and greater viscosity than water and as mud constantly circulates in the drill string, it can transfer these cuttings to surface[4]. For this process the mud needs to have the right chemical composition to keep the cuttings in suspension and prevent their dispersion.

2) Cooling and lubrication

As the drilling of formations continues, the constant rotation of the drill string as well as the crushing of the rocks from the bit increases the temperature existing in the well because of the friction development. However, the circulation of the mud helps to decline this friction not only between the drillstring and the sides of the hole, as it circulates through the annulus, but also between the bit and the formation’s surface. This friction reduction also cools the bit and the drillstring. Thus, the mud is used as a lubricant to decline the friction development and as a sequent the temperature increase.

[3]Skalle P., 2011
[4]Γεωργακόπουλος,

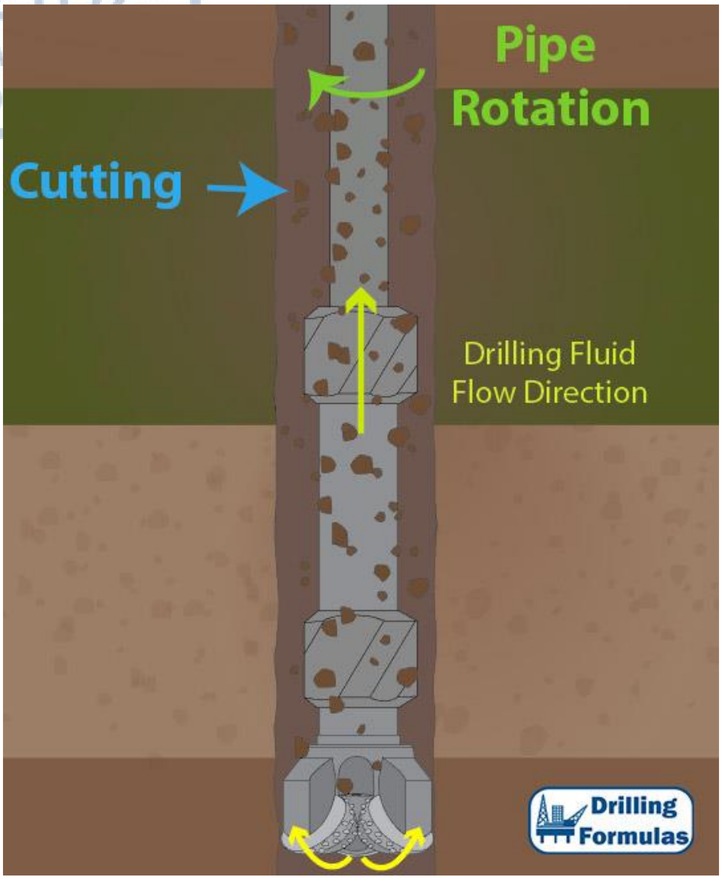

Figure 2.1*:* Cuttings removal (source: www.DrillingFormulas.com).

3) <u>Prevent fluid influx</u>

The drilling mud as a fluid with a relatively high density can exert hydrostatic pressure on the wellbore. This hydrostatic pressure needs to be at least equal or higher than the formation pressure of the drilled rocks to prevent the influx of the formation fluids. However, attention needs to be paid on the density of the drilling mud because on the one hand high densities could break the formations drilled down but on the other hand low densities could allow the influx of fluids. Thus, the drilling program needs to determine the appropriate density of the mud.

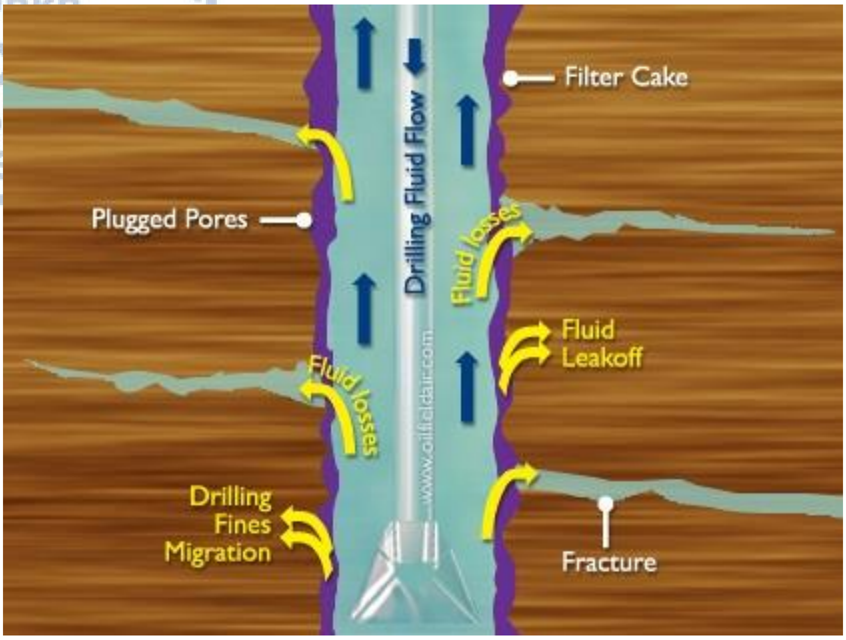

Figure 1.2: Hydrostatic and Formation Pressure (source: www.DrillingFormulas.com).

4) Preserves borehole stability

The aforementioned hydrostatic pressure exerted from the drilling mud to the sides of the wellbore has another function during the drilling process. This function is to keep the borehole stable by preventing any hole collapse or shale destabilization by creating a mud filter cake.[2] This cake is a layer of solids covering the sides of the well and not only closes any fractures or discontinuities of the drilled formations but also prevents any fluid loss from and to a permeable formation. This mud cake also keeps the well stable until cementing and casing installation, which is very important because in this way electric logs can be performed and provide information about the formations.

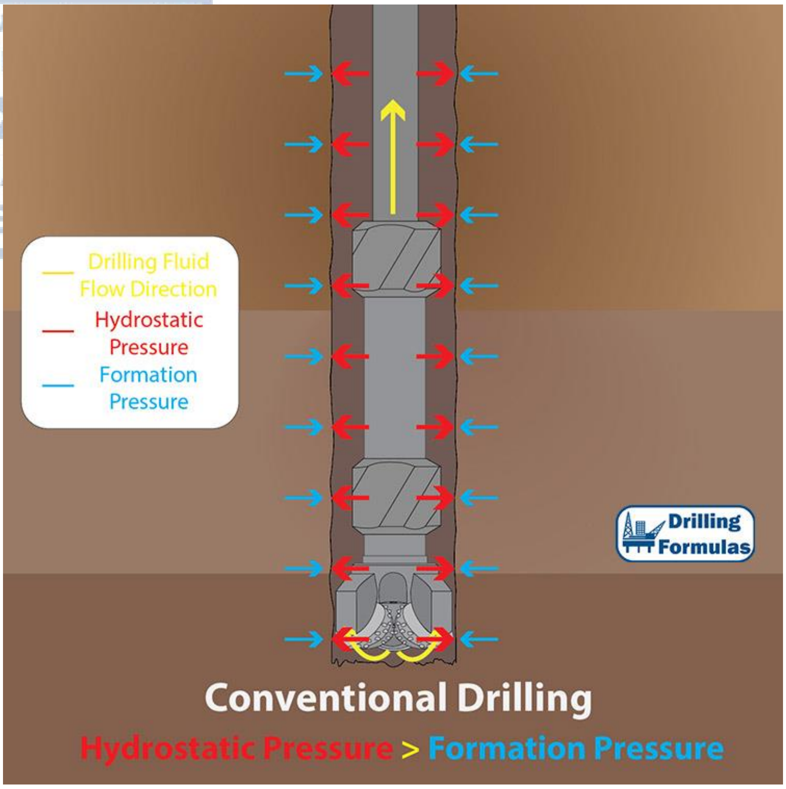

Figure 2.2: Mud filter cake (source: www.oilfield.com).

5) <u>Provides information about the wellbore</u>

The circulation of the mud is responsible for the cuttings' transfer into the surface and the only way to have some information about the drilled formations without coring. However, even when cores are needed to be taken, the mud makes easier the drilling and is essential for a lot of drilling techniques. Moreover, the changes that this mud may have regarding its properties when it returns to the surface are an indicator of the conditions existed in the well. Thus, the properties of the mud need to be checked before its addition to the well and after its return to the surface.

6) <u>Transmission of energy</u>

The mud is a combination of solids and fluids. The fluid of the mud can store the hydraulic energy and then, due to the circulation of the mud, to transfer it to the drill bit. In this way, it also transmits the necessary energy to the downhole motor in the case of directional or diamond-bit drilling.

7) Keeping in suspension

The mud can keep the cuttings and other solids in suspension even when the circulation stops. As a result, once the cuttings are moved from the bottom of the wellbore by the mud, they do not scale it again even if the drilling stops for some reason. Bentonite or other clays that are dispersed into the mud are responsible for this function, as they increase the viscosity of the flu

2.4. **Physical and chemical properties of the mud** [5]

- Physical Properties

I. Density

Density or else API Gravity is a very important property of the mud and is defined as weight per unit volume (kg/m^3). Density needs to be within specific limits to form some functions in the drill string such as exerting the appropriate pressure to the sides of the well or forming the filter cake, without however cause any damage or fracture to the drilled formation. To form these functions, the mud needs to exceed the pore pressure (formation pressure) by at least 200psi[6]. Laboratory testing is used to predict or estimate the density values, such as a mud balance. Thus, the control of the density value is an important factor for the efficiency of the drilling process and can be increased or decreased during the drilling operation depending upon the existed conditions and formations.

II. Critical velocity

Critical velocity is a property that defines the transition from a laminar to a turbulent flow. The more this velocity increases, the more the flow becomes turbulent and there is the danger of the wellbore erosion. Although this value must maintain low, there is a limit under which cuttings could not be efficiently removed, so it is important not to exceed it. The value of the velocity is mainly estimated by checking it around the *drill collar**, as it is the most constricted annular space in the drill string. Moreover, Critical Velocity is expressed by the Reynolds number, a dimensionless quantity used to help predict flow patterns. The Reynolds number lies between 2000 and 3000 for most drilling muds[7]. This velocity can be decreased when density increases or viscosity decreases.

**Drill collar*: A component that provides weight on the bit to equalize the weight of the drillstring.

[5] Oilfield Review
[6] H.C.H. Darley-George R. Gray, 1980

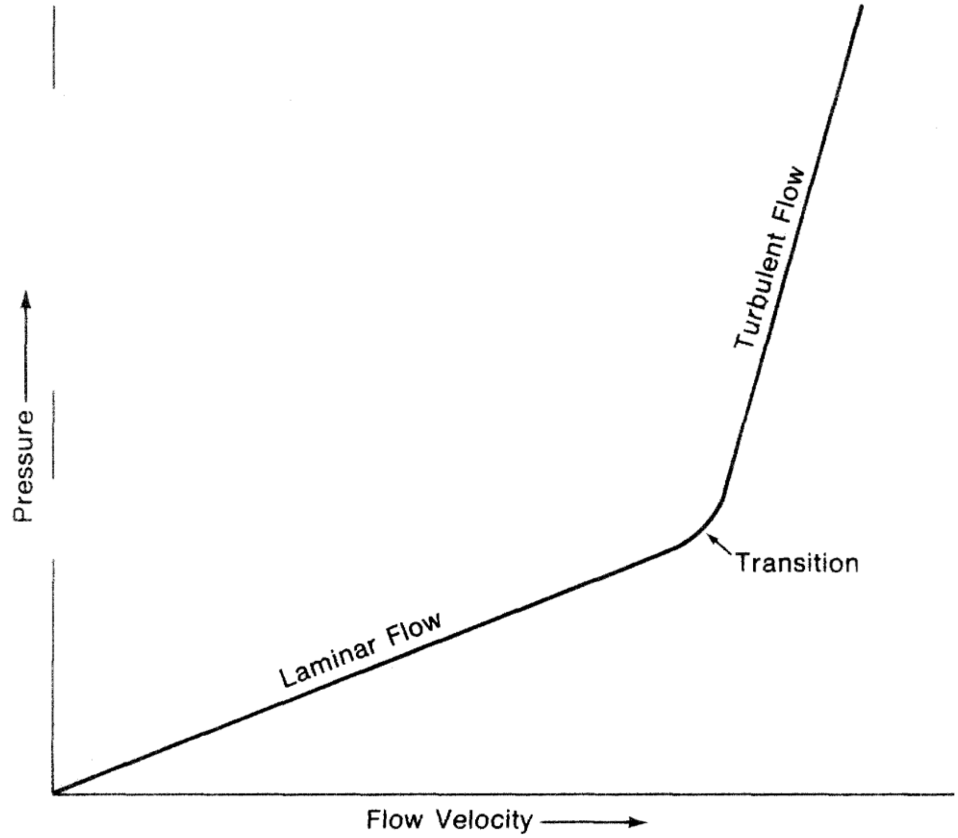

Figure 2.3: Transition from laminar to turbulent flow (source: H.C.H Darley-George R. Gray,1980).

III. <u>Viscosity</u>

Viscosity is the property of fluids that help them provide resistance to a deforming force. When it comes to a drilling operation, this deforming force is mainly shear. This is a property that also needs to be constantly controlled during a drilling operation due to its important role. The main role of it is to help the mud keep the cuttings in suspension and then transfer them into the surface. Thus, the right removal of the cuttings depends on the value of the viscosity. Bentonite or other clays are added to the mud to increase its viscosity and manage to complete its most important task; the cuttings' removal.

- Chemical Properties
    - PH

Keeping the PH between specific limits is a very important factor not only for the well but also for the equipment protection. Corrosion is a situation that needs caution because most of the drilling equipment is made of steel and so a low PH of the mud could affect it. A PH between 9 and 10 is the best option to keep corrosion in acceptable limits. Moreover, these PH limits are appropriate to avoid any non-desirable reaction between the mud and shales or the affection of polymers or other additives that control the viscosity and other conditions.

Chapter 3: Mud Circulating System

In the early 1900s Anthony Lucas discovered the connection between rotary drilling and the constant circulation of mud. It was then when the mud circulation started to be used and people understood the helpfulness of this fluid to the drilling process. When mud circulates in the drill string forms all these functions that were previously presented, which would not be possible to be developed otherwise. The most important functions of this system are the cuttings transfer into the surface, their separation from the mud, and most significantly the mud cleaning. As it is obvious all these tasks could not be completed if there was not the appropriate equipment. Thus, in this chapter are going to be presented not only the aforementioned functions but also the components helping the efficiency of this system.

3.1. Circulating system's components

a. Mud Pits

Mud pits are the first step for the creation of the mud. They are used for the preparation and mix of the mud components (a fluid base and bentonite) so that they can form a continuous phase. In mud pits is also determined the mud weight, a very important property that needs to be observed during the circulation by the mud loggers. After its return from the drill string and its cleaning, mud returns either to mud pits or to mud tanks, ready to "travel" again into the drill string.

b. Mud Pumps (pumps, standpipe, rotary hose)

The next step is for the pumps to draw the mud from the mud pits or tanks and using pistons channel it through a vertical pipe, the standpipe, into a very flexible pipe, the rotary hose, which is connected to the drill string.

c. Drill string

The rotary hose is connected to the swivel, a rotating power supplier, which is connected to a pipe called Kelly. Kelly is connected to a rotary table, which helps it rotate. Drill pipes are connected to the Kelly and in this way, a double purpose is succeeding: the rotation of the drill string and the insert of the mud into the well. Thus, the under-pressure mud circulates through these pipes until it reaches the drill bit.

d. <u>Drill bit</u>

Drill bits are connected to the overlying drill string and channel the mud through their nozzles, which are reduced diameter holes. In this way, the mud reaches the drilled formation and helps the removal of cutting underneath the bit

e. <u>Annulus</u>

The final step includes the circulation of mud and cuttings through the annulus and their transmission into the mud cleaning system, which is also a part of the circulating system, but it is going to be separately described in the following subchapter.

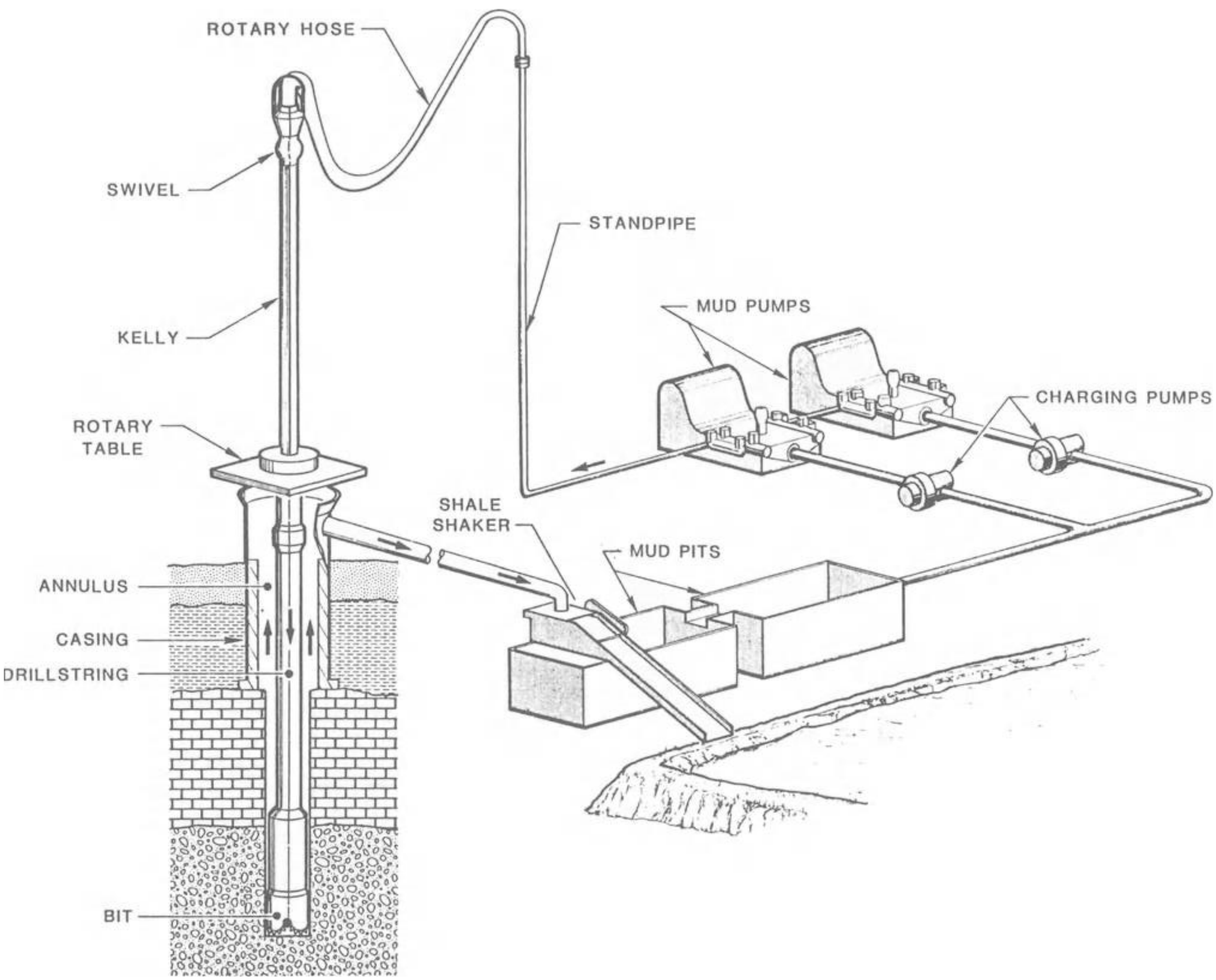

Figure 3.1: The rig circulating system (source: EXLOG Staff, 1985).

3.2. Mud Cleaning

One of the most significant developments in the oil industry was the understanding of the importance of a "clean" mud. What makes a mud "clean" in the oil industry is the solids' removal. Mostly two types of solids are circulating into the drilling mud; bentonite which increases viscosity and barite which increases the weight of the mud. Bentonite's particles are found in sizes up to 10μm while barite ranges from 5 to 80 μm. Simultaneously, after the circulation of mud, cuttings formed by the drilling process are also a part of the mud's solids. The mud cleaning equipment must have the following main goals; the first one is to remove all the cuttings, so that the drilling process constantly continues, and deposit them bearing in mind all the necessary environmental conditions. The second one is to remove a quantity of bentonite so that it does not form a very thick filter cake in the well which will lead to a stuck pipe problem. At the same time, barite needs to be as much as possible maintained into the mud because it is expensive and colloidal material has to be enough so that viscosity stays steady).[5] The mud cleaning equipment used in oil industries generally includes four main parts; shale shakers, degassers, hydrocyclones, and centrifuges, each described in the following subchapters.

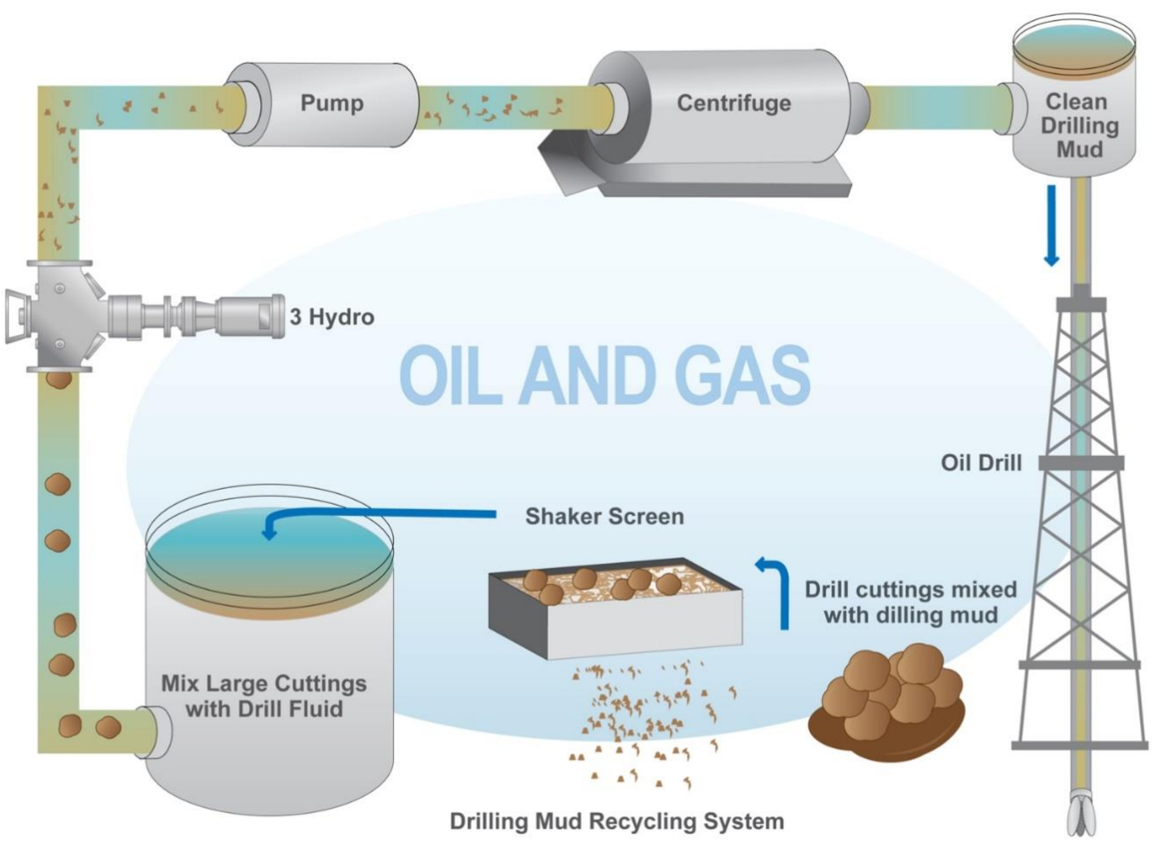

Figure 3.2: Mud cleaning equipment (source: www.jwce.com)

3.2.1. Shale Shakers [7]

Shale shakers are vibrating devices, used in drilling operations to discharge undesirable solids from the mud, which has returned to the surface after its circulation in the well. Shale shakers are the first and most significant part of the mud cleaning equipment as they can discharge the coarsest particles. Thus, they are the first devices, mud passes through until gradually continues to the other devices, which discharge finer particles.

The solids' removal, as has been previously mentioned, is a very important process and especially the role of the shale shakers for the following reasons: in most cases (when used correctly) they are cost-effective, they are easy to use and they prevent a lot of well problems as they remove the largest particles of the mud. (pdf 2)

Shale shakers have a double purpose in the mud cleaning operation; the first one is to remove as many solids as possible and the second one is to remove as little fluid as possible. To succeed in these purposes, shale shakers are vibrating and use screens.

The size of the screen is dependent on the geological conditions of the drilled region as well as on drilling conditions, e.g. circulation rate, drilling fluid properties. Depending on the screen size, larger particles than the screen's size remain on the screen, while the mud with the finer now particles passes through it and continues flowing to the next part of the cleaning equipment. The finest screen-mesh stops particles with 74μm diameter because every particle larger than 74μm is extremely undesirable and is likely to cause well problems. [5]

The vibration of the shakers is the mechanism that helps the separation between particles that are larger than the screen and the fluid that contains the finer ones. There are different types of vibration such as circular and linear. However, every type of vibration has two basic principles; the upward and downward motion. The upward motion of the shaker helps the fluid to pass through the screen while the downward motion helps solids move forward toward the collection pan.

Those cuttings collected by the pan, need to be deposited with safety in specific tanks. At the same time, the fluid and solids, passed through the screens need to continue their route into the cleaning equipment until finer solids' removal.

[7] American Society of Mechanical Engineers (ASME), 2005

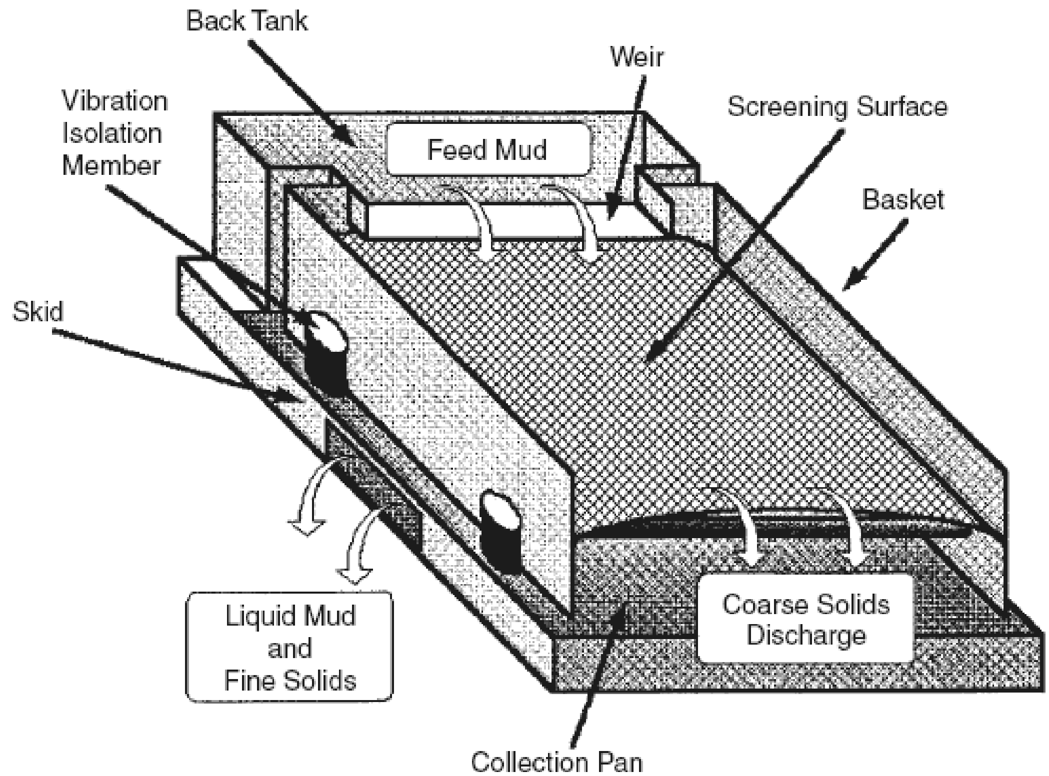

Figure 3.3: Shale Shaker's Mechanism (source: Society of Mechanical Engineers, 2005).

3.2.2. Degassers[8]

As the mud continues its circulation into the mud cleaning system, it passes through the degasser. The degasser is a device that removes the entrained hydrocarbon gasses (e.g. methane) that the mud contains after its circulation in a well. The hydrostatic pressure reduces as the mud reaches the surface and as a result the gasses expand and may form bubbles, affecting the accuracy and performance of the whole equipment.

It is essential that degassers are installed after the shale shakers and before mud enters the centrifugal pumps, as they are not able to discern gas bubbles from a viscous fluid and gasses could reduce their efficiency. The role of the degassers is very significant because otherwise, these gasses can make the pump operations unstable.

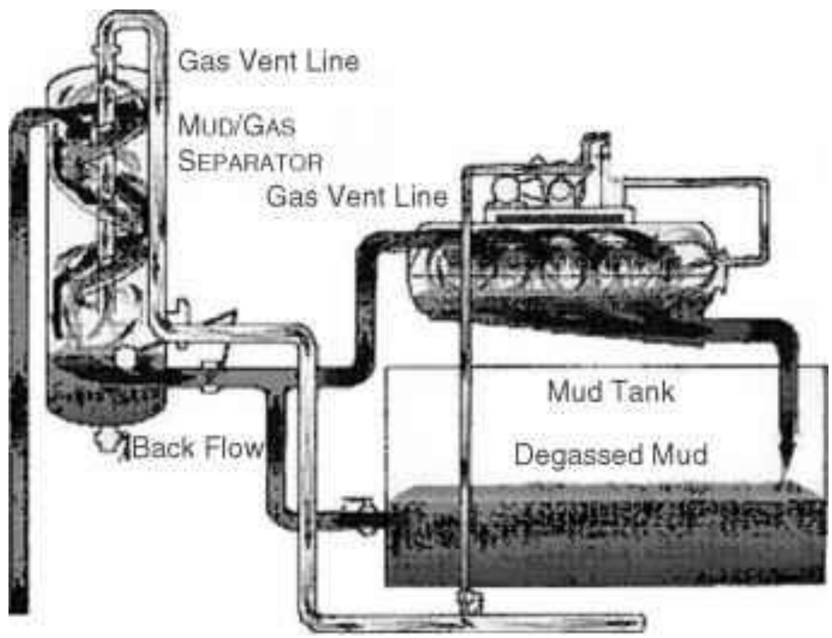

Figure 3.4: Swaco "Total Gas containment system" (source: American Society of Mechanical Engineers, 2005).

[8] American Association of Drilling Engineers, 1999

3.2.3. Hydrocyclones [7]

Particles larger than 74μm can be easily removed, as it was mentioned before, in the shale shakers. Nevertheless, finer particles are equally problematic in a drilling process, as they can also cause well troubles, e.g. very thick filter cake. Thus, other devices, able to remove finer particles are needed in such operations. The basic mechanism of these devices is controlled by the so-called Hydrocyclone. This is a piece of conical equipment using centrifugal forces to separate solids with size less than 80 microns from the drilling mud. Desanders, desilters, and mud cleaners are the devices that use hydrocyclones to manage to discharge solids, each appropriate for solids with different sizes.

There is a specific way in which hydrocyclones manage to separate solids from the rest of the drilling fluid. At this point, it is important to mention that the separation of solids in the hydrocyclones is based on the mass of each grain, which is a combination of density and the particle's size. However, in unweighted mud, density has limited influence, so the particle's mass identifies the particle's size. [5]

The mud enters the hydrocyclone having a great acceleration, which in combination with the conical shape of the hydrocyclone, results in a spiraling motion that creates centrifugal forces. These forces force the larger particles to move to the side of the cone and then drift down to be discharged. At the same time, the drilling mud with the finer solids -colloidal size- move to the center of the cone, eject by the top of it and continue to the next mud cleaning equipment.

As has been mentioned before, the desanders, desilters, and mud cleaners use this type of solids' separation in the drilling operations. Desanders use hydrocyclones that separate solids with size from 80 to 50 microns and are put after the shale shaker and degasser equipment. Desilters separate particles with a range from 40 to 12 microns and mud cleaners use the hydrocyclones with the smallest diameter, so they can separate the finest solids with size fewer than 12 microns.

Colloidal sized particles left in mud after all these separations are removed from the final in sequence mud cleaning equipment, the decanting centrifuges.

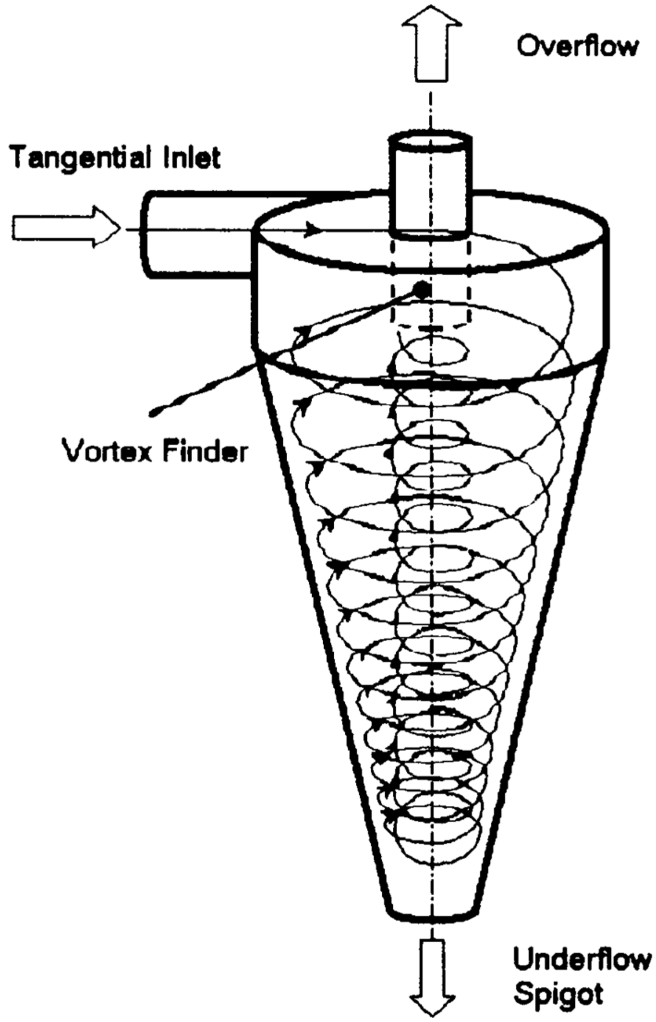

Figure 3.5: The hydrocyclone mechanism (source: www.researchgate.net).

3.2.4. Decanting Centrifuges [5]

After the separation of particles with sizes up to 12 microns, mud continues its cleaning route, entering some devices called Decanting Centrifuges and as their name reveals, they also use centrifugal forces to separate and discharge the solids. These centrifuges are used in specific cases and not in all drilling operations. They separate solids with colloidal size from the drilling fluid because such particles increase a lot the viscosity of the fluid. Having almost the same mechanism as the hydrocyclones, centrifuges create centrifugal forces by the different speed that their two components rotate; an Archimedes' screw that rotates in slow rates inside a conical tube that rotates in a higher rate in the same direction. Mud enters in the middle of this screw and the existed centrifugal forces separate it from the contained solids by forcing them to the sides of the centrifuges and discharge them. The "clean" mud remained, exits the centrifuge, and settles to a tank, ready to enter the well again.

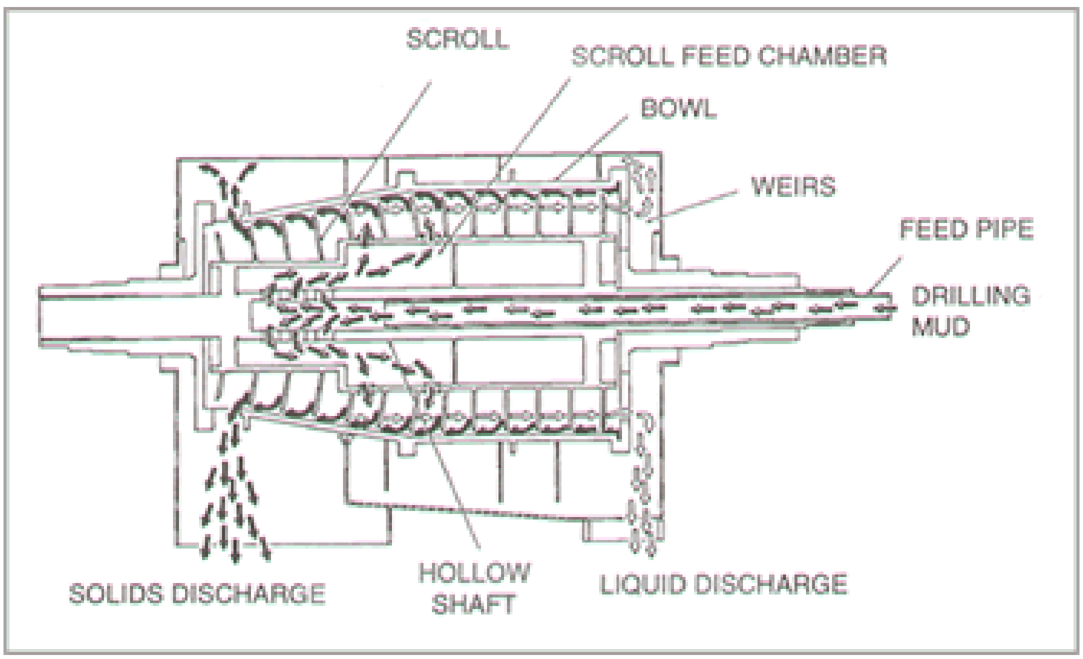

Figure 3.6: Decanting Centrifuges' Mechanism (source: www.mudcontrolequipment.com).

Chapter 4: Drilling Problems and Solutions

4.1. Introduction

As a drilling operation occurs, problems related to the drilled geological formations as to structural and mechanical factors, are likely to appear. Drilling problems are better faced when there is a plan to prevent them from trying to solve them after their appearance. Thus, every drill operation needs to bear in mind some basic steps to prevent such problems.

Firstly, it is essential to identify the problem, and this is only possible when someone knows that problems can very likely occur. Then there is the identification of the source of the problem and of the available tools that will help to prevent it. The next step includes the identification of the desired course of action depending on the source and tools that were previously determined. The final step includes the implementation of the course of action and the review of all these steps to conclude whether they were efficient or not.[9]

The reason why the prevention of drilling problems is so important is first the drilling cost that is affected rapidly due to the increase in the “trip time” or else non-productive time. Moreover, the adding equipment needed in order to deal with these problems and the equipment that may sometimes be lost also affects the operational costs. As a result, drilling operations that are safely performed and cost-efficient take all the necessary measurements in order to prevent the appearance of probable drilling problems.

Three basic drilling problems with their solutions are the basic subject of this chapter; loss circulation, high pressured formations and wellbore instability. These hazards are the most common and at the same time the most problematic, affecting the drilling operation immediately.

Each problem is going to be faced, bearing in mind the steps that were previously mentioned as this is the best way to determine the solutions to each problem. Based on the control of the drilling mud’s properties and the characteristics of the drilled formations, these solutions are mostly determined by the geological point of view.

[9] Fraser K., Peden J., Kenworthy A., 1991

4.2. Lost Circulation

Loss of circulation events are very common but at the same time they are the most expensive drilling problems as they are related to big amounts of drilling mud's leak. Additionally, it is the major factor that affects the increase of the non-productive time, an additional drilling cost, while it can cause a sequence of other conditions, which will also affect the drilling efficiency and cost.[10] This is the reason why every drilling operation needs to have a plan to prevent these cost-effective and sometimes dangerous events. Losses of circulation are not always related to total losses of drilling fluids. On the contrary, partial losses are the most common loss of circulation events. As with every problem, the first step, to prevent such an event, is the identification of the source of the problem. Gaining experience from the variable drilling operations, there have been detected some significant causes of the lost circulation in a borehole.

1. When the drilled formations are highly porous and permeable, some amount of the drilling mud inserts the existed vacancies, depending on their size and the mud's properties. These formations can be gravel, limestone with caves or generally karstified limestone. Moreover, extremely permeable structures can be the fault zones, as they are very flimsy.[9]

   These extremely porous and permeable zones are the so-called "Rubble Zones", consisted of fragmented pieces of rocks, formed because of some external or geological conditions such as the movement of the water table. These conditions change the intensive condition of the formations and lead to the formation of these rubble zones. Moreover, the movement of the water table can corrode the formations and remove any matrix or cement of the sedimentary rocks and as a result porosity and permeability increase. These factors need to be controlled to reduce the probabilities of a loss circulation event.

   As it is obvious, the water can be extremely destructive in a drilling operation. The corrosion act of it, it can also form the so-called "Cavernous Zone", by washing away minerals, matrix and cement and develop caves in the formations with irregular extent and shape. Even the small caves can cause the loss of a great amount of the drilling fluid, so it is important to be quickly detected. The detection of cavernous zones can be easily done by observing the rapid fall of mud level into the well. [10]

[10] Amanullah Md, 2018

A similar to the "Cavernous Zones" zone is the so-called "Vugular Zone". Vugs are also cavities in rocks or veins but unlikely to caves, they are usually filled with minerals. Depending on their size, extend, and inner connectivity vugs can lead to a moderate or severe loss of drilling mud. [10]

The most common and at the same time most hazardous loss of circulation event is when the drilling mud meets a fractured formation. In general, the structural condition of the drilled region is the most decisive factor for a loss circulation event. Fractures are some voids that cease the homogeneity of a formation and can be open, close or filled with minerals and cement. Depending on the size of the openness and the frequency of their appearance, fractures can lead to a severe loss of circulation.

Most of the formations among the Earth's crust is fractured because of the tectonic plates' movement and the dynamic evolution of the crust. Hence, it is more likely in drilling operations to meet fractured rocks than the opposite one. However not all the drilling operations have severe loss of circulation events because there is a necessary condition for this to happen; the fracture's pressure exceeds the wellbore pressure.

The aforementioned dynamic evolution of the Earth's crust also leads to the development of Fault Zones. Faults are a common problem among the drilling operations and their appearance is a possible escape for the drilling mud because of the flimsiness, loose consistency, and big number of vacancies, fractures and pores that they create to the rocks. All these factors with the addition of their high fluid conductivity, make faults a very likely to loss circulation structure. [10]

Another factor that can lead to the formation of a mechanical weaker zone is the phenomenon of the karstification. Soluble rocks such as limestones, dolomites and gypsum are prone to this dissolution, which creates multiple cavities and fractures that have their inter-connection. As a result, karstification creates an undersurface drainage system that decreases the mechanical properties of the rocks in the vicinity of it. Such conditions are appropriate for the appearance of a loss circulation event. [10]

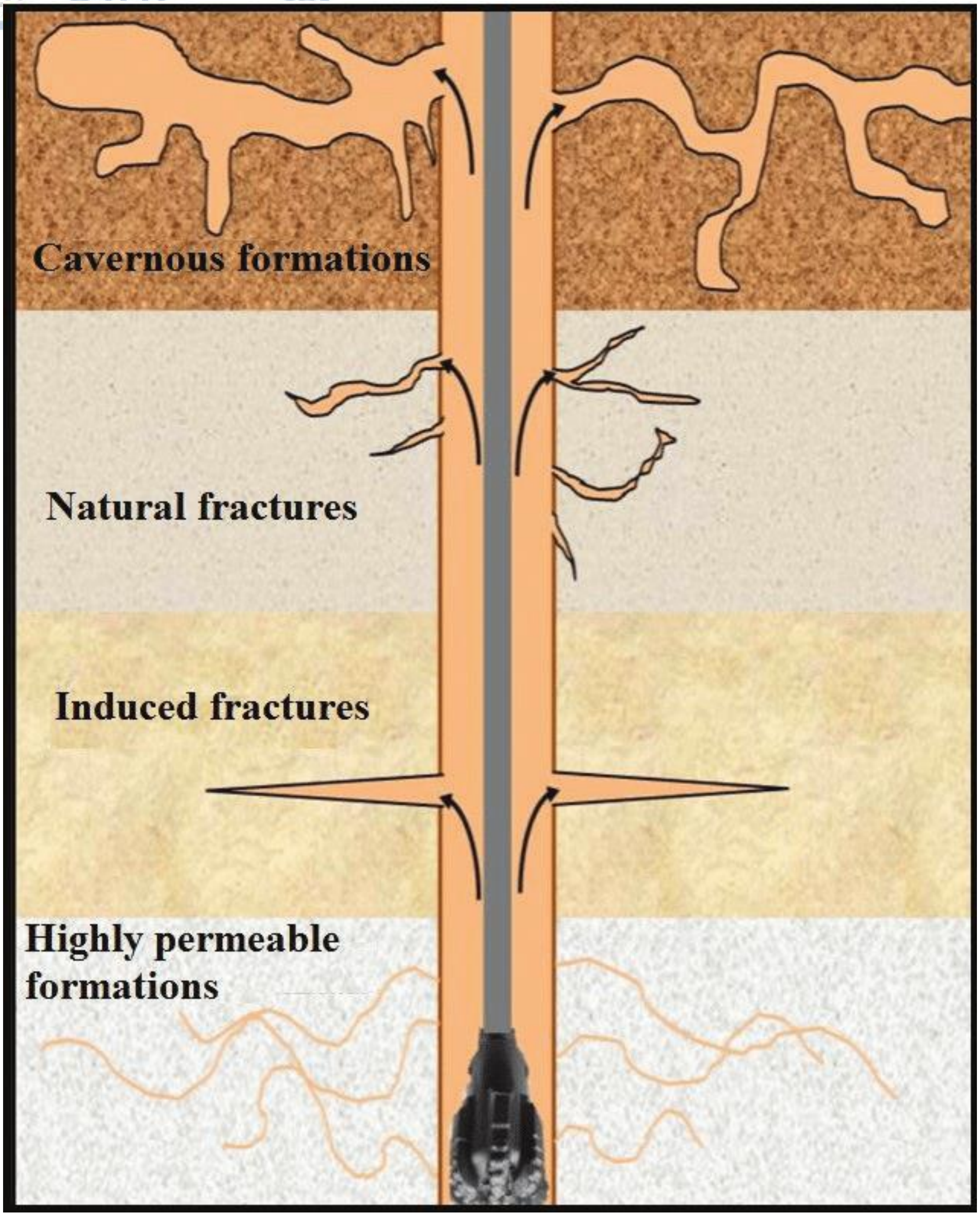

Figure 4.4: The figure shows the affection of different types of fractures, vacancies and geological properties of the rocks on the development of loss circulation events (source: www.researchgate.net)

2. Lost circulation of the mud can also be caused by an excessively thick cementing. During the drilling process it is very likely that weak formations can be met. The cementing, which helps the stabilization of the sides of the well and is a very important stage until the casing's addition, can also be hazardous when mechanically poor rocks are met. A thick cementing layer can fracture the weak formations, and, in this way, it creates a zone that is prone to loss circulation events. Thus, the weight of the mud and its quantity plays a very significant role in the control and prevention of mud losses.

3. Other factors that can lead to the rocks' fracture and consequently to the formation of probable zones of mud losses are the high mud weights, pressure surges because of different factors and high equivalent circulating densities (ECD).[9] An equivalent circulating density is the exerted density from the circulating drilling fluid against the drilled formations that takes into account the pressure drop in the annulus.[11] ECD is an important parameter especially for wells that have a narrow mud weight window.

4. The so-called narrow mud weight window effect is another cause of the mud's lost circulation. Geo-mechanical factors such as in-situ stresses and poor rock mechanical properties can lead to the selection of a mud with a safe mud weight window that is narrow, which means that the upper and lower limit of the drilling mud's weight is very close to each other and in extreme occasions they may be the same. To have this narrow window, ECD needs to be extremely low or strengthening materials need to be added to the circulating mud. These materials increase the fracture gradient of the drilled formations and as a result a loss circulation zone is developed. [10]

5. The process of the drilling itself can also cause the formation of loss circulation zones when it is not performed bearing in mind the properties of the mud and the problems that their change can create. For example, high penetration rates can lead to the formation of a very heavy mud, which affects, in turn the drilled formations by fracturing them. As has been in detail described in this chapter, fractures are possible zones of mud losses, so the prevention of their formation is the key to this problem's solution.

[11] www.glossary.oilfield.slb.com

6. Super K-zones are very prone to loss circulation events as they are extremely permeable zones within the drilled formations. Permeability is not the same in every direction of the rock, so in some cases narrow Super-K zones are developed, where there is a great fluid conductivity and, in this way, big amounts of drilling mud escape from the well. Because in these channels there is a great extent of gaps and voids with no matrix connection, there is a large effect on the core recovery. Thus, the very poor core recovery in core-drilling is an indication of the existence of a super-K zone. [10]

7. In a drilling operation it is obvious that the well site selection is one of the most crucial and decisive for the drilling efficiency factors. The reduction or prevention of a loss circulation event is immediately affected by this selection. As the geological procedures continue in the duration of the geologic time, the rock masses will incur a lot of changes ever after their deposition when they are sedimentary rocks. Leaching and removal of rock masses are those conditions that are connected the most with the loss circulation events. Positioning a well in areas where such rock removals exist, surely, mud losses will occur. Hence the careful selection of the well site can reduce or even fully prevent the appearance of this problem. [10]

8. An equally important factor for the development of a loss circulation zone is the appearance of unconformities. The unconformities are the result of the change of the geological conditions in a depositional environment which consequently led to the deposition of formations with significant differences regarding their geo-mechanical properties. These differences can easily lead to the formation of a loss zone. The shallower part of the unconformity is the one that is more likely to “host” the loss circulation zone since the consolidation is lower there. Hence, the rocks in the shallower part of the unconformity are poorer geo-mechanically and as a result the mud weight window is narrow, which may lead to the increase of the fracture gradient of the rocks and a loss circulation event. [10]

After the detection of the problem, it is important to determine some other factors before concluding to the most appropriate to lost circulation solution. Firstly, it needs to be checked whether the well is kicking or not. The term “kick” describes the condition when formation fluids insert the wellbore. This can be occurred because of different reasons such as when the formation pressure exceeds the wellbore pressure. Then is needed to check for any leak in the surface equipment and determine whether the losses are static or dynamic. Dynamic losses occur only when the mud is circulating while static losses are expected in all the cases.[9] The next step is to define the source of the problem, one or more of the aforementioned causes, and gradually decide the most efficient solution.

Depending on how severe the losses are, the wanted solutions could be categorized into two classes; the solutions that are referred to partial losses and the solutions that are referred to total losses. As was mentioned before, losses are not always total and most of the time partial.

Some probable solutions for partial losses depending on the source of the problem could be the following:

i. Reduce the mud weight in cases when weak formations are drilled or when mud tends to fracture the drilled formations.[9] The concept of reducing the mud’s weight is by the process of dilution. In the duration of this process a lightweight fluid is added in the mud so when they mix the final weight is lighter than the one at the beginning of the process.[12]

ii. When the loss circulation events occur because of the existence of a porous formation or in general a fractured, vugular, cavernous formation, the mud loss happens because the vacancies or pores of the formations are larger than the bridging particles of the mud. On such occasions the best solution is to add the so-called LCM (=Lost Circulation Materials). These materials are solid particles added into the mud to reduce or even prevent the losses by sealing the loss zones. These particles can be by-products from the food industry or chemical manufacturing industries such as mica, cellophane, walnut shells, plant fibers, polymeric materials.[11]

[12] www.drillingformulas.com

iii. What is more efficient in drilling operations than the LCMs in a mixture of different LCMs, called lost circulation pills and they can spot the loss zone and remain there for a short period. The amount of the pills needed to deal with the loss problem is depended on the magnitude of the loss. One, two or more pills can be used to prevent the losses. In the case of slight losses, mica (fine or coarse) is more preferred while in severe losses a mixture of different types and size particles is used. [9]

iv. If it has been proved that the well is kicking because of a loss circulation event, then this event must be the first to be controlled. To deal with a loss zone when the well is kicking the use of lost circulation pills is the best solution. On the contrary, when the loss circulation event has happened because of the wellbore kick, then the kick needs to be controlled first. The best way to deal with a kick is to either increase the mud weight below the loss zone and decrease it above it or placing a barite plug below the loss zone in the open hole. [9]

These solutions can also be applied to cases with total losses. These cases are not so often in the drilling operations and lost circulation events are most of the time curable. However, in some cases such as when there are very fractured rocks or when drilling in caves, total losses are possible. To deal with the total losses there are two options; either cure them or continue the drilling blind with a complete mud disappearance. Of course, in every drilling operation the priority is to try and cure these zones with one of the aforementioned solutions depending on the case. When these solutions are not effective then if there is a certainty that the reservoir is productive, the drilling operation continues blindly. [9]

4.3. Shale Instability

The wellbore instability is a very important parameter that needs to be examined and prevented in the maximum possible way. It is a condition that expresses the difference in size between the bit's and opened hole's diameter. It also describes the deviation in shape or structural integrity of the open hole. In normal circumstances the hole's diameters should be the same as that of the drilling bit. This state is best described by the term "gauge hole". However, what happens in a drilling operation is a lot different than the condition just described. Shale instability is the most common wellbore instability cause but before analyzing its characteristics, it would be better to mention some general information about the phenomenon of wellbore instability.

Overgauged or undergauged holes are the most common problems that geologists and engineers must deal with during a wellbore opening as an expression of wellbore instability. An overgauged hole is formed when the hole's diameter is bigger than the bit's that was used to drill it while an undergauged hole is formed when the hole's diameter is smaller than the bit's diameter.

The consequences of these wellbore instability's expressions are dramatic in the general outcome of a drilling process. Sticking pipe, loss of very expensive equipment such as logging tools, increasing of the non-productive time have the result of the rapid increase of the total drilling cost. In some cases, a complete hole collapse is also likely.[13]

Other problems related to wellbore instability could be categorized in four different groups; hole closure or narrowing, hole enlargement or washouts, fracturing and collapse.[13]

Hole closure is a process in which the hole narrows sometimes due to overburden pressure and it is likely to occur in plastic-flowing shales and salt sections. Pipe sticking and increase in torque and drag are some of the problems associated with this condition.[13]

Hole enlargement is a condition in which the hole is a lot bigger than expected and it can be caused by hydraulic erosion because of the fluids' circulation or by the abrasion exerted by the drill string to the sides of the well or by a phenomenon called shale swelling. This is a situation that reduces the formation's permeability because of the change of clays equilibrium, minerals by which the shales are consisted of. This clay equilibrium changes because of the contact of the shale with mostly water-based muds and in order to deal with this problem, KCl can be added into the circulation system. Cementing difficulty, problems with logging tools and hole deviation are some of the problems caused by hole enlargement.[13]

[13] Γεωργακόπουλος, (Ευστ.Γεωτρ)

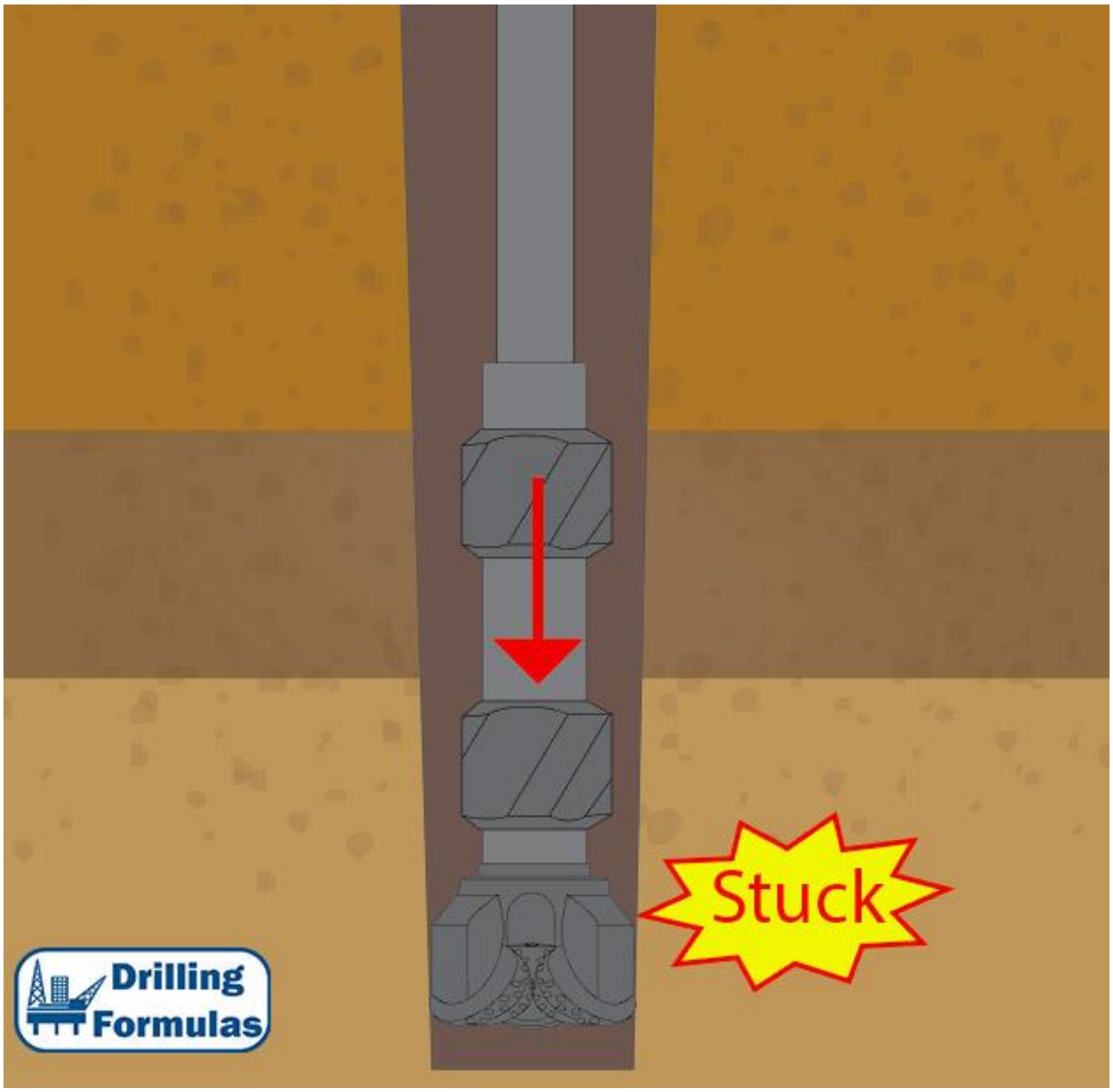

Figure 4.5: The figure shows an undergauged hole with its possible side effect, the pipe sticking. (source: www.drillingformulas.com)

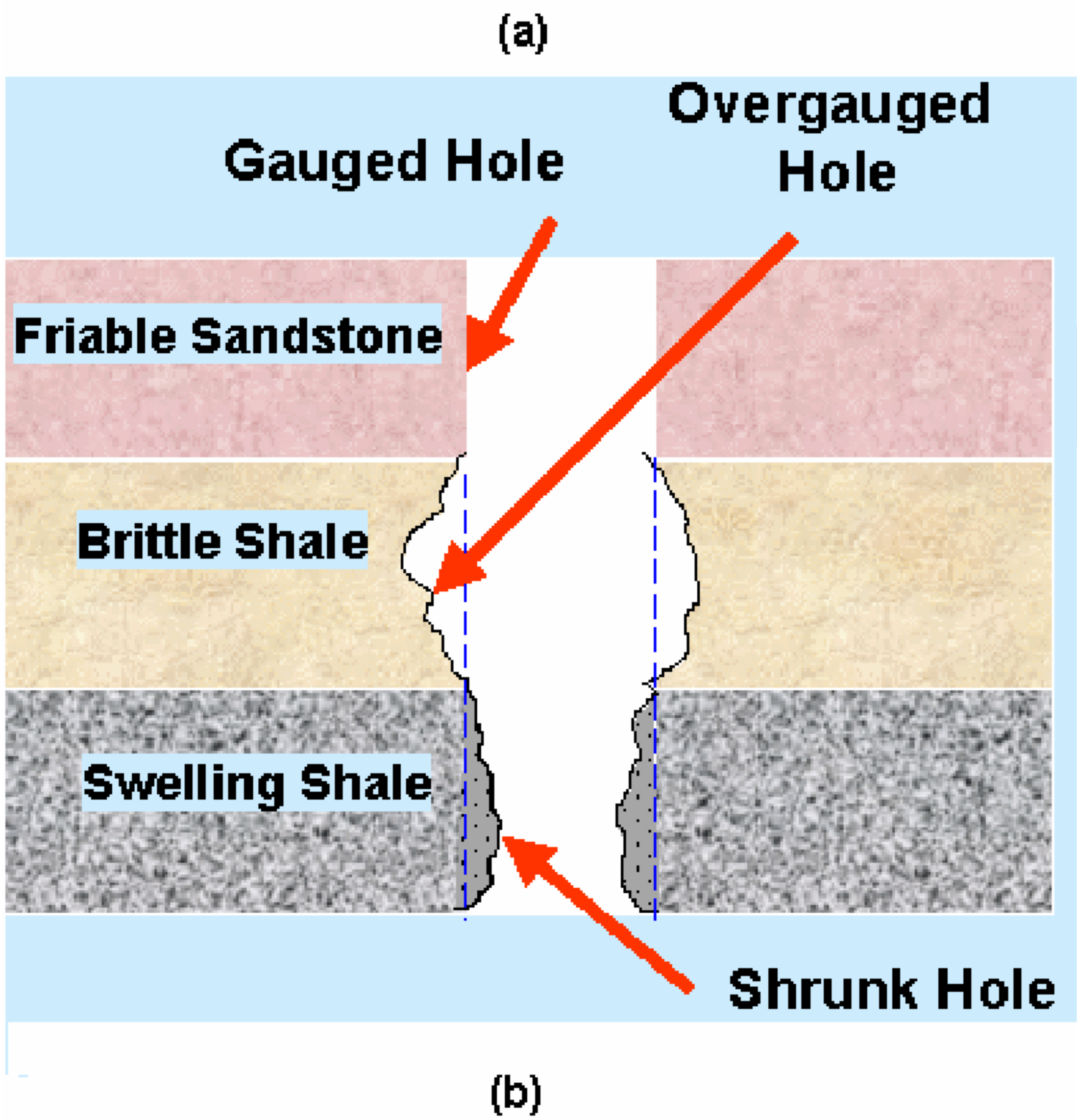

Figure 4.6: The three states of a drilling hole; gauged, overgauged and undergauged hole (source: www.semanticscholar.org)

Fracturing, as has been described in the previous subchapter, can occur when the drilling fluid's pressure exceeds the formation pressure. This process leads to the crushing of the formation making it unstable and helping in this way the formation of alternative routes for the drilling fluid's circulation and as a result a loss circulation event. Moreover, an intrusion of the formation's fluids into the wellbore is very likely if now the formation pressure exceeds the wellbore's, so a kick can happen.

Last but not least, one of the most undesirable wellbore instability events is the hole collapse. When the sides of the well cannot be supported by the pressure exerted by the drilling mud in an open hole condition, then the hole collapses resulting in very bad consequences. One of them is the pipe sticking in which the pipe cannot be pulled out of the hole without damaging the pipe.[2] This can cost a lot to the company that has loaned the drill and of course it destroys the whole drilling operation to the specific place.

In general, what causes the instability of a well is the disturbance of the equilibrium that exists in some depth between the rock strength and the in-situ stresses exerted to the rock.[13] When a drilling process occurs, the opening of the hole, crushing the underground formations is itself a condition that leads to this disturbance. At the same time, the intrusion of the drilling fluid, which helps the drilling operation in many ways as described in chapter 2, it contributes however to this instability, as it interacts with the drilled formations.[13]

Specifically speaking, the causes of a wellbore instability problem are:

i. Mechanical failure caused by in-situ stresses

On this occasion, failure occurs due to the change of the stresses-strength equilibrium. This means that a failure is likely to occur when the stresses exerted on the rock exceed the compressive or tensile strength of the rock. The compressive strength of the rock can be exceeded if the mud weight is so low that shear stresses act on the rock. The tensile strength can be exceeded if the mud weight is so excessive that normal stresses act on the rock.[13]

ii. Man-made wellbore instability

Not only naturally occurring causes are responsible for a wellbore instability. Sometimes the drilling practices are poor, and they can lead to such a problem. For example, excessive drilling vibrations or wellbore stresses and poor hole cleaning can be decisive for this problem. Furthermore, lack of adequate well planning can also be a man-made failure that leads to an instability problem, such as an unsuitable selection of the drilling fluid. As was mentioned in the second chapter of this thesis, each type of drilling muds has its own characteristics and must be carefully selected regarding the region and the formation's characteristics.[13]

iii. Shale instability

Shales are some of the most common formations when drilling for the exploration and production of hydrocarbons. 75% of the drilled formations in worldwide drilling operations are shales.[13] These rocks consist of clays, silt and sometimes of very fine sand, which make them very fine-grained sedimentary rocks. Their general characteristics are their low permeability and the high proportion of clay minerals in their composition. Because of their frequent appearance is the drilling operations, the problems that are related to them are very common and they consume an annual sum of one-half billion US dollars for their dealing.[13] Most of the problems related to shales are summarized into the term Shale Instability. This instability can lead to severe wellbore problems from washouts to total hole collapses. Due to different factors the shales' characteristics can change and create instabilities during the drilling process. The causes of this phenomenon can be categorized into two conditions; mechanical and chemical shale instabilities.

Mechanical shale instability is caused by the change in stress equilibrium that the formations have before the drilling. As mentioned before the hole opening itself contributes to this situation, so the circulating mud has the role of the stress state restoration. However, sometimes the mud cannot fulfill this goal and as a result the shale becomes unstable.

Chemical shale instability is an instability caused by the reaction between the drilling fluid and the shale. The swelling of the shales when being in contact with water is the most important result of this reaction, which leads to the dilution of the content minerals and the gradual disruption of the shales' structure. This happens because of the decrease of the mechanical strength of the formation or the pore pressure of the shale in the sides of the well as the shales absorb the water from the drilling mud. This phenomenon is time-dependent so it is possible that will not be observed from the first moment of its appearance.[12] Mechanisms that contribute to the chemical shale instability are the following:

- Capillary pressure which is developed because of the contact between the mud and the fluid inside the shale pores. In order to prevent the influx of these native fluids into the wellbore, capillary pressure needs to be increased by using an oil-based mud, when other conditions also allow it.[2]

- Osmotic pressure which when is formed, it makes the shales to function as a semi-permeable membrane. As a result, water can move from shales to mud or vice versa. Osmotic pressure develops when the energy level between the shale pore fluid and drilling mud is different. To reduce the water movement this difference must be also reduced by adding electrolytes into the circulating system such as seawater, gypsum, KCl, NaCl, polymers and others. [2]
- Pressure diffusion is a phenomenon occurring when the pressure changes in the vicinity of the wellbore sides. This happens because of the compression exerted by the drilling fluid pressure and the osmotic pressure in the shale pore fluid. [2]
- Borehole fluid invasion into shale. This phenomenon is always occurring in a drilling operation as it is expected that the difference between the borehole fluid pressure and the pore fluid pressure is positive. When shales are drilled, however, this fluid invasion can lead to shale swelling and as a result of chemical shale instabilities. To prevent this condition an increase in mud viscosity is a solution. [2]

In general, indications of shale instability problems can help a drilling operation observe and understand sooner this problem and as a result it will be easier to prevent its severe consequences. The in-time prediction of a shale instability problem can also prevent the formation of other problems related to shale instabilities. Some of the aforementioned indications are the following:[12]

- Torque and drag increase. Torque is the force that causes the rotation of the drillstring while drag expresses the difficulty in pulling up the drillstring.
- Worsening of the drilling mud's properties. An increase in viscosity or yield point shows that the mud becomes thicker as it becomes enriched to the diluted particles from the shales.
- Increase in pump pressure.
- Observe shale parts is shale shakers.

However, a shale instability problem can also lead to other drilling problems. It is not necessary that if a shale instability problem comes to an end, that it cannot provoke and "leave behind" other significant problems. Pipe sticking is one of the problems related to shale instability (Figure 4.3) because shales are starting due to swelling to fall apart causing a pipe sticking problem. Indications of a stuck pipe in such a circumstance is an increase in pump pressure when drilling at low rates and difficulty to mud circulation.[12]

To overcome a pipe sticking problem while shale instability exists, these are the possible steps: [12]

1. Mud needs to circulate at low pressure to manage to free the pipe because high pump pressures will pack the annulus harder.
2. In drilling state, an application of the maximum torque and jarring down with the maximum trip load is the best option while in tripping state the best option is to jar up with the maximum trip load and without any torque.
3. Repeat these steps until the pipe is free.

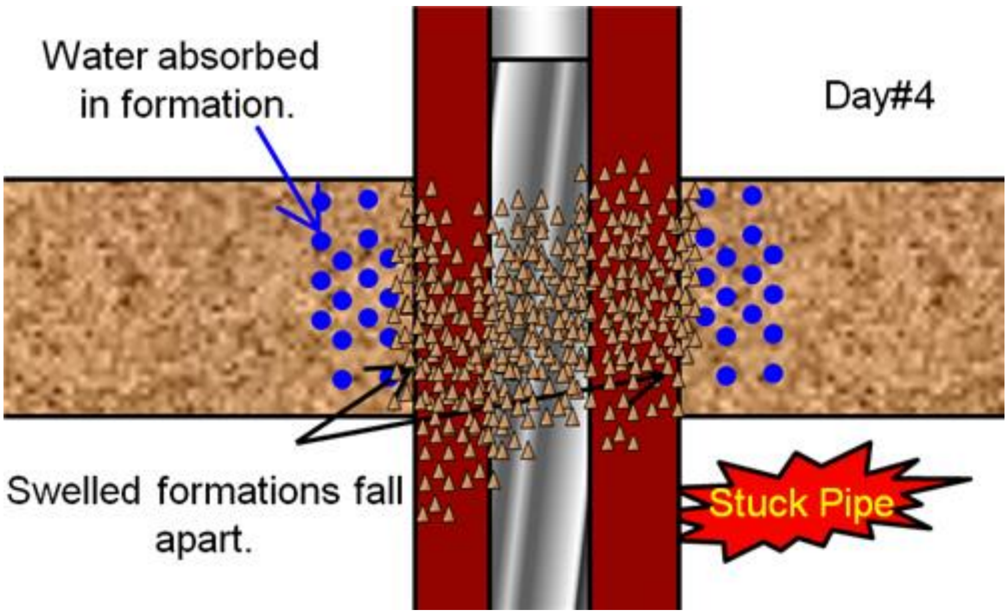

Figure 4.7: The figure shows an example of a chemical shale instability occurrence when swelling is observed. (source: www.drillingformulas.com)

Wellbore instability can be prevented but not fully eliminated as it is difficult to restore and redetermine the in-situ mechanical and chemical condition of the rocks once they have been disrupted. Some of the solutions that can be applied to prevent wellbore instabilities are the following:[13]

- The borehole fluid selection is very important for the prevention of this problem as water-based muds can be problematic when being in contact with shales and thus causing the chemical shale instability. The drilling mud needs to be compatible with the drilled formations so if water-based muds are the only suitable to the occasion fluids then the adding of salts can reduce the chemical reaction between the water and the shales. In cases in which oil-based muds can be used then it is preferable to do so when shales are drilled.

- The so-called safe mud weight window is also very important to keep the wellbore stable. As was mentioned before mechanical shale instabilities are controlled by the mud weight selection, so the proper weight, depending on the drilled formations, can help to protect the wellbore from instabilities.
- The proper hole-trajectory selection is also an important factor as man-made instabilities due to poor well planning is one major cause of wellbore instabilities.
- Controlling the Equivalent Circulating Density (ECD) is decisive for the prevention of a wellbore instability problem as it affected by the mud weight window.
- Minimizing the time that the hole is open is another practice that can contribute to this series of solutions, as in this way the probability of a hole collapse is reduced.
- Monitoring the trend changes such as torque, drag, mud pressure can be very helpful because such changes are indications of a shale instability event.
- Hole cleaning keeping a good flow rate is also an important factor as the removal of particles having inserted the wellbore helps to keep it stable.[12]

4.4. Abnormal Pressures

The detection and control of fluid pressures within a wellbore are one of the most important tasks needed to be carefully examined to keep the wellbore stable and the drilling operation efficient. Referring to the term “normal pressures”, we mean that the fluid pressures in the reservoir are between 0,43 and 0,50 psi/ft. Psi is a measurement of pressure, expressing the pressure resulting from a force of one-pound force applied to an area of one square inch (pounds per square inch).

As abnormal pressures are called the pressures of fluids in the reservoirs that are either higher or lower than the normal ones. On the first occasion the reservoirs are called overpressured while on the second occasion they are called subnormally pressured reservoirs.

In order to refer to the causes, results and indications of an abnormal pressure’s formation, some terms need to be presented.

Permeability is the ability of rocks that expresses how easy or difficult a fluid can circulate in their masses. This ability depends on the shape and magnitude of the grains of the rock and is separated into the vertical and horizontal permeability, as it can be altered both in the vertical and horizontal direction.

Porosity is a property of the rocks that expresses the volume of the voids existed in the rock’s mass over the total volume of the rock. These voids are called pores and can be filled with fluids or gasses and therefore a porous formation is important to produce hydrocarbons.

Abnormal pressures commonly occur during a drilling operation and their consequences can be severe, creating also other drilling problems. Each type of the aforementioned reservoirs with abnormal pressures is going to be separately described in this chapter.

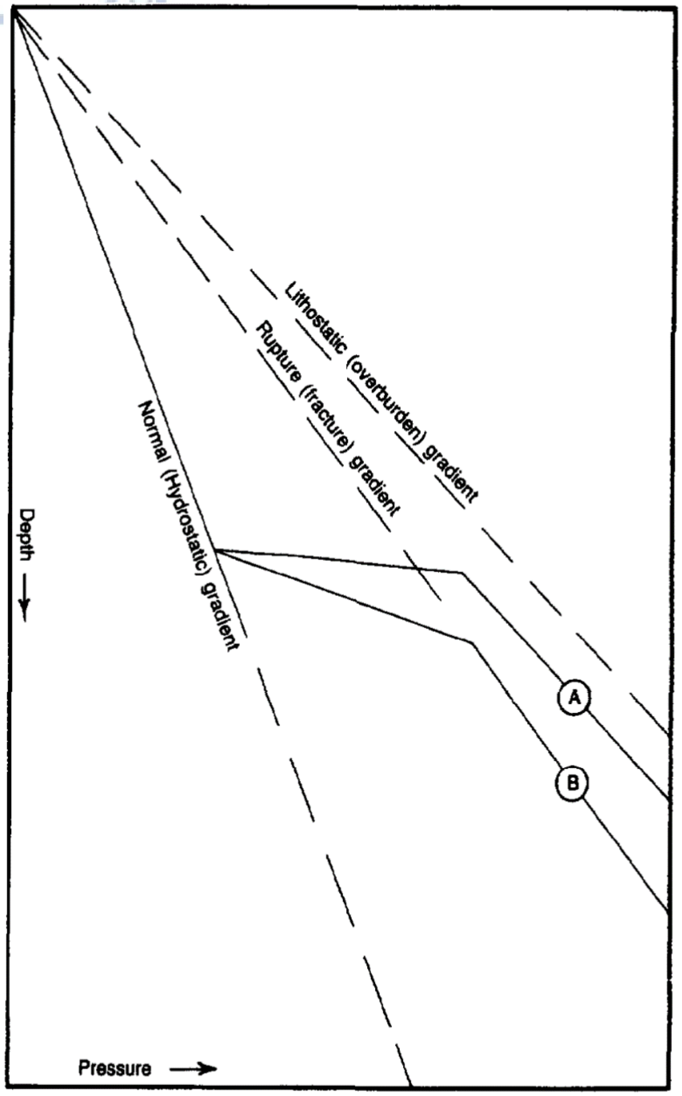

Figure 4.8: In normal conditions, hydrostatic pressure increases with depth reaching a pressure range between 0,43 and 0,50 psi/ft. Excelling this normal gradient leads to overpressures while not reaching this gradient leads to subpressures. (source: www.wiki.aapg.org).

4.4.1. Overpressured reservoirs

Overpressured reservoirs are those in which fluids have greater pressures than the normal ones (0,43-0,50 psi/ft). Various causes are leading to overpressured fluids within the pores of a reservoir.

The first one is connected to the arrested compaction of the shales. As was mentioned before, shales comprise 75% of the drilled formations, thus problems related to them are also frequently met. As shales are buried deeper, compaction is a naturally occurring process. In the duration of this compaction process, shales expulse the pore water as they are permeable enough to do so. This pore water is expulsed upwards, so vertical permeability is the one helping in this situation. However, as the compaction continues, the clay grains contained in the shales become parallel, reducing this vertical permeability. Moreover, if there is not a sandy or silty formation in the vicinity of the shales, water remains in the pores. Thus, as the weight of the overburden formations increases, the pressure of the pore water also increases for the shales to tolerate this additional weight. If a sandy bed is near to this shale, it shares the same pressure as the one of the shale pore water no matter what fluid it contains (oil, gas or water), and in this way can a reservoir become overpressured. This type of overpressured problem is connected to the depositional environment as it needs to be comprised of thick shale depositions.[14]

An equally important cause of overpressured reservoirs is the so-called aquathermal effect. This effect is an expected factor as it is connected to the temperature increase that happens due to the burial of the sediments which will be gradual with the diagenesis process converted into a possible reservoir. This temperature increase evokes an increase in the volume of the water existed in the sediments. If this sediment is sealed with an impermeable layer, e.g. shale, then the water volume increase will result in a pressure increase. This pressure is much greater than the one resulted from the weight of the overburden sediments. For example, for regions where the geothermal gradient is 25°C every 1Km and sediments have been completely sealed with an impermeable formation, the pressure increase is 1.8 psi/ft.[14]

The thermal cracking of the organic matter is another reason for the development of overpressured reservoirs. This is the process that leads to the formation of oil or gas as thermal cracking needs to be done for the kerogen to be converted to oil or gas depending on the temperature existing in the reservoir (oil or gas window). This cracking can lead to an increase in the volume of the fluids which would also lead to a pressure increase.[14]

[14] www.wiki.aapg.org

Tectonic phenomena are equally important factors that contribute to the pressure increase of the pore fluids. There are two ways in which tectonic phenomena affect the fluids' pressure. The first one is the so-called lateral tectonic loading which leads to an increase in lateral compressive stresses, because of the horizontal compaction of sediments. At the same time, there is vertical compaction of the sediments due to the addition of the overburden beds. These additional stresses in the sediments evoke the pressure increase in the pore fluids that have not been expulsed during the diagenesis.[15]

The second one is caused because of the movement of a fault but it is also based on the compression coming from tectonic phenomena. This movement of the plane of the fault results in bringing the high pressures' zones in contact with the lower pressures' sand bodies. The charged sand bodies can, after the closure of the fault, release their pressure to the surrounding shales, forming an overpressured shale zone.[15]

Overpressured formations are themselves very hazardous for the drilling operations especially costly and they are connected to the following drilling problems.[14]

- Blowouts are possible effects of an overpressured reservoir as high pressures can fracture the drilled formations and therefore formation fluids can be inserted into the well. This can lead to an uncontrolled influx of these fluids in the wellbore and as a result of a blowout event.
- Caving is a situation that occurs when the pore pressure is high in a low permeability formation resulting in a stress relief or the rock, called caving.
- When drilling an overpressured formation, stress relief will likely occur on the sides of the borehole. This can lead to stuck pipe problems.
- A loss circulation problem is also a probable side-effect of drilling an overpressured formation because an increase in mud weight, necessary for the pressure control around the drilling bit, may fracture the drilled formations. The existence of fractures is the most common cause for the formation of a loss circulation zone.

It is obvious that the prediction or, when not possible, the detection of an overpressured formation is significant for the efficiency of a drilling operation. As these problems are related to the in-situ formation pressure, it is almost impossible to interfere and directly give a solution. Thus, prediction or detection of indications which are connected to overpressure is the most powerful weapon for the drilling experts.

To predict the existence of an overpressured zone before the start of the drilling operation, a seismic geophysical survey is one of the most valid and reliable methods

[15] John Wiley and Sons, Inc., 2015

capable to detect such anomalies. This method uses the velocity in which seismic waves propagate in order to simulate the physical properties of the undersurface rocks and eventually to predict the type of the formations drilled. In normal conditions, a seismic survey would show that velocity increases with depth, as the compaction of the sediments is stronger as the sediments are buried. Thus, a sudden decrease in seismic waves' velocity can indicate a lack of compaction and consequently an overpressured formation.[14]

However, in some cases the detection of such formations is made during a drilling process. The methods that are mostly used for this purpose and are more reliable are the following:[14]

- Increase in drilling rates. When drilling shales, the drilling rate normally decreases with depth as the shales become more compact. An increase in this rate may be an indication of an overpressured formation.
- Rising mud tank level. This situation occurs when the amount of mud that returns to the mud tanks is greater than the amount of mud that inserts the wellbore. This is the so-called "kick" phenomenon which can also lead to a hazardous blowout problem and can be an indication of the existence of an overpressured zone.

Other less reliable indications are the delayed ones, meaning those that can be detected after drilling mud returns to the surface. One such indication is the gas detection in the mud. The source of this gas may be others such as from organic-rich shales. However, it can also be produced because in some shales there is methane dissolved in the pore water. Moreover, overpressured zones are connected to undercompacted shales. These shales have a lower density than the normal shales as their porosity is higher. Density can be measured in cuttings with several methods. Another useful method is well logging. Electric resistivity is the most reliable logging method as undercompaction makes shales having a lower resistivity than the ones that have been normally compacted.[14]

To prevent the development of further drilling problems related to overpressured zones, the change of the mud's properties is inevitable. Thus, after detecting an overpressured zone, "heavy" minerals should be added to the mud to increase its weight. A mineral that is mostly used in order to fulfill this goal is the barite. Increasing the weight of the mud leads to an increase in hydrostatic pressure resulting in controlling the overpressured zones. The reason that specifically barite is mostly used in this application is due to its efficiency in increasing the mud weight without causing any environmental problems as the Environmental Protection Agency does not consider barite additives as hazardous wastes.[16] Moreover, barite can be used even in high depths as it is efficient even in high-temperature wells.[16]

4.4.2. Subnormally pressured reservoirs

These reservoirs contain fluids with much lower pressure than the normal reservoirs. These pressures are less than 0,43 psi per ft. Underpressures are not well examined because they are not connected to a lot of drilling problems. Their source is still undetermined, but it seems that they are attached to erosion and uplifting. Specifically speaking, it is considered that when an isolated reservoir of oil or gas is subjected to a process that will remove overburden weight the volume of the pores increases due to an elastic rebound of the reservoir. However, this elastic rebound is much lower in water than in sandstones for example (most common reservoirs) leading to a pressure drop in pore water. [14]

Subnormally pressured reservoirs may not relate to severe drilling problems, nevertheless they are very common, and they can evoke some drilling problems. One of the most important problems is caused because of the difference between the formation pressure and drilling mud's pressure. If the pressure of the drilled formations is much lower than the mud's, filtration is very intense making the formation unstable as when shales are drilled, swelling is probable. In this case, an avoidance of water-based mud or in general the avoidance of high-density drilling fluids is the best option. Furthermore, setting casing when underpressures are detected is also an efficient solution.[14]

[16] www.halliburton.com

Chapter 5: Conclusion

Having described all the previous chapters, it is clear that the role of a drilling mud while drilling for the exploration or production of hydrocarbons is decisive. Its functions are so fundamental that without it the cost would be significantly higher, the process would be more difficult and some of the problems could not be easily solved.

Another important feature of the drilling mud is the range of types that exist, allowing the geologists or engineers to choose between them. Choosing between a water-based, oil-based, synthetic-based mud and a pneumatic drilling fluid is significant for the efficiency of the operation depending on the drilled formations' and region's characteristics.

Moreover, the efficiency of a drilling operation is highly dependent on the fact that the mud is circulated, meaning that it can help in transmitting geological information about the subsurface conditions, allowing at the same time its cleaning on the surface when it returns from the wellbore. In Chapter 3 all necessary mud cleaning equipment was described. This equipment is also very helpful for the detection of undesirable elements or mud's properties leading to the detection of a drilling problem.

Drilling problems are the context of the last chapter of this thesis, containing information about problems that are caused or related to the drilling fluids. The importance of the detection or even prediction of these problems was mainly highlighted in this chapter. Loss of circulation, shale or in general wellbore instability and abnormal pressures were analytically described, focusing on the causes, related problems and solutions to these problems.

Drilling problems are inevitable but planning a well-organized drilling program can eliminate their appearance and most importantly their hazards. Designing an efficient drilling program requires knowledge, experience and the ability to predict subsurface conditions. "Decoding" the mud's properties helps in succeeding in the aforementioned requirements and therefore overcoming the probable drilling geological hazards.

Abstract

Drilling geological hazards are some of the most significant factors that affect the efficiency and cost of a drilling operation. They are numerous and their prediction or prevention is decisive for the exploration or production of hydrocarbons. The most common and hazardous geological problems are; the existence of Loss Circulation Zones, the Instability of Shales and the presence of Abnormal Pressures in the production zones. All these problems are related to the so-called drilling fluids. Drilling Fluid or else drilling mud has a very important role to the success of a drilling operation but at the same time can cause some problems, like the aforementioned, if the geologists or engineers do not take into consideration other factors. Thus, the right management of this fluid, which requires a well-planned drilling program, as well as the control of the systems needed to clean or circulate this fluid, will contribute to a productive drilling operation. The drilling fluids' characteristics, the right selection of the mud cleaning's system components, the knowledge of the factors that can cause these hazardous problems as well as the actions needed to be made to deal with them result to a well-organized drilling program.

Περίληψη

Γεωλογικά προβλήματα τα οποία μπορούν να εμφανιστούν κατά τη διάρκεια μιας γεώτρησης μπορούν να επηρεάσουν σημαντικά την αποτελεσματικότητα καθώς και το κόστος αυτής της γεώτρησης. Τα προβλήματα αυτά είναι πολυάριθμα κι έτσι η πρόβλεψη της εμφάνισής τους ή η μετέπειτα αντιμετώπισή τους είναι καθοριστική για την έρευνα και παραγωγή υδρογονανθράκων. Κάποια από τα πιο κοινά αλλά ταυτόχρονα αρκετά επικίνδυνα γεωλογικά προβλήματα κατά τη διάρκεια μιας γεώτρησης είναι τα εξής: η ύπαρξη ζωνών από τις οποίες διαφεύγουν τα ρευστά της γεώτρησης, η αστάθεια των σχιστόλιθων και η παρουσία ανώμαλων πιέσεων στις παραγωγικές ζώνες. Όλα αυτά τα προβλήματα σχετίζονται με τον λεγόμενο πολφό της γεώτρησης, ο οποίος διαδραματίζει έναν πολύ σημαντικό ρόλο για την επιτυχία μιας γεώτρησης αλλά ταυτόχρονα είναι και υπαίτιος διάφορων προβλημάτων. Κάποια από αυτά τα προβλήματα είναι αυτά που αναφέρθηκαν προηγουμένως και εμφανίζονται όταν οι γεωλόγοι ή οι μηχανικοί δεν λαμβάνουν τόσο σοβαρά υπόψη κάποιους παράγοντες. Συνεπώς, η σωστή διαχείριση του πολφού της γεώτρησης, η οποία προϋποθέτει ένα πολύ καλά σχεδιασμένο διατρητικό πρόγραμμα, όπως επίσης και ο έλεγχος των συστημάτων που είναι απαραίτητα για τον καθαρισμό και την κυκλοφορία του εντός της γεώτρησης, συμβάλλουν στην ύπαρξη μιας παραγωγικής γεώτρησης. Ένα καλά οργανωμένο διατρητικό πρόγραμμα μπορεί να σχεδιαστεί μόνο εάν ληφθούν υπόψη οι παρακάτω παράγοντες: πρέπει να είναι γνωστά τα χαρακτηριστικά του πολφού της γεώτρησης, να έχει επιλεγεί ο σωστός εξοπλισμός για το σύστημα καθαρισμού της λάσπης, και τέλος να είναι γνωστοί όχι μόνο οι παράγοντες που μπορούν να προκαλέσουν γεωλογικά προβλήματα αλλά και οι απαραίτητες δράσεις που θα οδηγήσουν στην επίλυσή τους.

References

[1] Spears & Associates, (2004), *Oilfield Market Report*, [https://spearsresearch.com/reports].

[2] https://petrowiki.spe.org/Drilling_fluids

https://petrowiki.org/Borehole_instability

[3] Skalle P., (2011), *Drilling Fluid Engineering*, Skalle P. & Ventus Publishing ApS.

[4] Γεωργακόπουλος Α., *Κοιτασματολογία Πετρελαίου.*

[5] Oilfield Review, *Drilling Mud: Monitoring and Managing it.*

[6] H.C.H. Darley, George R. Gray, (1980), *Composition and Properties of Drilling and Completion Fluids,* Gulf Publishing Company, Houston, TX.

[7] American Society of Mechanical Engineers [ASME], (2005), *Drilling Fluids Processing Handbook,* Elsevier Inc.

[8] American Association of Drilling Engineers, (1999), *Shale Shakers and Drilling Fluid Systems*, Gulf Publishing Company, Houston, TX.

[9] Fraser K., Peden J., Kenworthy A., (1991), *Managing Drilling Operations*, Elsevier Science Publishers LTD.

[10] Amanullah Md, Alouhali R., Arfaj M., (2018), *Impact of Geological and Geo-Mechanical Controls in Creating Various Drilling Problems.*

[11] https://www.glossary.oilfield.slb.com/Terms/e/equivalent_circulating_density.aspx

https://www.glossary.oilfield.slb.com/Terms/l/lcm.aspx

[12] https://www.drillingformulas.com/reduce-mud-weight-by-dilution/

http://www.drillingformulas.com/shale-instability-causes-stuck-pipe/

[13] Γεωργακόπουλος Α., *Ευστάθεια Γεωτρήσεων*

[14] https://wiki.aapg.org/Pressure_detection

[15] John Wiley and Sons, Inc., (2015), *Fundamentals of Gas Shale Reservoirs.*

[16] https://www.halliburton.com/en-US/ps/cementing/materials-chemicals-additives/agents/heavyweight/barite-heavyweight-additive.html